- FORESEE -

Future proofing strategies FOr RESilient transport networks against Extreme Events

Deliverable 6.3

Case Study #2 A16 km.80-110, IT

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1. INTRODUCTION

This deliverable will consist in the test and validation, on the A16, in Italy, of the project outcomes in order to select and design the best technical solutions for preventive maintenance, to provide ground and road control (risk assessment), to ensure user's safety (notices and events management), to plan future maintenance interventions and to set up of procedures for events management[1]-[3]

2. CASE STUDY #2 DESCRIPTION

Transport infrastructure faces new challenges with regard to environment, mobility, technology as well as individual and collective aspirations.

In particular, there is the need to develop "greener" and "smarter" Transport Systems, taking into account the benefits for citizens and society while respecting environment and natural resources, while assuring "smooth" conditions of travel, by reducing the number of accidents and disruptions from networks jamming and their impact on transport, energy and trade.

Moreover, infrastructure managers and operators have to ensure that transport assets and services function continually and safely against increasing hazards and extreme events.

The target is to improve the level of service and resilience offered, by highly efficient management and operation of networks with the use of the latest technologies and throughout their life-cycle, is a must.

Economic investments are needed to preserve the existing infrastructure heritage, by maintaining and upgrading it, and by reducing the negative impacts and consequences of increased mobility.

The aim of FORESEE is to provide cost-effective and reliable tools **to improve the resilience** of infrastructure, considered as "the ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event".

The aim of the demonstration is to understand how these tools can increase the efficiency and efficacy of the service offered to customers in terms of safety, functionality and mobility.

2.1 INFRASTRUCTURE DESCRIPTION

The A16 has been built in late 60's and it runs along the TEN-T Corridor n.5 Scandinavian – Mediterranean. The A16 connects Naples, on the Tyrrhenian coast, with Candela, on the Adriatic Sea, close to the port of Bari, playing a strategic role for the connectivity of the country.

Most of the geological formations emerging along the highway in question are characterized by thick layers dominated by the clayey component, with rare inclusions of a lithic nature.

The highly clayey nature of these soils strongly influences the stability of the slopes.

Along the infrastructure, we can distinguish morphologies related to surface instability ("slow surface deformations"), but also deep instability phenomena, referring to the slope scale.

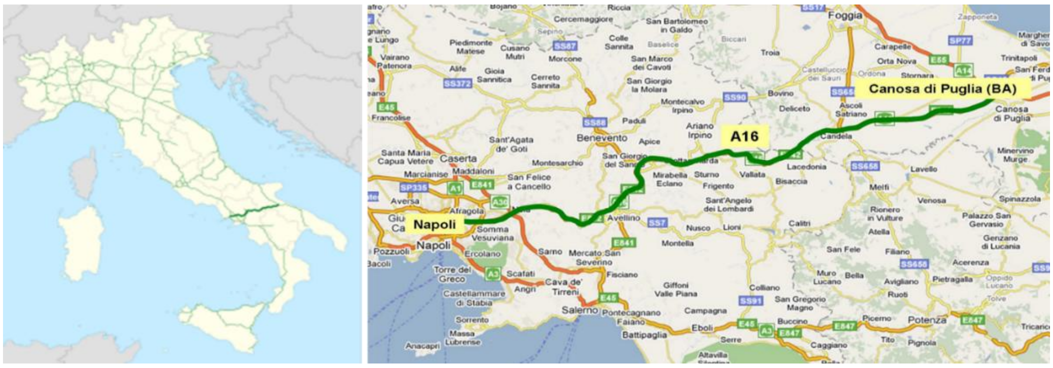


Figure 1. Highway A16 part of the TEN Corridor n.5 Source: Wikipedia (2021), from Annex 1.1.

The highway is also subject to extreme weather conditions (i.e. snow) as it crosses a mountainous region and presents a high degree of seismicity.

The highway is subject to a heavy traffic of goods and passengers all over the year.

A major event took place in 2005 at km.122, causing the immediate closure of the relevant highway section. The structures involved were a 100 m long viaduct and the adjacent embankment. No user was involved in the event. A by-pass was eventually built to restore traffic conditions and the old bridge was abandoned.

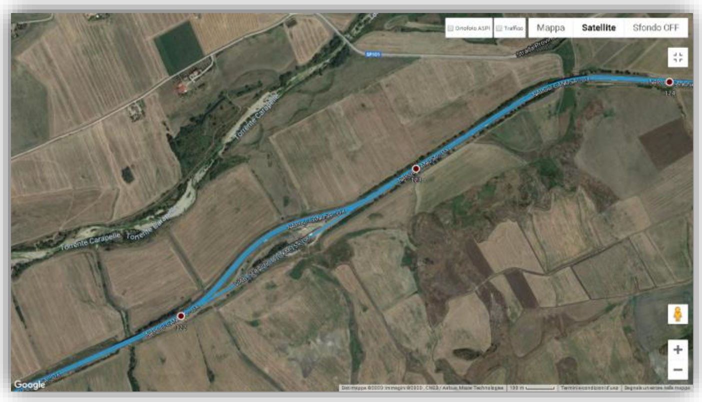


Figure 2. Highway bypass at the km.122

The demonstration is developed using a section of the highway A16 of approximately 30 km, between km. 80-110.

A total of 20 bridges (for a total length of approx. 3 km) are located in the proposed highway section. They have, in general, a simply supported structural scheme with beams and cross-beams in prestressed post-tensioned concrete, and may be considered representative of a wider population of structures of the same age across Italy, in similar conditions of environmental attack and hydrogeological risk.

Their data have been used for the development of the fragility and vulnerability tool under T.3.4.2.

Following the preliminary results of WP2 on the level of slope movements in the area, it has been decided to focus on the section between km. 97-99, where 3 bridges are considered.

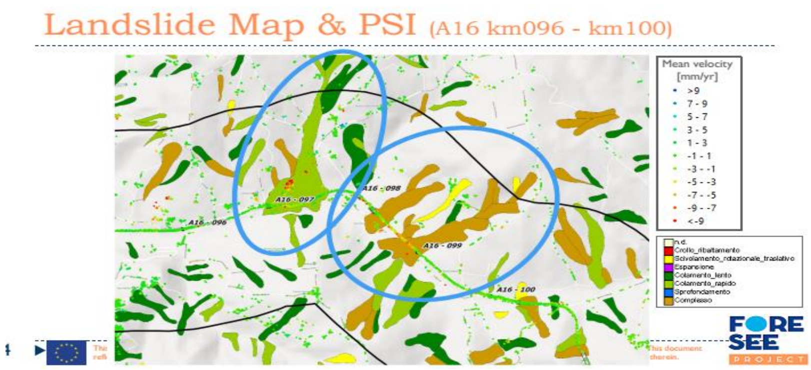


Figure 3. Landslide Map from WP2

Figure 4. Bridges between km. 97-99

2.2 HAZARD DESCRIPTION

In order for the consortium to develop and validate the proposed solutions and tools, a wide range of data and information have been made available to partners (Annex 1).

Moreover, two monitoring systems have been installed on two bridges to validate and improve the solutions from WP2: the monitoring data will be integrated into the SHM BIM based alerting SAS Platform and the RAG alerts will be updated based ion field data.

2.3 GNSS BRIDGE MONITORING SYSTEM DEPLOYMENT

As the bridges are located in an area subject to landslides as well as seismic events, it is important to carry out constant and continuous monitoring of significant points both on the structures and in the nearby landslide area. This allows correlating land displacements with any subsequent displacement of the bridges. For these reasons it is assumed, for each of them, the monitoring of the geometric displacements of abutments and piers and a of significant point on the landslide area, close to the viaduct. The deployment of 1 thermometric probe on the bridge has been foreseen in order to measure the temperature with respect to different conditions of solar radiation.

Furthermore, a GNSS receiver/antenna per viaduct is of the dual-frequency type and its data are used, as well as for computing the position of the point, also for the calculation in near real-time (one or two hours latency) of the numerical value of the precipitable water vapor content, estimated at the zenith of the bridge.

Monitoring activities

Considering one of the two antennas on the abutment as fixed, the three-dimensional displacements of the GNSS antennas placed on the piers and the other abutment can be measured to highlight any deformation of the individual piers but also rotations and displacements of the structure as a whole (relative mode). In turn, the stability of the reference point can be verified through its monitoring with respect to a permanent external public GNSS station or through stand-alone PPP positioning (absolute mode). Similarly, it is possible to check the movements of the point on the landslide.

The solutions are calculated:

- in relative mode with daily frequency (computed every day and available the day after data collection: it represents an estimate of the average position of the point in the 24 hours - accuracy of about 1 mm/day or better) and hourly frequency (computed every hour and available the hour after the data collection: it represents an estimate of the average position assumed by the point in the hour - accuracy of about 1-3 mm/hour).

  However, the possibility of obtaining hourly positioning depends on the sky visibility of the GNSS antennas; the antennas must therefore be installed in areas without visual obstructions such as trees, poles, etc. in every direction.

- in absolute mode with daily frequency (computed every day and available the day after data collection: it represents an estimate of the average position of the point in 24 hours - accuracy approximately of 1-2 mm/day). The availability of the absolute measurement depends on the functioning of the permanent public GNSS station defined as an external reference and the availability of its data. For the monumented points with receivers and GNSS antenna, it will be possible to calculate the absolute position through the standalone PPP, which does not require the use of a third-party permanent station.

Bridge B1 monitoring system

The first bridge consists of three 32-meter spans. It is assumed the installation of an antenna for each abutment and an antenna on the header of each pier. In addition, the installation of an antenna placed on a pillar anchored to the ground nearby the bridge for monitoring the landslide is foreseen. The detailed location of this point will have to be agreed accordingly to the geological significance and the administrative relevance of the area. Considering the mutual distance between the points, it is planned the installation of two double-receiver GMU control units for the viaduct and a single-receiver GMU control unit for the landslide. It is proposed a dual-frequency receiver for one point on the abutment, in order to better describe the movements even in the global reference frame.

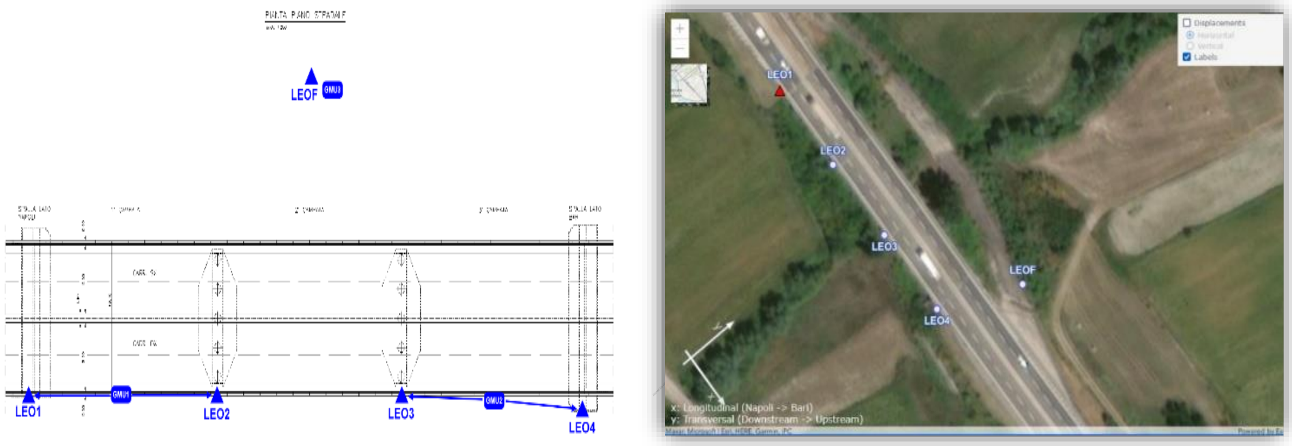


Figure 5. Proposed layout for the bridge B1.

Figure 6. Sensors location on the bridge B1

Bridge B2 monitoring system

The viaduct is constructively similar to the other one (3 spans of 32 meters). It is therefore assumed that the same solution is feasible, except for the point on the ground outside the bridge, that is not present.

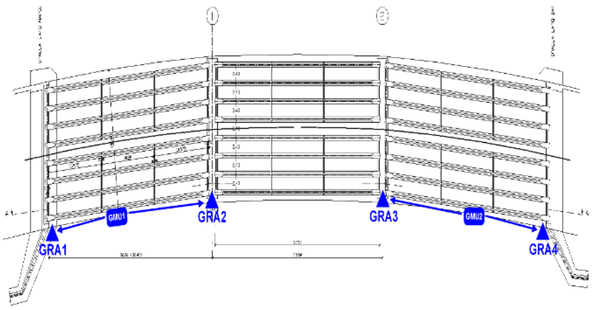


Figure 7. Proposed layout for the bridge B2

3. SCENARIO CARD & VALIDATION CONDITIONS

3.1 SCENARIO CARD FOR CASE STUDY #2 A16

Landslides are the specific risk scenario taken into account as the area around the A16 is subject to hydrogeological risk. The following main project outcomes will be applied and validated from a theoretical and real point of view.

- Assessment of the Level of service and resilience (WP1).
- Landslide awareness (WP2).
- Fragility and Vulnerability Analysis (WP3).
- Design & Construction plans (WP7).
- Operational and maintenance plans (WP7).

As far as it concerns WP1, Level of Service (LOS) and resilience have been computed under two different situations:

1. The first one is based on data from past "extreme" events (a major landslide hit the infrastructure in 2005 at km. 122, even if outside the chosen area of interest) to increase the comprehension of all the relevant elements or factors affecting the specific event and to assess the possible consequences and actions to be undertaken.

   Data have been used for the development and further validation of the methodology and guidelines under D.1.1 and D.1.2.

2. In the second one, the expected event is the triggering of a landslide, to hit the infrastructure in presence of normal traffic and/or in case of heavy traffic (works, accidents).

As far as it concerns WP2, CS#2 has been used to develop and test the SHM BIM based alerting SAS Platform, for the purpose of operation and emergency management. Data from the monitoring systems will be used for validation purposes.

At the network level the Fragility and Vulnerability Analysis and Decision Support Toolkit has been used to understand the impact of different hazard scenarios on traffic demand in terms of loss of service and resilience estimation (WP3).

As far as it concerns the validation of WP7, the case study of A16 has been studied under the:

- **Design & Construction**, D phase, definition of the design resilient to the specific risks (landslides).
- **Operation & Maintenance**, M phase, definition of the Operation and Maintenance plan, based on design resilient of the specific risk.

Case Study#2	**Scenario 1**	**Scenario 2**
phase	**Design & Construction, D**	**Operation & Maintenance**
risks	Landslide, **L**	Landslide, **L**
transport	Road, **R**	Road, **R**
scale	National, **N** Regional, **R**	National, **N** Regional, **R**
location	Italy, **IT**	Italy, **IT**
	*risk (**W,F,S,M**), transport ®, scale (**N,A**), location (**IT**)*	

Table 1. CS#2 Scenario

3.2 VALIDATION METHODOLOGY AND PROCEDURE

Selected FORESEE Tools for CS#2

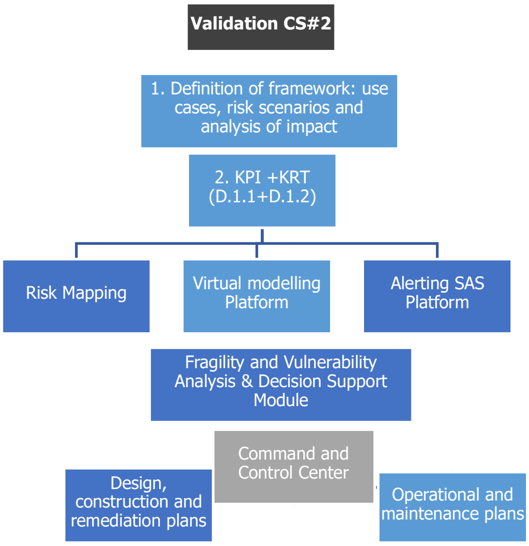
In the following, the output from the newly developed FORESEE tools that have been applied on CS#2 will be validated and commented. Comparison will be carried out with actual practice.

The FORESEE tools selected to improve the resilience of this infrastructure are:

TOOL	Name	Developer	#2	Case Study 2		
				Design & Construction	Operation & Maintenance	Management Contingency
D 1.1	Resilience Guidelines to measure Level of Service & Resilience	ETHZ	Comparison with operational data	√	√	√
D 1.2	Set Targets	ETHZ	Comparison with operational data	√	√	√
T 2.2	Risk Mapping	UC	Hazard maps		√	√
T 2.4	Virtual modelling Platform	UEDIN	Installation of SHM		√	√
T 2.5	Alerting SAS platform	TVUK	Installation of SHM		√	√
T 3.4.1	Traffic Module	WSP	Not developed for CS#2			
T 3.4.2	Fragility and Vulnerability Analysis & Decision Support Module	RINA-C	Fragility curves		√	√
T 5.5	Command and Control Center	FRA	Not developed for CS#2			
T 7.1	Definition of framework: use cases, risk scenarios and analysis of impact	CEM	Use-cases Theoretical			
T 7.2	Design, construction and remediation plans	CEM	Resilience curves Theroretical	√		
T 7.3	Operational and maintenance plans	TEC	Catalogue of measures Theoretical		√	
T 7.4	Management and contingency plans	ICC	Not developed for CS#2			√

Table 2. CS#2 Tools to be validated

4. SYSTEM VALIDATION IN CASE STUDY #2 BY CASE STUDY LEADER



- The infrastructure is digitized through Indicators, KPI and thresholds KRT.
- The tool Definition of framework: use cases, risk scenarios and analysis of impact, defines the potentials risks.
- The tool Risk Mapping analyzes the real risks graphic.
- The tool Virtual Modeling Platform is expected to predict ground displacements over time.
- The tool SHM BIM based alerting SAS Platform is finalized to operation and management of infrastructure.
- The Traffic Module (not applied).
- The tool Fragility and Vulnerability Analysis & Decision Support Module assesses the LoS and resilience.
- The tool Command and Control Center (not applied).
- Design & Construction Plans, along resilient definition.
- Operation & Maintenance Plans, along resilient definition.
- The Management and Contingency Plans (not applied).

5. OUTPUTS COMING FROM THE VALIDATION PHASE

The results of the application of the FORESEE Tools to the CS#2 are summarized in the following table.

Task	Deliv.	Descrip.	Tool Dev.	OUTPUTS	KRI
T 7.1	**D7.1**	Framework use cases, risk scenarios and analysis of impact	CEM	Definition of a framework to develop the Resilience Plan for the Use Case: Roadway+Highway+Landslides	Framework for T 7.2/3/4
T1.1	**D 1.1**	Resilience Guidelines to measure Level of Service & Resilience	ETH	Guidelines and tools for management of assets and infrastructures under different hazards	L1-Infrastructure L2 Environment L3 Organization
T.1.2	**D 1.2**	Set Targets	ETH	Guidelines and tools for management of assets and infrastructures under different hazards	L1-Infrastructure L2 Environment L3 Organization
T 2.2	**D.2.7**	Risk Mapping	UC	Hazard maps and risk maps of the infrastructure's area to identify the risks prior to the more accurate and more local scale quantification.	1.3.2 3.1.1 3.1.2
T 2.4	**D.2.8**	Virtual modelling Platform	UEDIN	Prediction of ground displacements over time Installation of SHM	1.3.2 3.1.1 3.1.2
T 2.5	**D.2.9**	Alerting SAS platform	TVUK	Operation and management of infrastructure. Installation of SHM	1.3.2 3.1.1 3.1.2
T 3.4.1	**D3.3/D3.7**	Traffic Module	WSP	Not developed for CS#2	
T 3.4.2	**D3.8**	Fragility and Vulnerability Analysis & Decision Support Module	RINA-C	Asset's fragility characterization against the considered hazards depending on the criticality levels of the asset's main features and functionality to evaluate asset's operativity losses for different damage levels scenario	3.1.1 3.1.2
T 5.5	**D5.3**	Command and Control Center	FRA	Not developed for CS#2	
T 7.2	**D7.2/D7.5**	Design, construction and remediation plans	CEM	Development of design, construction and remediation plans in order to adapt and increase the resilience of the infrastructure	3.1.2 3.1.3
T 7.3	**D7.3/D7.6**	Operational and maintenance plans	TEC	increase transport infrastructures' safety, efficiency and productivity factors regarding the occurrence of extreme events	3.1.2 3.1.3 3.2.4 3.2.5 3.2.6
T 7.4		Management and contingency plans	ICC	Not developed for CS#2	3.2.1 3.2.2 3.2.3

Table 3. Outputs by Phase Foresee Tool CS#2

5.1 REQUIREMENTS OF THE FORESEE TOOLS IN CS#2

As a basis for the subsequent validation and test phase, the selected FORESEE tools are briefly described below in the form of a requirements analysis for each tool applied to CS#2.

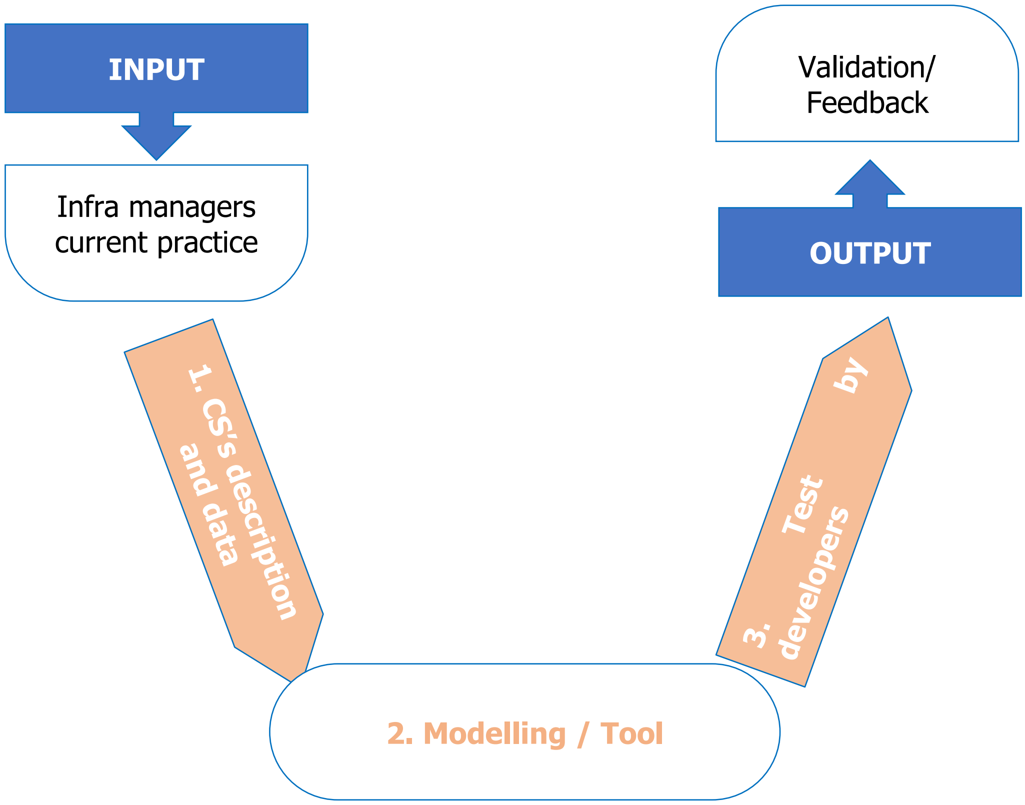


Figure 8. Requirements for CS#2

5.1.1 Definition of a framework to develop the Resilience Plans

The guideline presented in D.7.1 offers a useful insight to the different aspects linked to the evaluation of resilience, from its understanding down to the consequences of events and associated recovery measures, indicating the main steps to follow in the assessment of resilience plans. A set of use cases covering a wide range of transport infrastructure and risk scenarios, to guarantee a holistic approach, is proposed. Use 07: Roadway + Landslide is relevant for CS#2. Results have been built by interaction with the different partners and by shared questionnaires. The validation is made from a theoretical point of view.

5.1.2 Resilience Guidelines to measure Level of Service & Resilience and targets

The needed requirement is to have a tool to assess the level of service of the infrastructure and to understand on which parameters/aspects to intervene to increase resilience and, if possible, to predict future performances face to a set of constraints and boundary conditions to be covered in the analysis (risks, ageing assets, company's policies , socio political context, etc).

Different are the results produced in WP1 (D1.1. and D.1.2):

a. The guidelines is to be used to determine how to measure, the service provided by, and the resilience of, transport infrastructure, with their associated target levels to attain. It promotes different levels of analysis, starting with indicators, but a more sophisticated approach based on traffic analysis is possible. Cost benefit analysis allows the choice of optimal solutions.
b. Excel file implementing the above-mentioned approach which allows infra managers to make a sensitivity analysis as it is possible to test the excel file with the data of the infrastructure.
c. Implemented toolkit internet based interfaced with the other tools. In this case it is only possible to analyse the application in test phase done by the developers.

Strict contact among CS#2 leader and ETH has been carried out. In addition, the results have been presented together with the tool developers to the FORESEE 4th SRG WEBINAR on 21.01.2021. Some of the results of the work done under WP1 and their application to CS#2 have been already published in scientific journals (Annex 1.1).

5.1.3 Risk mapping

The GIS based risk analysis platform generating prioritised ranked site/asset risk map aims at identifying the strategic areas where to implement measures to mitigate the impacts of extreme natural events (D2.5). The tool is built on GIS public databases.

The application of the "Risk Mapping" tool may be derived from D.2.5. The associated appendix shows that the tool provides specific outputs for the present CS#2 in the form of colour-coded risk and hazard maps, input for the further development of the Virtual modelling Platform and Alerting SAS platform.

5.1.4 Virtual modelling platform

The Virtual Modelling platform and asset failure prediction, described in D.2.8, integrates both (in situ) terrestrial and satellite data, GIS, and numerical modelling, to predict failure of assets and considering rainfall a triggering factor. This would be extremely valuable from the point of view of preventing/managing emergency situations. The validation is made:

1. from a theoretical point of view on the basis of the results described in D.2.9,
2. on the basis of the demo of the toolkit that has been made available.

Development, calibration and testing has been conducted on the basis of quite a large amount of data from complementary sources and collected over a number of years of surveillance and monitoring.

5.1.5 Alerting SAS platform

The final and comprehensive result from WP2 is the tool described under D.2.9, " to generate RAG alerts over the different elements of a BIM corresponding to a critical infrastructure and to allow a 3D visualization of those alerts. Different level of alerts are raised in correspondence with the datasets of motion observed near or on each BIM element".

The SHM BIM based alerting SAS maybe validated:

1. from a theoretical point of view on the basis of the results described in D.2.9,
2. on the basis of the demo of the toolkit that has been made available,
3. on the basis of the data collected from the permanent monitoring systems installed on two bridges.

Regular contacts have been kept between WP2 leader and CS#2. Some of the results of the work done under WP2 have been already published in scientific journals and presented at conference and events (Annex 1.2).

5.1.6 Fragility and Vulnerability Analysis & Decision Support Module

The requirement is to assess asset's fragility characterization against the considered hazards depending on the criticality levels of the asset's main features and functionality to evaluate asset's operativity losses for different damage level scenarios. The validation is possible:

1. from a theoretical point of view on the basis of the results described in D.2.9
2. on the basis of the demo of the toolkit that has been made available.

Development, calibration and testing has been conducted on the basis of quite a large amount of data from complementary sources and collected over a number of years of surveillance and monitoring.

Regular contacts have been kept between tool developer and CS#2.

5.1.7 Design, construction and remediation plans

Design, construction, and remediation plans may be validated from a theoretical point of view. These plans are based on resilience-based performances criteria and offer a view on new design procedures in order to adapt and increase the LOS and resilience of existing and future infrastructures.

Moreover, the T.7.2 tool can be tested in practice to some extent, as the tool developers provided form-based Excel tables, which the users (in this case the CS leaders) can fill with input. These plans should include new design approaches based on performance-based design procedures in order to adapt and increase the LOS and resilience of existing and future infrastructures

5.1.8 Operational and maintenance plans

Operational and maintenance plans may be validated from a theoretical point of view. These plans should provide a process to determine optimal intervention programs to increase the level of reliability and service of the infrastructures covering methodologies, systems, procedures and materials to increase factors such as safety, efficiency or productivity.

5.2 FORESEE TOOLKIT PERFORMANCE ASSESSMENT & BENCHMARKING

RAMSSHEEP (qualitatively) and Resilience Principles (according to D.7.1) for CS#2 leads to the indications of the following table where:

a. Reliability—indicates the failure probability of a system in which its functions cannot be fulfilled.
b. Availability—indicates the time duration in which the system is functional, and its functions can be fulfilled.
c. Maintainability—the ease in which the system can be maintained over time.
d. Safety—the absence of human injuries during using or maintaining the system.
e. Security—a safe system with respect to vandalism, terrorism and human errors.
f. Health—the objective argument of good health with respect to the physical, mental and societal views.
g. Environment—influence of the system on its direct physical environment.
h. Economics—a serious reflection in terms of costs versus benefits (as well as direct and indirect) to provide more insight for an economical responsible choice.

As far as it concerns the application of the **Resilience Principles** [D.7.1-D.7.5] for the different tools and results:

1. Robustness: the ability for transport infrastructure to overcome and absorb disruptive event shocks and continue operating. This concept is mainly (oriented toward the physical parts of the infrastructure.
   - D.2.8 Virtual modelling Platform
   - D.2.9 Alerting SAS platform
   - D.3.8 Fragility and Vulnerability Analysis & Decision Support Module
   - D.7.1 Framework: use cases, risk scenarios and analysis of impact
   - D.7.5 Framework: use cases, risk scenarios and analysis of impact
   - D.7.6 Operational and maintenance plans

2. Resourcefulness: the ability to skilfully manage a disruption as it unfolds. It is primarily people oriented as it is related for example to prioritizing what should be done.
   - D.2.8 Virtual modelling Platform
   - D.2.9 Alerting SAS platform
   - D.3.8 Fragility and Vulnerability Analysis & Decision Support Module
   - D.7.1 Framework: use cases, risk scenarios and analysis of impact
   - D.7.5 Framework: use cases, risk scenarios and analysis of impact
   - D.7.6 Operational and maintenance plans

3. Rapid recovery: the ability to get "back to normal" as quickly as possible after a disruption. It is oriented towards people as well as towards the infrastructure.
    - D.2.8 Virtual modelling Platform
    - D.2.9 Alerting SAS platform
    - D.3.8 Fragility and Vulnerability Analysis & Decision Support Module
4. Adaptability: the ability to absorb new lessons that can be drawn from past events to improve resilience.
    - D.1.1 Resilience Guidelines to measure Level of Service & Resilience
    - D.1.2 Set Targets
    - D.2.7 Risk Mapping
    - D.2.8 Virtual modelling Platform
    - D.2.9 Alerting SAS platform
    - D.3.8 Fragility and Vulnerability Analysis & Decision Support Module
    - D.7.1 Framework: use cases, risk scenarios and analysis of impact
    - D.7.5 Framework: use cases, risk scenarios and analysis of impact
    - D.7.6 Operational and maintenance plans

Task	Deliv.	Descrip.	RAMSHEEP									Resilience principle			
			Reliability	Availability	Maintainability	Safety	Security	Health	Environment	Economics	Politics	Robustness	Resoucesfulness	Rapid-Recovery	Adaptability
T 7.1	D7.1	Framework: use cases, risk scenarios and analysis of impact													
T 7.2	D7.2/D7.5	Design, construction and remediation plans	X	X	X	X		X	X	X	X	Green	Green		Yellow
T 7.3	D7.3/D7.6	Operational and maintenance plans													
T1.1	D 1.1	Resilience Guidelines to measure Level of Service & Resilience	X	X	X			X	X	X	X				Yellow
T.1.2	D 1.2	Set Targets													
T 2.2	D.2.7	Risk Mapping	X	X	X				X	X					Green
T 2.4	D.2.8	Virtual modelling Platform	X	X	X				X	X		Green	Yellow	Yellow	Yellow
T 2.5	D.2.9	Alerting SAS platform	X	X	X				X	X		Green	Green	Yellow	Yellow
T 3.4.2	D3.8	Fragility and Vulnerability Analysis & Decision Support Module	X	X	X				X	X	X	Green	Green	Green	Green

Table 4. RAMSHEEP approach

6. FORESEE IMPACT IN CASE STUDY#2

6.1 RESILIENCE SCHEME APPLICATION

Work Package 7 (WP7) is focused on developing resilience plans, covering the whole life cycle of the infrastructures, with the aim of:

a. reducing the impact and consequences of extreme events,
b. increasing the ability to recover from them.

According to D.7.1-Framework based on use cases, risk scenarios and analysis of impacts [6], resilience plans should include:

1. Design, construction, and remediation plans.

New design approaches based on performance-based design procedures in order to adapt and increase the Level of Service (LOS) and resilience of existing and future infrastructure.

2. Operational and maintenance plans.

Process to determine optimal intervention programs to increase the level of reliability and service of the infrastructures, including methodologies, systems, procedures and materials to increase safety, efficiency or productivity.

3. *Management and contingency plans.*

New and more effective contingency and communication strategies in order to enhance the resilience of the transport system.

Resilience plans may serve as a guideline to help infrastructure owners and operators in understanding not only the underlaying meaning of resilience, but also to understand how it develops over time and how it can be improved/modified during the infrastructure's life cycle.

Resilience can be measured with the two different procedures, developed in the project, recurring to traffic simulations or to indicators as in D1.1. and D.1.2 [4][5].

In the proposed approach, resilience indicators may be assembled in function of the four fundamental concepts underlining resilience:

a) Robustness: the ability for transport infrastructure to overcome and absorb disruptive event shocks and continue operating. This concept is mainly (oriented toward the physical parts of the infrastructure.
b) Resourcefulness: the ability to skilfully manage a disruption as it unfolds. It is primarily people oriented as it is related for example to prioritizing what should be done.
c) Rapid recovery: the ability to get "back to normal" as quickly as possible after a disruption. It is oriented towards people as well as towards the infrastructure.
d) Adaptability: the ability to absorb new lessons that can be drawn from past events to improve resilience.

This would lead to understand where to concentrate efforts possibly also in function of the organization's strategies and objectives.

The procedure would be particularly useful in the phase of conception and planning of the infrastructure where design may be modified as a result of the "resilient approach".

	MAX VALUE	ACTUAL VALUE	% FULFILLMENT
Robustness Performance Index (RoPI)	13	6,58	50,6%
Resourcefulness Performance Index (RePI)	6	3,50	58,3%
Rapid Recovery Performance Index (RrPI)	15	9,45	63,0%
Adaptability Performance Index (AdPI)	5	2,50	50,0%

Figure 9. Example of assessment of resilience indicators

The deliverable D.7.1 promotes a Resilience Plan Framework based on four steps:

1. system definition,
2. hazard definition and potential impacts from the point of view of the operation, as well as from an economic, social and environmental perspective,
3. resilience evaluation,
4. resilience plans application.

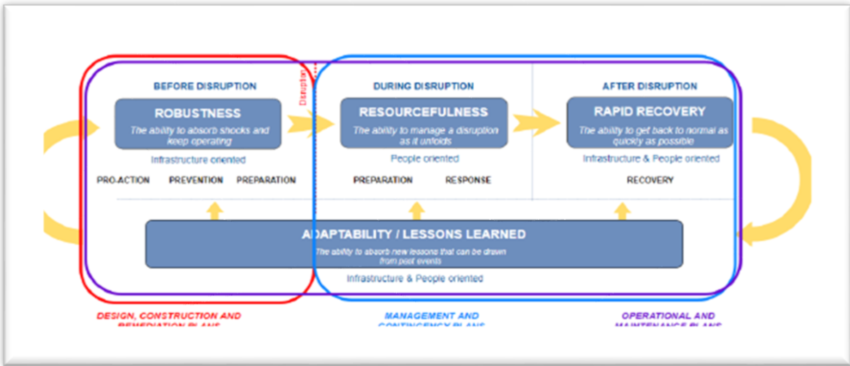


Figure 10. Resilience Concepts and FORESEE Resilience Plans (from D.7.1).

Apart from being applicable in different stages in the life cycle, the different resilience plans are focused on the different elements that contribute to the "system infrastructure" with the aim of assuring safe and seamless, even if reduced, mobility, in the presence of an event.

It has to be noticed, however, that the stages do not represent steps in the service life of the infrastructure, but are defined with reference to the resilience approach (D.7.1):

a. Pro-action: activities aimed at avoiding the occurrence of the disaster (disruptive event).

b. Prevention: activities aimed at minimising the vulnerability of an element to a given hazard.
c. Preparation: activities carried out in preparation of an extreme event to reduce consequences.
d. Response: activities developed during an extreme event.
e. Recovery: activities developed after a disruption to restore services as soon as possible.

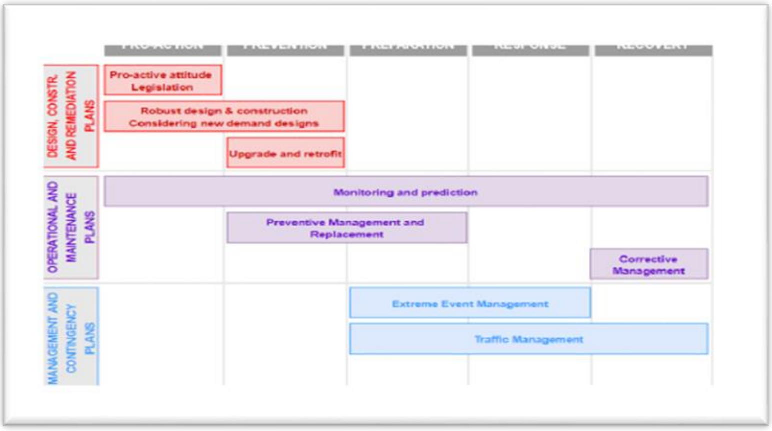


Figure 11. Resilience stages and FORESEE Resilience Plans (from D.7.1)

Resilience plans are developed according to the following scheme, where the actions to be done for each step are indicated and how resilience contributes to the definitions of the different resilience plans.

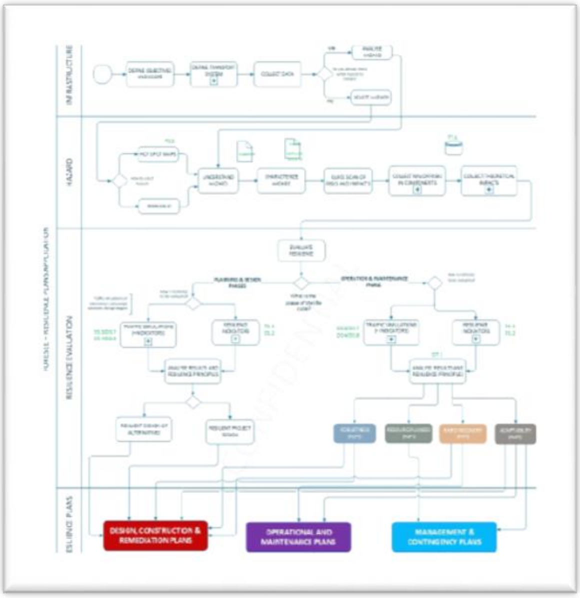


Figure 12. Resilience Plans application (from D.7.1)

A set of use cases has been defined covering a wide range of transport infrastructure and identifying what are the main risks and impacts that a hazard may cause in a transport system. As far as it concerns roads, the system infrastructure is identified by the following physical components (Figure 13). These elements represent, in general, a set of possible components that should be further detailed in function of the specific risks addressed.

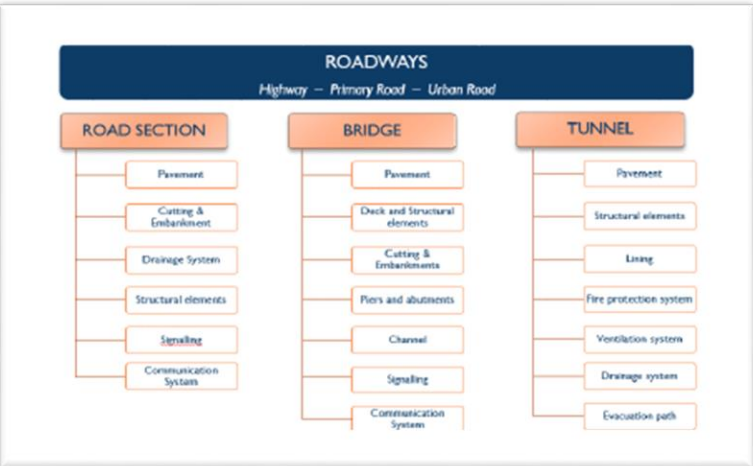


Figure 13. Roadway networks, systems and components

As far as it concerns CS#2, the most relevant use-case for the development of resilience plans is <u>"use case 07 for landslides"</u>. For each component, a set of possible general risks is defined that may be triggered by a landslide, independently from the main components. The same applies to the definition of the theoretical impacts as a consequence of a landslide. The process should therefore be tailored to the specific problem at hand.

COMPONENT	RISK ID	MAJOR RISKS
	PV.01	Cracking
vement	PV.02	Loss of capabilities
	PV.03	Loss of integrity
mmunication system	CM.01	Equipment failures
	DR.01	Exceedance of drainage capacity
rainage system	DR.02	Obstruction
	DR.03	Structural damages and erosion
	DR.04	Collapse
	EC.01	Erosion
nbankment / cutting (slope)	EC.02	Lack of stability
	EC.03	Retaining walls tilting and bulging
rmation / subgrade	FS.01	Lack of stability
laterial	MA.01	Loss of loading capacity
vement, structure and foundation (global)	PSF.01	Increase of uplift pressures
	SI.01	Equipment failures
gnalling	SI.02	Damage to signs, lighting and supports
	SI.03	Collapse
	ST.01	Loss of loading capacity
ructural elements (global)	ST.02	Cracking
	ST.03	Collapse

Table 5. Use Case 07: Risks on components (from D.7.1)

TYPE OF IMPACT	IMPACT ID	IMPACT DESCRIPTION
	OP.01	Reduced traffic capacity
	OP.02	Temporary closure
perational	OP.03	Collapse / long-time closure
	OP.04	Traffic restrictions
	OP.05	Travel delays
	OP.06	Infrastructure lifespan decrease
	SF.01	Accidents (vehicles)
	SF.02	Accidents (objects)
ifety	SF.04	Involuntary vehicle displacement
	SF.05	Passage obstruction
	SF.07	Vehicle immobilization
	SS.01	Direct loss of lives
cial - safety	SS.02	Indirect loss of lives
	SS.03	Difficulty for response operations
cial	SO.01	Quality of transport service
	SO.02	Loss of reputation
conomic	EC.01	Maintenance costs
	SE.01	Isolation of areas
cio - economic	SE.02	Reduced access to destinations
	SE.03	Disruption of economic activity
wironmental	EN.01	Pollution
	EN.02	Hazardous products release

Table 6. Use Case 07: Theoretical impact (from D.7.1)

DISCUSSION

The guidelines presented in D.7.1 offer a useful insight to the different aspects linked to the evaluation of resilience from its understanding down to the consequences of events and associated recovery measures, indicating the main steps to follow in the assessment of resilience plans.

As the document is built upon the results from other WPs of the project, it would have been interesting to apply the computation of the Resilience-principles Performance Indicators to the set of data resulting from the application of the D1.1. and D.1.2 to the different CS where the Level of Service, the resilience and related targets have been calculated.

As far as it concerns to Task 7.2 (D.7.5), its aim is to develop design, construction and remediation plans in order to adapt and increase the resilience of existing or future infrastructure facing extreme events.

The proposed approach is based on resilience performance criteria and "consists of establishing performance objectives (expressed as performance levels and recovery times associated) which will allow evaluating the functionality of a transport infrastructure under different risk scenarios (earthquake, flooding,….), in function of different hazard levels (routine, design level, extreme level), during and after an extreme event, and taking into account the needs of the community and stakeholders".

This approach allows to include a resilience perspective since the design phase and it is to be used for operation, in the day to day activities, and maintenance purposes to assure that the service provided will remain so throughout the expected life of the asset.

A methodology for applying this approach is presented (Figure 14) in function of the various categories of "criticality", that is the importance of the infrastructure for maintaining its social and economic functions, that an asset may assume. Once criticality is assessed, it is possible to evaluate the resilience curves of the asset, in function of the hazard to be analysed, the threshold for each hazard level (routine, design and extreme) and the desired performance objectives. A Criticality Assessment and Resilience Performance Tool has been implemented using Microsoft Excel.

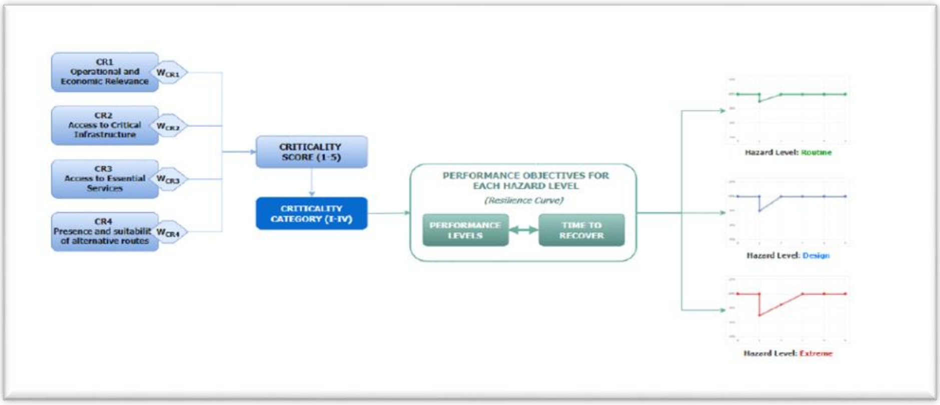


Figure 14. Methodology overview (from D.7.5)

A number of factors are defined to assess the criticality and performances of the infrastructure with respect to the different risks, in function of the possible impact on the operation of the infrastructure, according to the following table. Of course, in the proposed approach, not only the level corresponding to codes and standards is taken into account.

HAZARD	**Routine Level** *Transport infrastructures should remain functional. No significant damage to disrupt the service provided*	**Design Level (Codes)** *Transport infrastructures should remain sufficiently functional to support response and recovery activities*	**Extreme Level** *Hazards that plausibly impact a community but may not be the greatest possible hazard*
Earthquake	95-year event	475-year event	2,500-year event
	41% in 50 years	*10% in 50 years*	*2% in 50 years*
Flooding	Locally determined	100 to 500-year event	Locally determined
		10-40% in 50 years	
Landslide	Locally determined	Locally determined	Locally determined
Wind	1-year event	100-year event	10,000-year event
	100% in 50 years	*40% in 50 years*	*0.50% in 50 years*
Snow	50-year event	300 to 500-year event	Locally determined
	64% in 50 years	*9-15% in 50 years*	
Fire	Locally determined	Locally determined	Locally determined
Terrorism	Locally determined	Locally determined	Locally determined

Table 7. Hazards (from D.7.5)

In response to these risk scenarios, performance levels are required for the accessibility/availability of the infrastructure, according to the following table. It should be adapted to the different situations and standards in force in the different countries, for the different types of infrastructure and geographical location.

Performance Level		Description	
		Service	**Damage**
A	**80 - 100 %**	Full access to normal traffic is available immediately (or almost immediately) following the hazard event.	Only slight damage that requires routine maintenance
B	**60 - 80 %**	Available for slow access, only partial lane blockages, erosion, or deformations.	Minor damages requiring clean-up of small volumes of debris and culverts.
C	**40 - 60 %**	Single lane access.	Moderate damage requiring removal of a moderate volume of debris, minor repairs to walls, culverts, and other structures.
D	**20 - 40 %**	Difficult single-lane access, only available for emergency vehicles.	Severe damage requiring removal of large volumes of debris, stabilization and/or major repairs to walls, culverts and other significant structures.
E	**0 - 20 %**	Closed and unavailable for any use.	Total collapse or extensive damage.

Table 8. Performance levels for roadways (from D.7.5)

It is expected to restore normal traffic conditions in the short term up to the long run. The definition of the recovery time depends on the level of damage and/or on the organization's targets and/or on public requirements.

Short-term				*intermediate*			*Long-term*		
days				**weeks**			**months**		
0 – 6h	6 – 12h	12 - 24h	1 - 3d	1	2 – 4	4 – 8	2 - 4	4 – 12	12+

Table 9. Recovery time frames (from D.7.5)

The application of the proposed procedures to CS#2 under the conditions described in WP1 (same data) leads to the following conclusions (Figure 15):

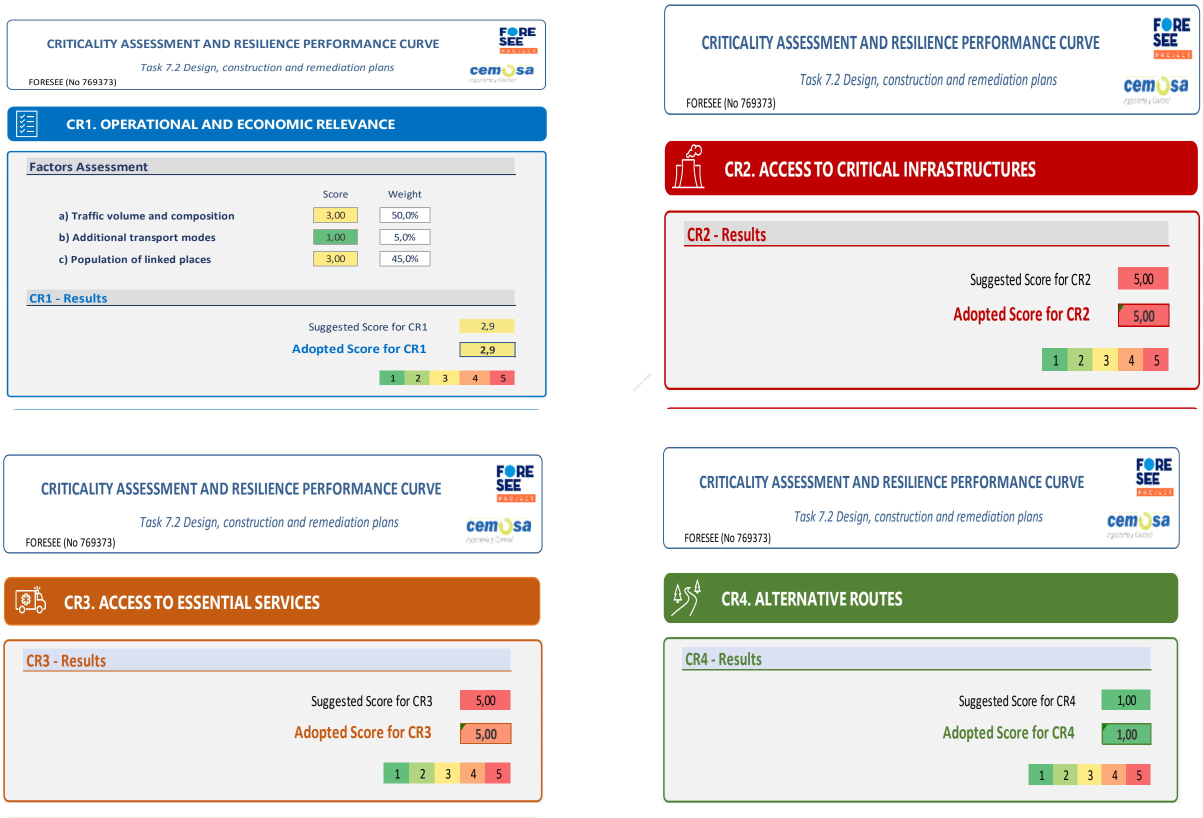


Figure 15. Criticality evaluation

1. The level of CR1-Operational and Economic Relevance, measured in terms of traffic volumes, additional transport modes (the criterion is not applicable for highways and biases the result), population of linked places, leads to an overall value of 2.9 on a scale 0-5 (most critical).

2. The level of CR2-Access to Critical Infrastructures as and the level of CR3-Access to Essential Services (i.e. schools, hospitals,….) leads to the maximum score of 5, as in this case we are considering highways that, for their own nature, may be considered critical.
3. CR2 is measured in terms of availability of key utilities (i.e. water),critical transport hubs (i.e. ports and airports) and other evacuation routes.
4. The level of CR4-Alternative Routes measures the criticality in terms of availability of alternative routes (able to absorb extra traffic). Alternative routes, however, may not be designed to carry the same level of loads and therefore, even if existing, they may not be relevant for the specific risk. In principle if we consider highways it is not easy to have alternative routes available, while it is true the other way round.
5. Within this approach, the most sensitive "critical parameter" are CR2-Access to Critical Infrastructures and , while the less relevant is CR4-Alternative routes (Figure 16).
6. The overall score leads to an overall value of 3,48. According to this final score, the route is classified as Major (on a scale: Vital, Major, Significant, Normal): "its failure would have a significant economic or social impact to more than one major area, or is a regionally significant lifeline, ensuring access or continuity of supply of essential services during an extreme event".

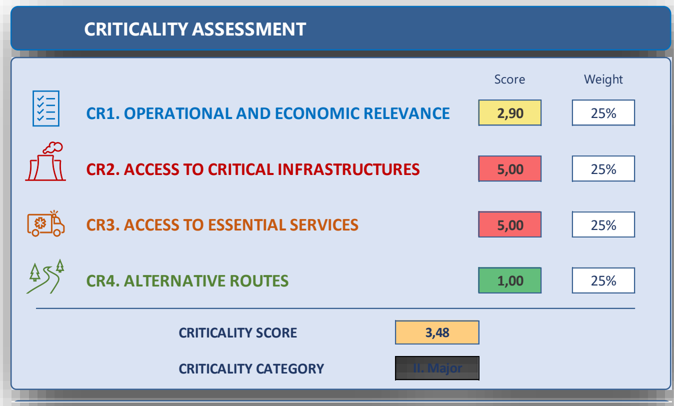


Figure 16. Overall score for CS#2 (data from WP1)

Once defined the criticality, it is possible to build the Resilience Performance curve, where performance levels (Figure 17) have been defined in terms of Damage States and Service differently for the bridge/section in function of the diverse time horizons.

It is expected the recovery/intervention to take longer for the individual component (i.e. bridge) while it is assumed to re-open to traffic quite quickly after an event.

The duration of the different time horizons (short, medium, long) should be discussed with owners and operators and internally within the same company to define overall strategies and objectives.

DISCUSSION

It has to be said that in general highways are considered "critical infrastructures", independently from their criticality, not only for daily mobility of persons and goods (TEN-T network), but in particular for rescue or emergency operations or for military purposes. This means that they are expected to be always accessible.

In this light, recourse to a resilience performance-based design to complement the current performance-based design may be of great help in understanding and improving the performance of the network, face to any type of risk and therefore the approach presents an added value.

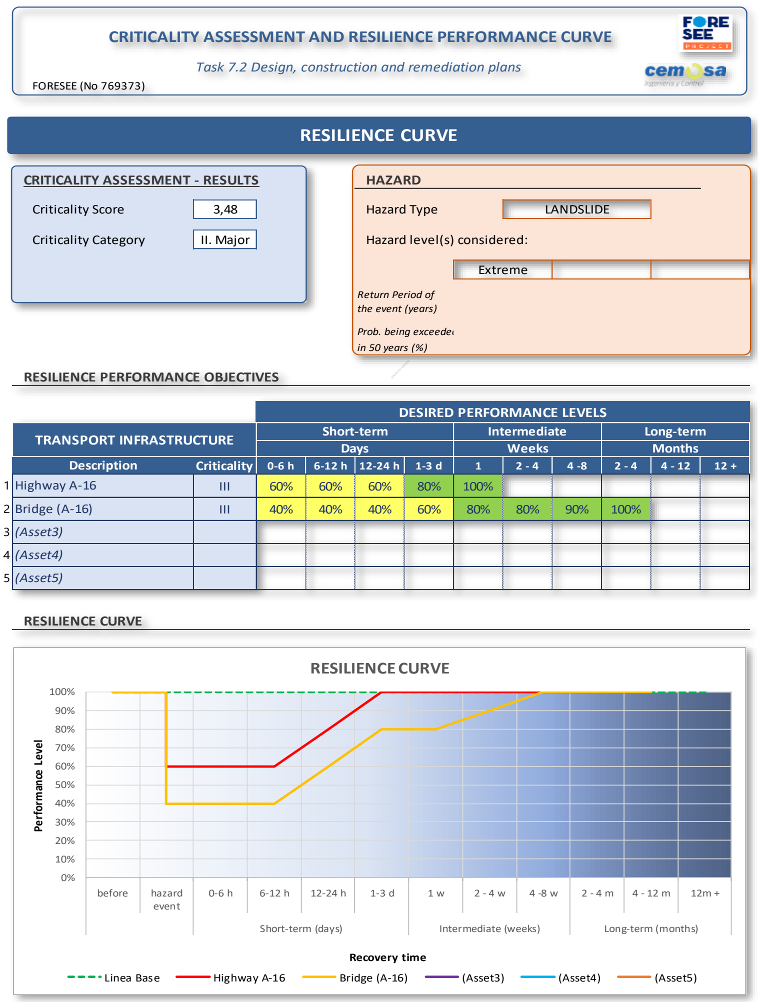


Figure 17. Resilience curves

<u>As far as it concerns the approach</u> to the assessment of level of service and resilience, the Italian Ministry of Transport has published in 2020 the "Guidelines for the management of risk, the evaluation of structural safety and the monitoring of existing bridges", a procedure for managing the safety of existing bridges, based on a synthetic assessment of the risk factors associated with the bridges, in order to prevent inadequate/unacceptable levels of damage and risk [9].

The Guidelines follow a multi-level approach justified by the number of existing infrastructures on the Italian territory. The complexity and, therefore, the burden of inspections, investigations, controls, monitoring and computations to be carried out, is calibrated through an approximate and qualitative evaluation of the actual need and urgency in function of the current state of the structures.

The proposed multilevel approach provides for quick assessments and screening extended at the territorial level, such as inventory and inspections, and punctual evaluations, of greater complexity, concentrated on individual bridges.

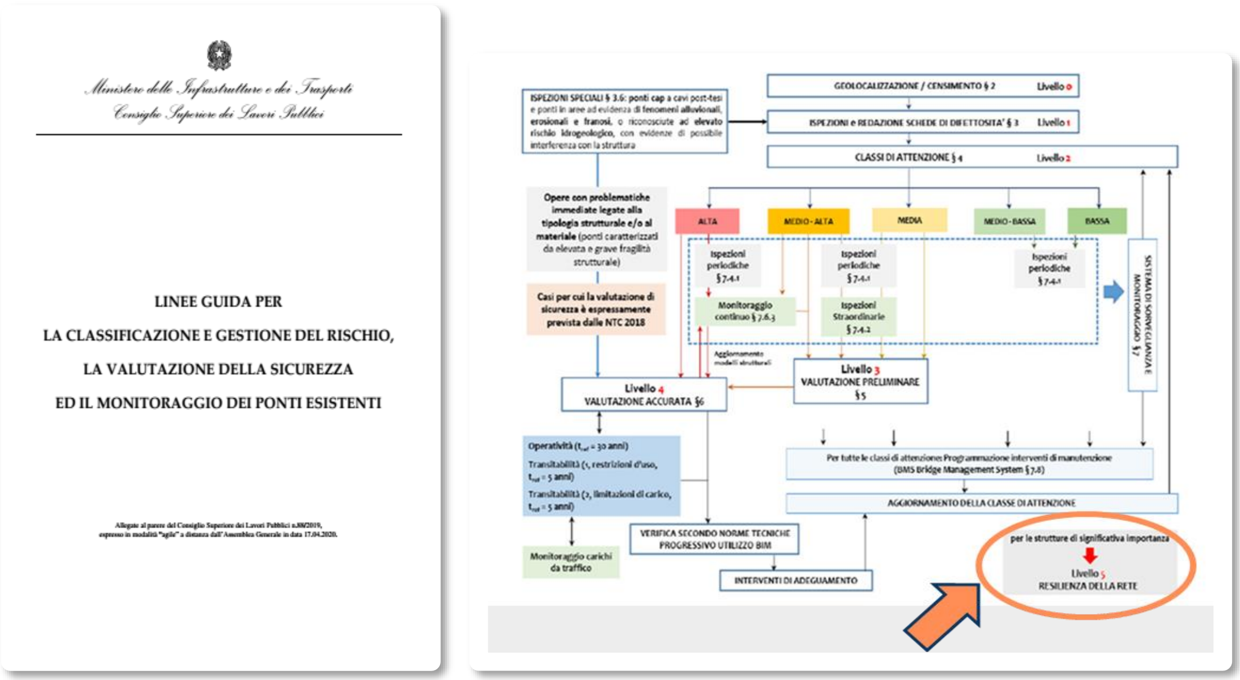


Figure 18. Discussion (from 4TH WEBINAR, 2021)

The multi-risk and multi-level approach introduces 5 levels of assessment:

1. From a first analysis performed on the entire existing infrastructural heritage (Level 0 = inventory) and carrying out visual inspections (Level 1), the Class of attention to be attributed to each bridge is defined (Level 2) and, therefore, the degree of complexity of the following steps.

3. The choice of the level of assessment is based on the overall class of attention given by the combination of four distinct classes of attention that refer to the analysis of four different types of risk: structural and foundational (deterioration and defects), seismic , landslides, hydraulics. Each of them is obtained by analyzing three factors (risk, vulnerability, exposure) whose combination by means of logical operators and flow diagrams allows to obtain the overall class.
4. Depending on the overall class obtained, the bridge will be subject to all actions in terms of investigations, monitoring and structural computations set by the guidelines (Level 3 and Level 4). In particular, at level 5 specific mention of resilience is given as:
5. Level 5: Bridges of significant importance within the network, for which it is useful to carry out more sophisticated analyses of the resilience of the section of the road network and/or of the transport system of which it is part, evaluating the transport relevance, analyzing the interaction between the structure and the road network to which it belongs and the consequences of a possible interruption of the operation of the bridge on the socio-economic context in which it is inserted.

In the definition of the class of attention a number of parameters (close to those proposed in FS) are covered. However, it has to be said that they are not translated in corresponding monetary values (monetized).

The FORESEE Toolkit Catalogue, proposed under D.7.5 [7] , gathers the variety of tools and procedures that have been developed to improve the resilience of transport infrastructures to different extreme events and offers an useful guide for the their application.

Each tool is described in terms of:
- Main characteristics: location, hazard, asset and life cycle phase.
- Resilience stage: proaction, preventative, preparation, response, recovery.
- Related performance indicators (WP7): robustness, resourcefulness, rapid recovery, adaptability.
- Related resilience indicator as in WP1 per category and part (i.e. prevent or post event measures, organization, environment, infrastructure).

The most relevant tools for CS#2 are (the relevant sheets are presented in Annex 1.3):
- Risk mapping tool (applied to CS#2)
- Virtual Modelling Platform (applied to CS#2)
- SHM BIM based Alerting SAS Platform (applied to CS#2)
- New Slope Stabilization-Protection System
- Guidelines for the adoption of sustainable drainage systems
- Fragility and Vulnerability Functions and Decision Support Module (applied to CS#2)
- Development of algorithms for the selection and definition of efficient and optimal actions
- Data-driven, Model-Based and Combined SHM Algorithms for Damage Detection, Quantification and Location.

As far as it concerns Task 7.3 (D.7.6), the operational and maintenance interactive tool is meant to offer guidelines and indications for the implementation of resilience schemes to reduce the impact and consequences of extreme events into different types of infrastructures covering their whole life cycle; otherwise told how to increase the level of reliability and service for the different risk scenarios considered.

These plans are based on risk assessment and cost-benefit analysis, and are meant to implement the new FORESEE strategies and tools. In particular they offer a catalogue of how the different FORESEE tools may increase safety, efficiency and productivity in maintenance planning and in daily operation.

TOOL NAME	Deliverable Id.	Tool Id.	Tool description	Event Detected	Infrastructure type	Life Cycle Phase applied (planning, design, construction, operation, maintenance)	Resilience Cycle applied (prevention, preparedness, response, recovery)	Inputs required	Outputs obtained
SHM BIM based alerting SAS platform	D2.9	T2.5	The tool is an API that generates RAG alerts over a BIM and allows 3D visualization. The alerts are raised in correspondence with the datasets of motion observed near on the BIM using landslide failure prediction model, in-situ sensors data and InSAR data.	Landslides	Roads	operations	prevention	Landslide failure prediction model, in-situ sensors data and InSAR data. Rainfall data.	RAG alerts list and RAG-coloured BIM adapted to be visualized by Cesium JS. Prediction of the timing and nature of potential failures along infrastructure corridors
Decision Support Module DSM	D3.8	T3.4.2	The tool provides an efficient instrument allowing to infrastructure managers and owners to manage assets and financial resources to guarantee the optimal level of service.	All	All	All	All	Transport Network description Asset description Hazard data (e.g hazard curves) Traffic volumes, Travel times and Travel Speeds from the Traffic Module	Risk assessment Direct and Indirect Losses Resilience Assessment Level of Service
GIS risk analysis platform generating prioritised ranked site/asset risk map	D2.4	T2.1	The tool provides a risk occurrence assessment for the most significant natural disasters (floods, landslides, and earthquakes).	Flood, landslide, or earthquake	All	Design, Operation	All	Historical data of natural disaster related to the asset hazards	Identification of areas with high vulnerability

Figure 19. FORESEE Toolkit description (From D.7.6)

The toolkit, as described in the deliverable presents:

- a method for the assessment of risk to identify the actions and their relevance and main hazards associated to the infrastructure,
- for the chosen hazard and infrastructure type, the new operational and maintenance plans are listed proposing the guidelines on how to implement the new FORESEE tools and strategies into the service life of the asset,
- a resilience assessment where two scenarios are compared: before and after the application of FORESEE tools,
- a cost-benefit analysis to prove the economic benefits of incorporating the new strategies and tools into Operational and Maintenance planning,
- the potential benefit, in monetary terms, may be measured in terms of impact on the different KPIs and on the level of service and by recurring to the procedures defined in WP1, thus comparing the situation before and after the application of FORESEE tools.

RISK ASSESSMENT

		Risk Id.
FLOODING	Flash flood.	1
	River flood.	2
	Groundwater flood.	3
	Coastal flood.	4
	Structural failure flood.	5
EARTHQUAKES	Tectonic Earthquakes.	6
	Volcanic Earthquakes.	7
	Explosion Earthquakes.	8
	Collapse Earthquakes.	9
LANDSLIDE	Landslides.	10
	Rockfalls.	11
	Flows.	12
	Lateral Spreads.	13
SNOW/ICE	Snowstorm.	14
	Snow cover.	15
	Snowslide/avalanche.	16
	Black ice/clear ice.	17
WIND	Gale.	18
	Storm.	19
	Hurricane.	20
FIRE/EXPLOSION	Wildfire.	21
	Electrical fire.	22
	Flammable/explosive material discharges fire.	23
	Vehicle fire.	24
	Terrorist attack.	25
CYBERATTACK	Internet connected vehicles attack.	26
	Traffic Control System / Centre Attack.	27

Id	Impact description
A	Intangibles (media coverage and intervention of managers)
B	Damage to buildings, equipment and infrastructure
C	Human damage
D	Cuts of circulation due to maintenance
E	Reduction of transport capacity
F	Environmental deterioration

Figure 20. Risks and impacts (From D.7.6)

This is extremely important for the application of the results as a unique and consistent system of guidelines and assessment is used throughout the project.

For instance as far as it concerns use case roadways landslides, if we do use the input data used by ETH in WP1 for implementing the guidelines as in D.1.1 and D.1.2, in the hypothesis of a major event impacting on the infrastructure and by applying the guidelines and tools proposed in the catalogue, we have the following results with a reduction of overall costs.

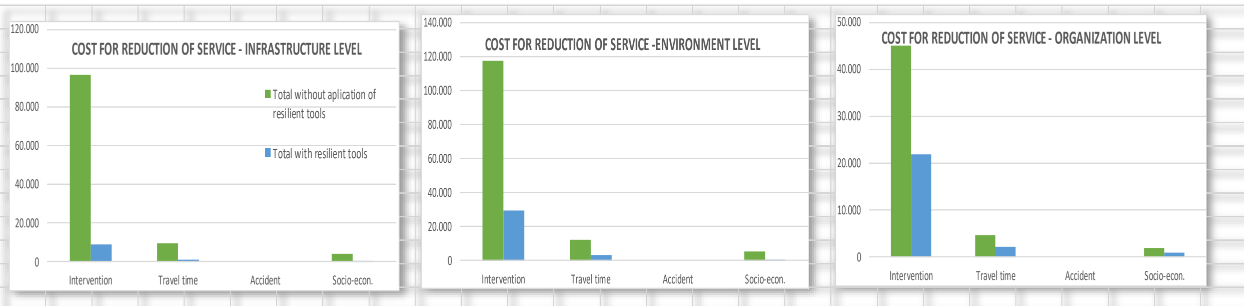


Figure 21. CBA (data from WP1 for CS#2)

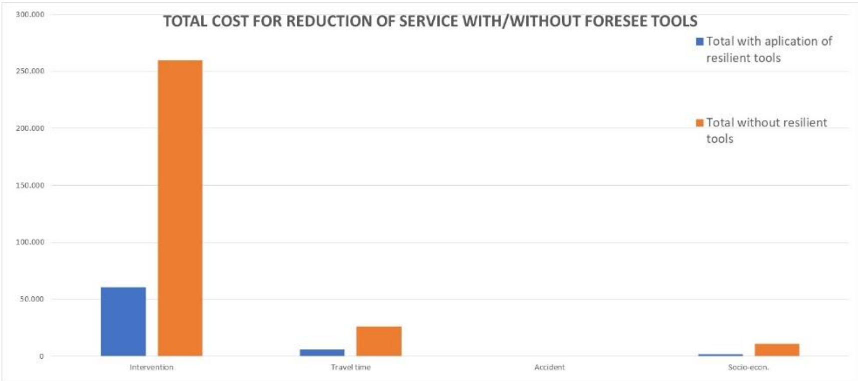


Figure 22.-Total costs reductions (data from WP1 for CS#2)

Finally, in the following table the impacts for WP7 are summarised.

Question	**Impact**
Was this type of analysis made before FORESEE? How it was made?	Risk management is carried out within the Company, where risks, impacts and actions to the undertaken are identified. As far as it concerns the planning and design stages, different standards and procedures are available and the process is clearly defined both in terms of assessment and public permissions. The process of planning and/or assessing the needs of a new infrastructure is quite complex and see the involvement of different stakeholders from public authorities (i.e. Ministry of transport) down to local communities. As it concerns operation and maintenance, the tool may be used to improve the level of service with its standardized procedure.
How does FORESEE improve the results/analysis previously made?	The proposed approach could be used to guide the definition of framework resilience plans for design and for operation & maintenance purposes in compliance with the risk strategies, objectives and management procedures of the organization.
How does this FORESEE result improve your infrastructure's management	As result of the application of the tools, improved traffic flow and increased mobility are expected.
If it was not made, how does this FORESEE result improve your infrastructure's management?	The tools, with their guided" and "objective" approach could complement the actual procedures and allow comparison among different risk scenarios; different territorial needs, different time steps, taking into consideration public socio-economic objectives.
What cost/resource efficiencies you expect these tools/results to have on your day-to-day business? (e.g. 10%-20% decrease in working hours over the first year; reduction of maintenance costs (20%-25%), Return on Investment (ROI) – 10-15%, increase in productivity 25-30%)	In general, an optimization of resources (economic, personnel, safety and travel time) is expected. In particular, as far as it concerns the operation & maintenance, it can be seen that a clear reduction of costs is possible both for safety ad interventions. As it is a tool that may be used at "high level" to assess a strategy to approach risk and resilience, a positive ROI is expected.

Table 10. Questions & Impacts for D.7.1, D.7.5, D.7.6

			MAINTENANCE PLANNING					
ELEMENT	DAMAGE	DETAILS	How is it measured/detected?	How is it monitorized?	How often?	How is it maintained?	How often?	FORESEE new tools/solutions/options
STRUCTURAL ELEMENTS	Loss of loading capacity.	Damaged estructure of tunnels, bridges, culverts, retaining walls...	Partial collapse of the structure during or after an extreme event. Reduction of service capacity.	Command and Control center can detect an important anomaly if a structure is damaged, in combination with SHM Algorithms.	Hybrid Data Assessment For Diagnosis & Prognosis provides the damage state of the structure once a flooding event is happened. The results will provide the degree of damage, and in combination with Decision Support Module stablishes a proper monitoring frequency after the flooding.	Proper design of the structure, and stablish a maintenance strategy to keep the resilience of the system as high as possible.	According to Governance Module outputs.	Command and Control can detect the collapse as an anomaly is raised. Hybrid Data Assessment to stablish the state of the structure after a landslide, depending on the magnitude of it. Governance Module to provide a fast decision-making support if collapse is reached. Decision Support Module to stabish the optimal monitoring frequency after a landslide. SHM Algorithms can early detect a structural damage by changes on the structural reponse.
STRUCTURAL ELEMENTS	Cracking.	Structural cracking appear, being these superficial or structural due to differential movements.	Visible detection of cracking, mainly on the peak stressess direction.	Fissure meter devices to monitor the evolution of cracking.	Depending on the growing rate of cracking and the criticality of the structural element.	Two main types of cracking is identified: The superficial ones, due to retraction/contraction of the external layers of the material, can be repaired by adding coating material. Structural cracks are a signal of differential movements, meaning an action is required if these are not stable.	Algorithms for the selection and definition of efficient and optimal actions / Intervention & Mitigation can provide the actions to be performed in order to assess and intervent on this risk. If structural cracking is identified, a repairing action must be performed urgently prior to bigger damages. SHM algorithms in combination with Command and Control center can provide a continuous monitoring that reflects the evolution and affection rate of the cracking.	SHM Algorithms to evaluate the structural damages. Command and Control to detect anomalies caused by structural damage by cracking. Algorithms for selection of optimal actions can provide the actions to be performed or the inspection frecuencies.
STRUCTURAL ELEMENTS	Collapse.	Collapse off different structural elements: bridges, retaining walls, tunnel structures, hub buildings, parking slots.... In addition to ground surface and geotechnical failures, bridges are vulnerable to complete structural collapse.	Collapse of the structure during or after an extreme event. Total lack of service capacity.	Command and Control center can detect an important anomaly if a structure collapses.	Hybrid Data Assessment For Diagnosis & Prognosis provides the damage state of the structure once a landslide event is happened. The results will provide the degree of damage, and in combination with Decision Support Module stablishes a proper monitoring frequency after the landslide.	Proper design of the structure, and stablish a maintenance strategy to keep the resilience of the system as high as possible.	According to Governance Module outputs.	Command and Control can detect the collapse as an anomaly is raised. Hybrid Data Assessment to stablish the state of the structure after a landslide, depending on the magnitude of it. Governance Module to provide a fast decision-making support if collapse is reached. Decision Support Module to stabish the optimal monitoring frequency after a landslide.

Figure 23. FORESEE Tools strategies and application for the different elements and damage – Maintenance planning (From D.7.6)

			OPERATION PLANNING					
ID	IMPACT	DESCRIPTION	How is it measured/detected?	How is it monitorized?	How often?	How is it managed?	How often?	FORESEE new tools/solutions/options
OP.01	REDUCED TRAFFIC CAPACITY	Occasional / brief lane closure, but roads remains open. This impact includes lane obstruction due to snow, debris, fallen trees, rock falls, etc.)	By measuring the traffic flow of the road.	Counter vehicles devices / satellite monitoring / CCTV	Continuosly.	Traffic agents need to provide alternative routes to the traffic.	Prior to expected traffic demand peak	Governance module: To identify critical transport system sections, and define critical dates of peak demand Traffic module: Evaluation of affection of different scenarios
OP.02	TEMPORARY CLOSURE	Minor damages that result in temporary closure of road or in closing railway lines, from hours to weeks up to 60 days. Vehicles would be forced to reroute to other roads during rehabilitation works.	Interruption of the traffic in a section leads to diverged traffic flow to other areas.	SHM BIM based alerting SAS platform can raise an alarm as soon a congestion is detected in the traffic flow.	Continuously.	Preventive actions can be provided in order to avoid unexpected events that cause a temporary closure, as improved drainage systems. A continuous monitoring of the network is recommended to detect as soons as possible the irruption.	Needed actuation as soon as it happens.	Governance module: To identify critical transport system sections, and define critical dates of peak demand Traffic module: Evaluation of affection of different scenarios SHM BIM based alerting SAS platform: Detection of a disruption from satellital information or other source. Hybrid Data Assessment: Prediction of the performance of a temporary closure of a part of a transport network. Guidelines to the adoptation of suistanable drainage: To improve the drainage capabilities of a road, improving resilience of the transport system against floodings.
OP.03	COLLAPSE / LONGTIME CLOSURE	Total loss or ruin of asset. It implies immediate road/line closure and requires major repair or rebuild over an extended period of time.	Interruption of the traffic in a section leads to diverged traffic flow to other areas. Anomalies can be detected by Command and Control Center, using the predictive algorithms to avoid the collapse in conjunction with the SHM Algorithms.	SHM BIM based alerting SAS platform can raise an alarm as soon a collapse is detected in the network. Command and Control Center can detect an anomaly, in conjunction with SHM Algorithms.	Continuisly.	Alerts can be raised from predictive tools (Command and Control Center, SHM Algorithms) in order to perform an action prior to the collapse, or to be detected once these are trigered (SHM BIM based alerting SAS platform).	Needed actuation as soon as it is detected, any kind of anomaly or once it has been trigered.	Governance module: To identify critical transport system sections where to focus the continuous monitoring. Traffic module: Evaluation of affection of different scenarios, assessment of alternative routes. SHM BIM based alerting SAS platform: Detection of a disruption from satellital information or other source. Hybrid Data Assessment: Prediction of the performance of a diverged part of a transport network. Command and Control Center: To predict and detect any anomaly to prevent the collapse. SHM Algorithms: Perform a continuous monitoring of any signal of potential collapse.

Figure 24. FORESEE Tools strategies and impacts for the different elements–Operational planning (From D.7.6)

6.2 RESILIENCE INDEXES AND TARGETS (KPI AND KRT)

The functioning of society depends on the transportation of goods and persons. As reductions in service due to natural hazards (i.e. floods, earthquakes, etc.) can affect mobility of persons and goods, it is fundamental to provide cost effective and reliable tools **to improve the service and resilience of the infrastructure**, as it promotes:

- ✓ holistic approach,
- ✓ **unique measure** to take into account all these factors and their weight,
- ✓ tool for governance to understand which actions to take and where to improve service and reduce negative impacts.

In order to do so, however, it is necessary for transport infrastructure managers to,

a. on the one side, have a clear idea of the service that the infrastructure is providing and an understanding of its resilience, if it is affected by natural hazards, and,

b. on the other, to understand how the resilience of a network can be modified to balance the loss of service following a hazard and to provide the specified levels of service during and following the occurrence of extreme events, that is, to set resilience targets (Martani et al.)

In Figure 25 some of the parameters and factors to be taken into account to operate infrastructure daily and strategically in the long run are resumed

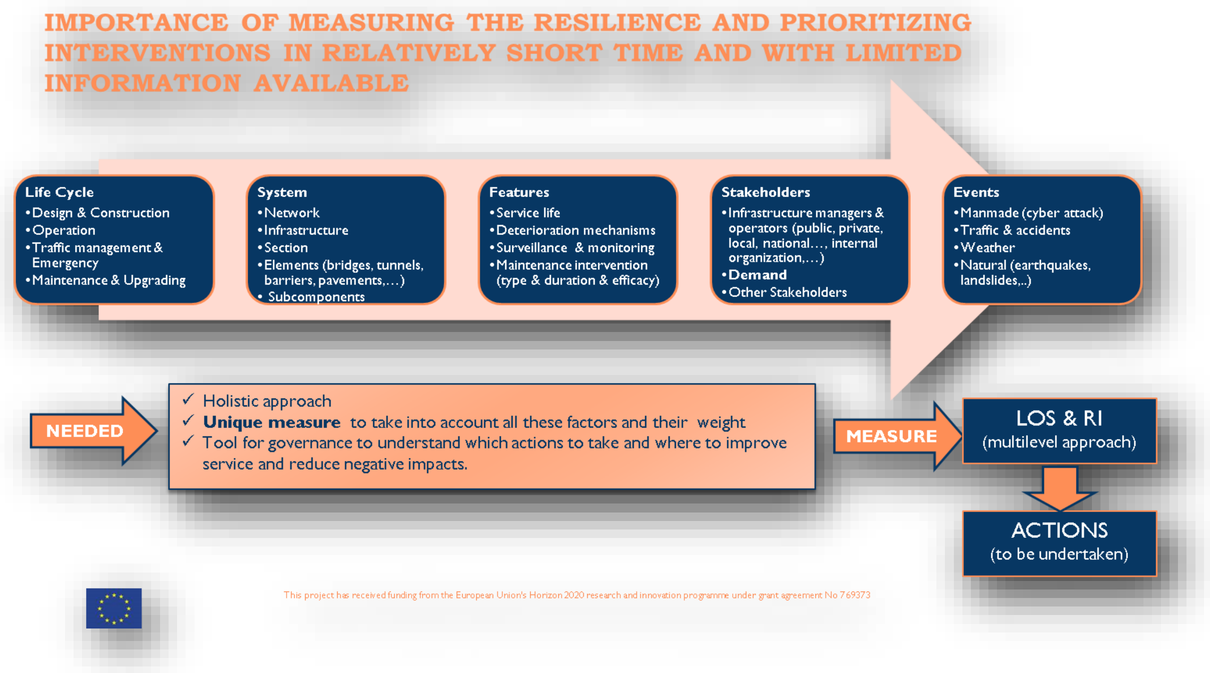


Figure 25. Discussion (from 4TH WEBINAR, 2021)

Deliverable D1.1[4] provides a comprehensive guideline to measure the resilience, as well as the level of service, in a relative short time and with limited information available, through indicators.

The guideline is to be used by managers to establish targets for the service provided by, and the resilience of, transportation infrastructure, especially when the desire is to have a standardised, repeatable and comparable process.

The guideline is a valuable support in understanding the impact of the different factors on the daily operation of the infrastructure.

Service is defined as the ability to perform an activity in a certain way, provided by transport infrastructure and in the project, four types of service are proposed:

1. Travel time.
2. Safety: the cost of repairing damaged property, the number of injuries and deaths due to people travelling across the proposed section.
3. Interventions: the cost of keeping the infrastructure in, or restoring it to, an acceptable state.
4. Socio economic activities: the costs for the society due to the additional travel time for all the people and goods travelling after a hazard.

If we consider the level of service associated to the different proposed scenarios, the values vary as in the following table.

CS#2	LOS as a Cost Value [10^3€]	
	D1.1.	Scenario b)
Interventions	2.988.298	87.215
Travel time	17.731.488	13.234
Safety	306.487.588	0
Socio-economic activities	559.330	10.136

Table 11. Level of Service for CS#2

Resilience is defined as the "ability to continue to provide service if a hazard event occurs and when considering extreme events, resilience is therefore measured as the difference between the service provided by the infrastructure if no hazard event occurs and the service provided by the infrastructure if a hazard event occurs and the costs of intervention if no hazard event occurs and the costs of interventions if a hazard event occurs. It may be measured in terms of travel time, expected cumulative injuries and fatalities or intervention costs".

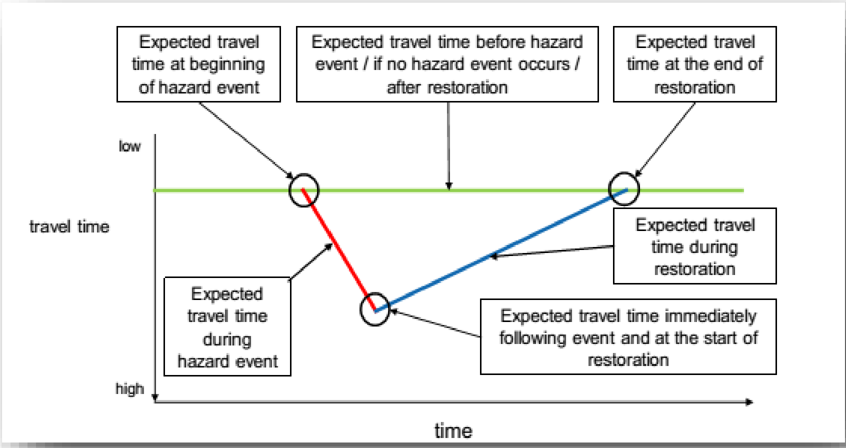


Figure 26. Resilience and service (from D.1.1), measured in travel time

In the following table the transport system is described through its indicators, set of possible parameters and proposed values, assembled in three main categories:
The transport system is considered to have three main components (Table 12):

1. the physical infrastructure, divided in condition state, protective measures and preventive measure,
2. both the environment in which the infrastructure is embedded that might affect the provision of service and the organisational environment in which the infrastructure management organisation is embedded,
3. the organisation responsible for ensuring that the infrastructure provides service with a set of pre-event and post-event activity indicators with reference to the specific risk.

All indicators, parameters and attributes have been extensively discussed with ETH, and within the Company's different Departments, during the progress of WP1, to identify quite a wide set of potentially applicable indicators. Of course, these indicators have to be customised for the specific risk, type of infrastructure and overall objective of the assessment.

As far as it concerns the application of D.1.1, it has to be said that as the guidelines are to be generally applied, some of the indicators may not be relevant for the problem at hand.

In this case, it is to be evaluated if these indicators should be removed from the list as they may bias the overall judgement or should be kept for the sake of comparison, but should be correctly weighted.

The proposed guideline has been applied in two different scenarios as described in previous chapters:

D	Level 0	ID	Level 1	ID	Indicator	Scale	Measure	Impact			
								Interv.	Travel time	Accident	Socio-econ.
L.1	Infrastructure	L.1.1	Proactive measures	L.1.1.1	The possibility of building a temporary alternative route for vehicles	2	0		X		X
				L.1.1.2	The possibility of using another means to satisfy transport demand	2	1		X		X
				L.1.1.3	The number of possible existing alternative ways to deviate vehicles	1	1		X		X
				L.1.1.4	The presence of a warning system	2	2		X		X
				L.1.1.5	The presence of a safe shutdown system	1	0		X		X
				L.1.1.6	The presence of emergency / evacuation paths	2	1		X		X
				L.1.1.7	The presence of special measures to help evacuate persons	2	0		X		X
		L.1.2	Preventive measures	L.1.2.1	Complience with the current slope stability design code	2	2	X	X	X	X
				L.1.2.2	Presence of protection barries (e.g. to rockfalls, snowfalls, etc.)	1	1	X	X	X	X
				L.1.2.3	Adequate protection barries (e.g. to rockfalls, snowfalls, etc.)	1	1	X	X	X	X
		L.1.3	Condition state of the infrastructure	L.1.3.1	Age / Age of replacement of the warning system	3	2			X	X
				L.1.3.2	Condition state of infrastructure	5	4	X	X	X	X
				L.1.3.3	Condition state of protective structures/systems	5	2	X	X	X	X
				L.1.3.4	Condition state of assistance alert systems	5	2	X	X	X	X
				L.1.3.5	Expected condition state of infrastructure	3	1	X	X	X	X
				L.1.3.6	Expected condition state of protective structures/systems	3	2	X	X	X	X
				L.1.3.7	Expected condition state of assistance alert systems	2	2	X	X	X	X
L.2	Environment	L.2.1	Physical	L.2.1.1	Height	2	1			X	
				L.2.1.2	Accessibility	3	2	X			
				L.2.1.3	Presence of persons/property below the infrastructure	1	0			X	
				L.2.1.4	Extent of past damages due to hazards	3	1	X			
				L.2.1.5	Hazard zone	2	1	X	X	X	X
				L.2.1.6	Frequency of past hazards	3	2		X	X	X
				L.2.1.7	Severity of past hazards	3	1		X	X	X
				L.2.1.8	Frequency of future hazards	3	2		X	X	X
				L.2.1.9	Severity of future hazards	3	2		X	X	X
				L.2.1.10	Land type	3	2	X		X	
				L.2.1.11	Terrain type	2	1	X	X	X	X
				L.2.1.12	Extent of vegetation cover	3	1	X	X	X	X
				L.2.1.13	Traffic	3	2	X	X	X	X
				L.2.1.14	Hazards goods traffic	2	1			X	
				L.2.1.15	Flammable goods traffic	1	1			X	
		L.2.2	Non-physical	L.2.2.1	Budget availability	2	2	X	X	X	X
L.3	Organization	L.3.1	Pre-event activities	L.3.1.1	The presence of a monitoring strategy	2	1	X	X	X	X
				L.3.1.2	The presence of an maintenance strategy	2	1	X	X	X	X
				L.3.1.3	The extent of interventions executed prior to the event	2	1	X	X	X	X
		L.3.2	Post event activities	L.3.2.1	The presence of an emergency plan	2	1		X		X
				L.3.2.2	Practice of the emergency plan	4	2		X		X
				L.3.2.3	Review/update of the emergency plan	2	1		X	X	X
				L.3.2.4	Expected time for tendering	3	2	X	X		X
				L.3.2.5	Expected time for demolition	3	3	X	X		X
				L.3.2.6	Expecetd time for construction	3	2	X	X		X

Table 12. Indicators for CS#2

a. The first one is based on data from past "extreme" events (a major landslide hit the infrastructure in 2005 at km. 122)[1] to increase the comprehension of all the relevant elements or factors affecting the specific event and to assess the possible consequences and actions to be undertaken.

   No impact on safety was observed (no fatalities or injuries). A reduction instead on traffic volumes was presumably caused by the landside during the period of execution of the works (1,5 on the average, approx. 20% in correspondence of the event).

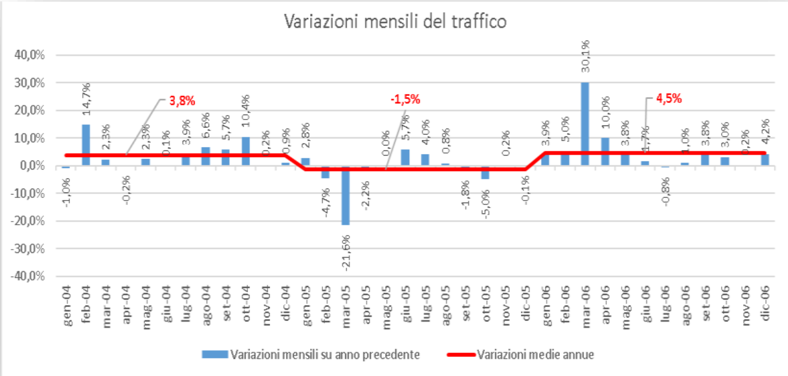


Figure 27. Traffic distribution after the event

b. In the second one, the expected event is the triggering of a landslide, to hit the infrastructure in presence of normal traffic and/or in case of heavy traffic (works, accidents). The average rate of movement of the landslide is on the average of a few mm. per year, thus allowing the infrastructure manager to put in place all the contingency (if necessary) measures and execute all the maintenance interventions necessary not to reduce the level of service of the highway with low or null impact on mobility

   Delay per unit (person or truck) per day after an event [min/p.u.] is of evaluated in 30 minutes considering all types of event [2] (works, snow, accidents…) and impacts of safety is reduced as well. Delays due to rerouting are limited for the chosen section and would be higher if we had to consider the entire highway.

   .

[1] Disclaimer:The work presented is a mere exercise, for which the vast majority of inputs have been set based on authors' assumptions –that is, the inputs are realistic but fictive and as such do not reflect the current situation of the highway chosen for the present application. Therefore, the results cannot be in any way connected to the actual resilience of the real transport infrastructure

[2] data 2013-2019

For demonstration purposes it has been assumed the values of all indicators were taken as averages for the entire 30 km road section and were thought of only in general terms and defined through interviews with internal stakeholders.

The situation is represented in the following figures where major impact is on interventions travel time and socio-economic activities. It can be seen that in case a) most efforts are concentrated on safety, as a very negative solution has been chosen, while in case b) most efforts are concentrated on intervention activities to increase service and resilience, as we are in free condition of flow or average queue length. Some indicators are the same, for instance as far as it concerns the contribution of the infrastructure its condition has to be kept under control or the level of hazard and its frequency past and expected impacts on the environment.

Finally, as it concerns the organization, monitoring or maintenance strategy are to be implemented as well as in same cases the presence and practice of emergency measures.

	Element	**Intervention**					**Travel time**	**Safety**					**Socio economic activities**
Case a	**Infrastructure**							1.3.2	1.3.3	1.3.5	1.3.6		
	Environment							2.1.3	2.1.5	2.1.6	2.1.7	2.1.13	
	Organization							3.1.1	3.1.2	3.1.3			
Case b	**Infrastructure**	1.2.1	1.3.2	1.3.5									
	Environment	2.1.4	2.1.5	2.1.13									
	Organization	3.1.1	3.2.2	3.2.3									

Table 13. Indicators relevant for the different scenarios

LEGENDA

1 Compliance with the current slope stability design code
1.3.2 Condition state of infrastructure
1.3.3 Condition state of protective structures/systems
1.3.5 Expected condition state of infrastructure
1.3.5 Expected condition state of infrastructure
1.3.6 Expected condition state of protective structures/systems

3.1.1 The presence of a monitoring strategy
3.1.2 The presence of a maintenance strategy
3.1.3 The extent of interventions executed prior to the event
3.2.2 Practice of the emergency plan
3.2.3 Review/update of the emergency plan

2.1.3 Presence of persons/property below the infrastructure (quite a rare situation)
2.1.4 Extent of past damages due to hazards
2.1.5 Hazard zone
2.1.6 Frequency of past hazards
2.1.7 Severity of past hazards
2.1.10 Land type
2.1.11 Terrain type
2.1.13 Frequency of past hazards

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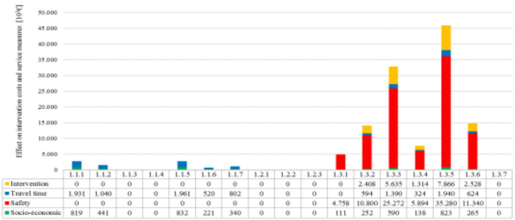

Figure 28. Infrastructure: measures of resilience for each indicator, using the actual value of all indicators, by intervention costs and each measure of service, scenario a) (landslide km 122)

1.3.2 Condition state of infrastructure
1.3.3 Condition state of protective structures/systems
1.3.5 Expected condition state of infrastructure
1.3.6 Expected condition state of protective structures/systems

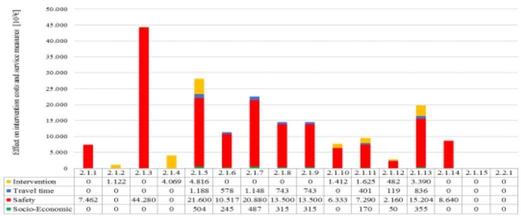

Figure 29. Environment: measures of resilience for each indicator, using the actual value of all indicators, by intervention costs and each measure of service, scenario a) landslide km 122)

2.1.3 Presence of persons/property below the infrastructure (quite a rare situation)
2.1.5 Hazard zone
2.1.6 Frequency of past hazards
2.1.7 Severity of past hazards
2.1.13 Frequency of past hazards

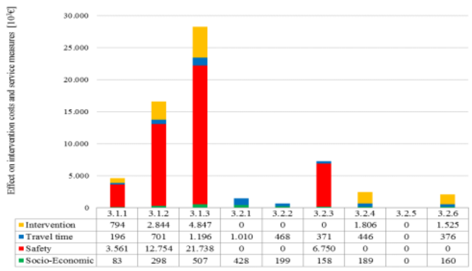

Figure 30. Organisation: measures of resilience for each indicator, using the actual value of all indicators, by intervention costs and each measure of service, scenario a) (landslide km 122)

3.1.1 The presence of a monitoring strategy
3.1.2 The presence of a maintenance strategy
3.1.3 The extent of interventions executed prior to the event

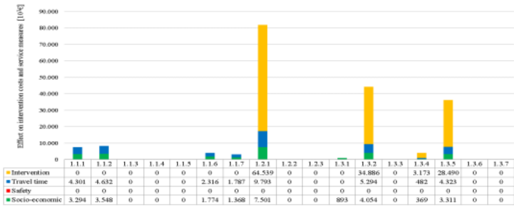

Figure 31. Infrastructure: measures of resilience for each indicator, using the actual value of all indicators, by intervention costs and each measure of service, scenario b)

1.2.1 Compliance with the current slope stability design code
1.3.2 Condition state of infrastructure
1.3.5 Expected condition state of infrastructure

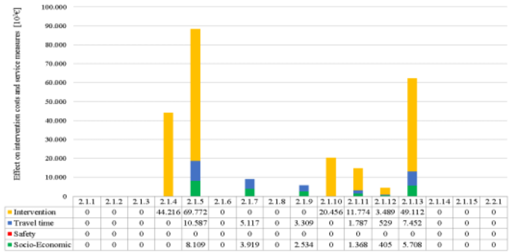

Figure 32. Environment: measures of resilience for each indicator, using the actual value of all indicators, by intervention costs and each measure of service, scenario b)

2.1.4 Extent of past damages due to hazards
2.1.5 Hazard zone
2.1.13 Traffic

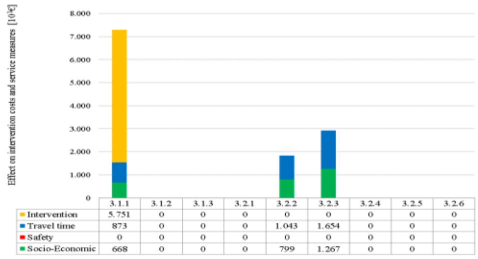

Figure 33. Organisation: measures of resilience for each indicator, using the actual value of all indicators, by intervention costs and each measure of service, scenario b)

3.1.1 The presence of a monitoring strategy
3.2.2 Practice of the emergency plan
3.2.3 Review/update of the emergency plan

In D.1.2 [5], when extreme events occur, their ability to provide this service can be reduced. To counteract this, a network can be modified to be more resilient and to provide specified levels of service during and following the occurrence of extreme events. The guideline should allow managers to set specified, i.e. target, levels of service and resilience during and following the occurrence of extreme events, in a structured and consistent way.

The guideline sets out the principles and basic steps to be used. The choice of the target setting method depends on the specific problem to be addressed, the time frame at disposition, the expertise available, the availability of data, and how the level of service and resilience are measured.

In the following the results are relative to the first scenario proposed for the validation, based on data from past events.

With the goal of improving resilience, it is necessary to improve the values of the relevant indicators. It is to be kept in mind that some of these may be relatively easy to modify, others are difficult if not impossible to modify, i.e. the hazard zone of the infrastructure .

In this perspective the resilience indicators targets for the A16 highway transport system have been set for those indicators that were considered to be in the control of the infrastructure operator (31 out of the 42), (Annex 1.1).

Both legal and internal requirement (i.e. the things that they simply thought had to be done) were chosen. For the example at hand, three "legal requirements" were set and two "internal requirements".

Type	ID	Indicator	No. of possible values	At least
Legal	1.1.6	The presence of emergency / evacuation paths	2	1
	1.2.1	Compliance with the current slope stability design code	2	1
	1.3.2	The condition of infrastructure	5	3
Stake-holder	1.3.3	The condition of protective barriers	5	2
	3.1.3	The extent of interventions executed prior to the event	2	1

Table 14. Requirements for the indicator values

Then the approximate costs and benefits of improving the values of each of the indicators were estimated with respect to the likely restoration costs and the likely reductions in service, with respect to the reference landslide. Finally, the target values that were likely to give the maximum net-benefit were selected, while satisfying all of the requirements.

From Table 15, it can also be seen that only 4 indicators have actual values below the target values (Table 15): the condition state of protective barriers indicator (1.3.3), the expected condition state of infrastructure indicator (1.3.5), the presence of a maintenance strategy indicator (3.1.2), the presence of an emergency plan indicator (3.2.1).

ID	Indicator	Scale	Actual value	Target value	Costs to reach target 10³€	Benefit of reaching target 10³€	B/C	Net benefit of reaching (10³€)
1.1.1	The possibility of building a temporary alternative route for vehicles	2	0	**0**	0	0	0.00	0
1.1.2	The possibility of using another means to satisfy transport demand	2	1	**1**	1'200	1'481	1.23	281
1.1.3	The number of possible existing alternative ways to deviate vehicles	1	1	**0**	0	0	0.00	0
1.1.4	The presence of a warning system	2	2	**2**	2'500	3'046	1.02	546
1.1.5	The presence of a safe shutdown system	1	0	**0**	0	0	0.00	0
1.1.6	The presence of emergency / evacuation paths	2	1	**1**	0	0	0.00	0
1.1.7	The presence of special measures to help evacuate persons	2	0	**0**	0	0	0.00	0
1.2.1	Compliance with the current slope stability design code	2	2	**1**	0	0	0.00	0
1.2.2	Presence of protection barriers	1	1	**0**	0	0	0.00	0
1.2.3	Adequate protection barriers	1	1	**1**	2'000	43'567	21.78	41'567
1.3.1	Age / Age of replacement of the warning system	3	2	**0**	0	0	0.00	0
1.3.2	Condition of infrastructure	5	4	**3**	0	0	0.00	0
1.3.3	Condition of protective barriers	5	***2***	**5**	30'000	54'811	1.10	24'811
1.3.4	Condition of assistance alert systems	5	2	**1**	2'500	2'557	1.02	57
1.3.5	Expected condition of infrastructure	3	***1***	**2**	35'000	45'910	1.15	10'910
1.3.6	Expected condition of protective barriers	3	2	**0**	0	0	0.00	0
1.3.7	Expected condition of assistance alert systems	2	2	**0**	0	0	0.00	0
2.1.12	Extent of vegetation cover	3	1	**0**	0	0	0.00	0
2.1.13	Traffic	3	2	**0**	0	0	0.00	0
2.1.14	Hazards goods traffic	2	1	**0**	0	0	0.00	0
2.1.15	Flammable goods traffic	1	1	**0**	0	0	0.00	0
2.2.1	Budget availability	2	2	**1**	20'000	20'027	1.00	27
3.1.1	The presence of a monitoring strategy	2	1	**0**	0	0	0.00	0
3.1.2	The presence of an maintenance strategy	2	***1***	**2**	25'000	33'193	1.11	8'193
3.1.3	The extent of interventions executed prior to the event	2	1	**1**	20'000	28'287	1.41	8'287
3.2.1	The presence of an emergency plan	2	***1***	**2**	9'000	36'912	3.08	27'912
3.2.2	Practice of the emergency plan	4	2	**1**	3'000	3'021	1.01	21
3.2.3	Review/update of the emergency plan	2	1	**1**	5'000	9'268	1.85	4'268
3.2.4	Expected time for tendering	3	2	**2**	14'000	23'175	1.05	9'175
3.2.5	Expected time for demolition	3	3	**3**	520	2'929	4.58	3'773
3.2.6	Expected time for construction	3	2	**1**	10'000	14'177	1.42	4'177
3.2.2	Practice of the emergency plan	4	2	**1**	3'000	3'021	1.01	21
3.2.3	Review/update of the emergency plan	2	1	**1**	5'000	9'268	1.85	4'268
3.2.4	Expected time for tendering	3	2	**2**	14'000	35'070	1.59	21'070
3.2.5	Expected time for demolition	3	3	**3**	620	16'027	16.69	15'407
3.2.6	Expected time for construction	3	2	**1**	15'000	19'200	1.28	4'200

* The grey shaded and red actual values highlight the ones that are below the target.

Table 15. Targets proposed for the 31 resilience indicators considered to be in the control of the infrastructure operator

In particular (Figure 34), improving the expected condition of the infrastructure following the occurrence of the reference landslide would provide the greatest net-benefit (€35 million), followed by improving the condition state of the protective barriers (€27 million), adding a maintenance strategy (€25 million) to ensure a solid preventive maintenance throughout the whole infrastructure, and then developing an operative emergency plan (€6 million).

This means that if only one thing can be done improving the expected condition of the infrastructure following the occurrence of the landslide should be prioritized, requiring €27 million. If all are to be done approximately €93 million would be required.

The greatest net-benefit (€12.5 million) would be developing and improving the operative emergency plan, and the second best would be improving the condition state of the protective barriers (€10.9 million).

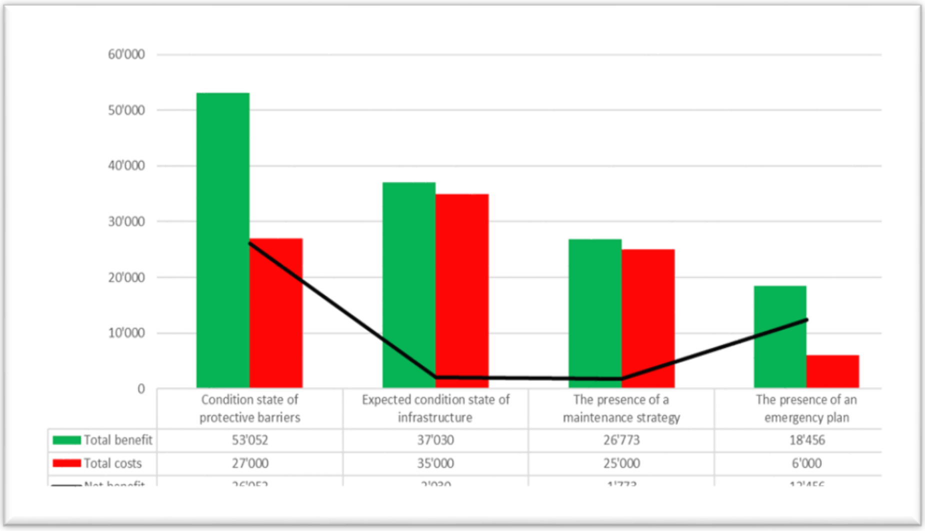

Figure 34. Total benefit, total costs and net benefit to align the current four indicators out of target to their targets

The use of the guideline helps (Table 16) ensure that infrastructure managers define service and resilience clearly and consistently, and that they are systematically considered when evaluating the resilience of the transport system, as well obtaining an idea of how to improve resilience. The example shows that this is possible, with relatively little input and effort. Of course, if the results of such an analysis are not sufficient to plan risk-reducing interventions, they can also be used to focus more detailed future analysis.

Guidelines should be of course be developed/applied for the different risk scenarios to allow comparison, best use of available resources and optimal decisions.

Question	Impact
Was this type of analysis made before FORESEE? How it was made?	It is expected to include measures of service and resilience of elements and infrastructure in the daily and long term management of the assets to comply with national regulations.
How does FORESEE improve the results/analysis previously made?	The resilience target system used by Foresee makes it possible to better correlate the infrastructural condition with the quality of the service. It identifies the areas where to concentrate activities.
How does this FORESEE result improve your infrastructure's management	○ To have a clear idea of the service that the infrastructure is providing and an understanding of its resilience, if it is affected by natural hazards, and, ○ To understand how the resilience of a network can be modified to counteract the loss of service following a hazard and to provide the specified levels of service during and following the occurrence of extreme events–that is, to set resilience targets.
If it was not made, How does this FORESEE result improve your infrastructure's management ?	The guideline s and methodology allow : ○ to provide a unique measure, also toward the other stakeholders and public authorities, ○ to provide a tool for governance to understand which actions to take and where to improve service and reduce negative impact.
What cost/resource efficiencies you expect these tools/results to have on your day-to-day business? (e.g. 10%-20% decrease in working hours over the first year; reduction of maintenance costs (20%-25%), Return on Investment (ROI) – 10-15%, increase in productivity 25-30%)	It is expected an optimization of costs meaning there is an improved allocation of resources among the different needs and actions to be undertaken rather than a saving of some sort.

Table 16. Questions & Impacts for D.1.1. and D.1.2

6.3 WP2: DATA ACQUISITION, COLLECTION, INTEGRATION AND MANAGEMENT SYSTEM

CS#2 has been used to develop, test and validate the tools, procedures and models developed in this WP, since the early stages. The basis of analysis is on satellite data, complemented for development and validation purposes by instrumental data.

InSAR is an effective radar technique for terrain displacement mapping useful to many applications including subsidence, landslides, earthquakes and volcanic phenomena. The technique uses repeated SAR images to measure millimetre-scale changes in deformation over periods of days to years. Even though it presents some limits (i.e. atmospheric conditions, phase disturbance…), it is a powerful tool to map and monitor large areas and elements such infrastructures and their components.

For the application to CS#2, in **deliverable D2.1 and D2.2,[10][11]**, two different kind of InSAR data have been used: for a macroscale study (Task 2.1), using medium resolution motion information over the assets and their surroundings, and, for a higher resolution study, focused on the assets structure, with a monitoring phase of one year (Task 2.3).

The design of a Satellite Acquisition Program under Task 2.1 to provide a service on satellite data provision from archived to smart image acquisition tasking has been built on CS#2.

The first results of Task 2.1 have led to the decision to modify the area of interest from the originally planned section from km 70-100 to the actual area between km 80-110 where more movements had been observed.

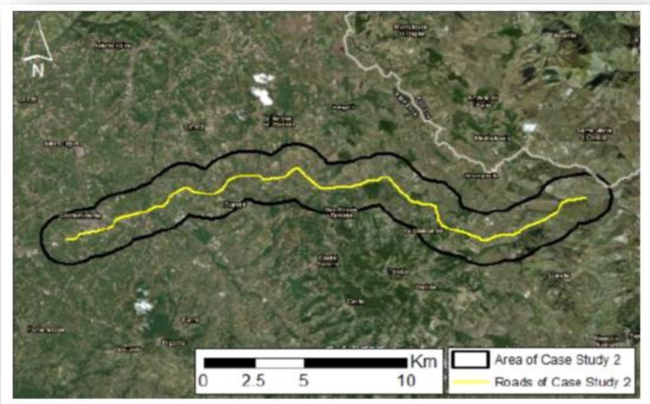

Figure 35. CS#2 Area of interest

Deliverable D2.2 "Strategies for Change Detection and Surface Movement through Satellite Technology", describes the techniques used in T2.3 for the processing of satellite data.

Figure 36 shows the regional displacement estimated with SBAS Interferometric technique by using Sentinel-1 SAR images. The results cover around 200km length of central Italy including CS#1 and CS#2 locations (**deliverable 2.3**) **[12].**

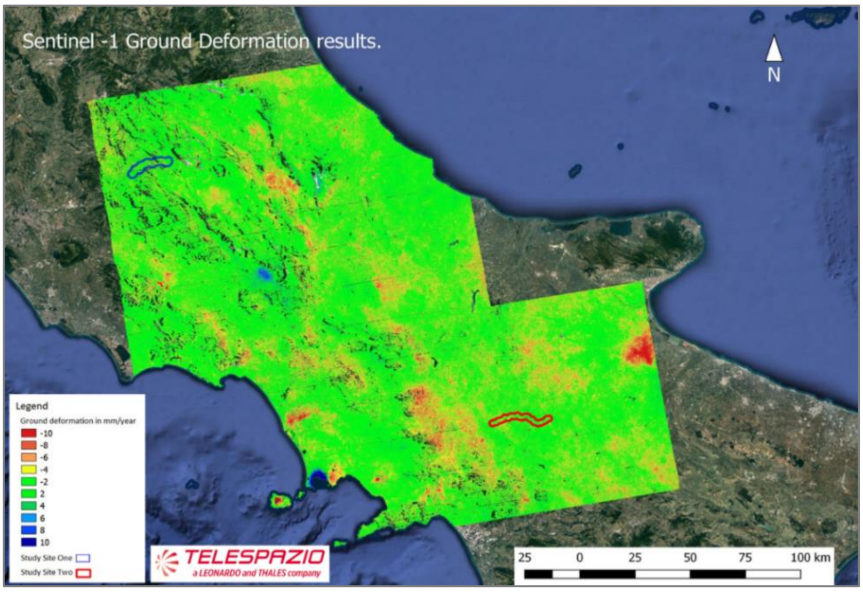

Figure 36. Regional displacement detected over CS#1 and CS#2 using SBAS Interferometric technique.

The GIS based risk analysis platform generating prioritised ranked site/asset risk map developed in the project **(deliverables D2.4 and D2.5) [13][14]** and could be a valuable tool to be used as it is aimed at identifying the strategic areas where implementing the measures to mitigate the impacts of extreme natural events (D2.5) and to optimise the use of available resources as efficiently as possible. Moreover, it is built on GIS public databases. The hazards and vulnerability maps may be developed on this GIS reference system, the weight given to each factor and risks can be adjusted by the user if more accurate information is available, if their weights differ from those defined in this project or to adapt the tool to future innovations in the field of risk assessment, according to the methodologies and models developed in WP2.

The GIS-based application provides a wide range, large scale, indicator based approach for stakeholders to risk evaluation that identifies the potential occurrence of the most important natural extreme events - landslides, floods and earthquakes -, as a first step for the design of more resilient infrastructures and prior to a more accurate and detailed quantification.

The GIS-based application might be interfaced with the company's AGE-Autostrade Google Earth, where the network and infrastructures and elements are registered, in particular as far as it concerns the hazard and vulnerability maps.

In view of the development of the subsequent tasks i.e. for the definition and quantification of the risk -landslides- to which the road infrastructures are exposed, the GIS tool has been tested on CS#2. The resulting risk maps are proposed in Figure 37.

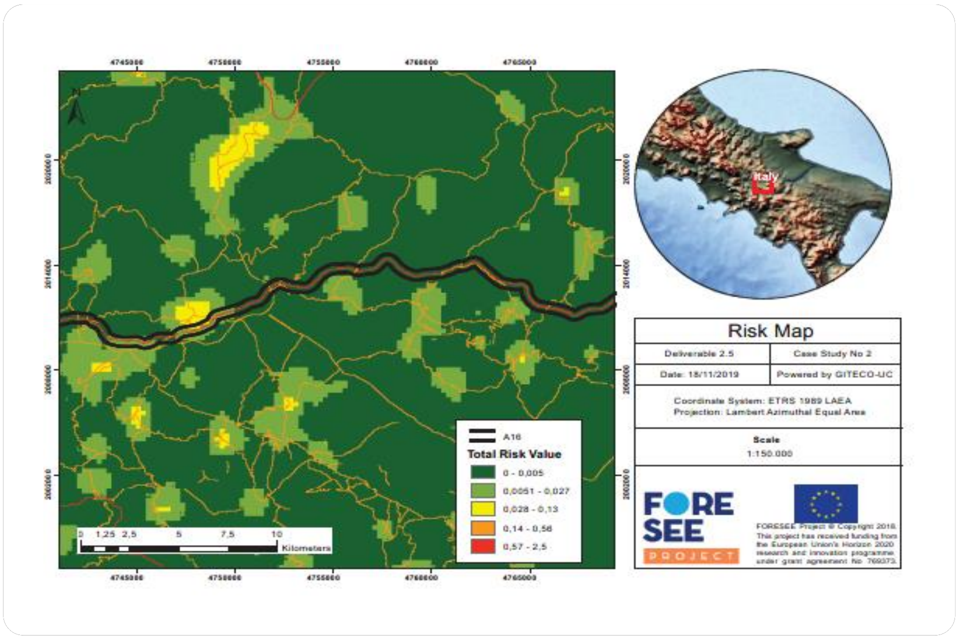

Figure 37 .Risk Maps and CS#2

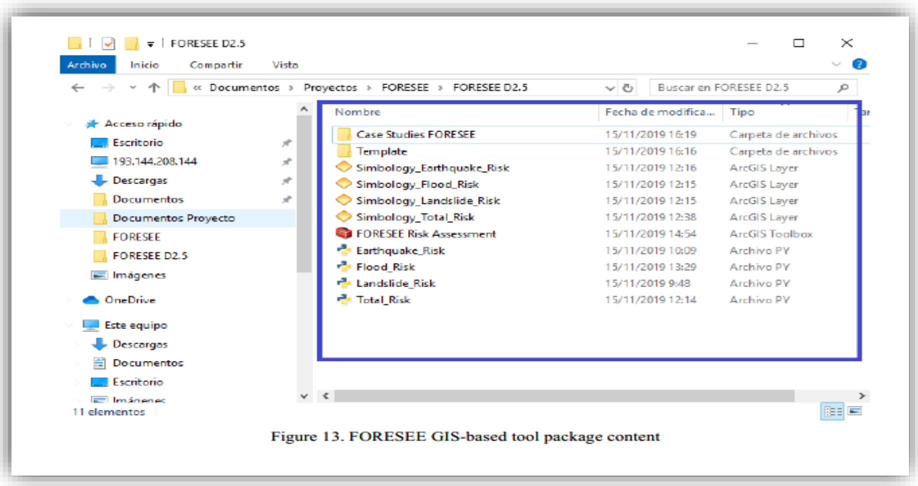

Figure 38. GIS tool

Deliverable D.2.7 [15] includes the description of an approach on slope monitoring covering its implementation and validation over Case Study #2, A16 Highway. Moreover, this report describes and analyses change detection and PSI satellite radar results over the same area. The results cover not only the slopes of the area but also the asset itself, including 30km of A16 highways, where several bridges are included. In addition, this deliverable includes the GIS files with the change detection and PSI results. This report corresponds to the second delivery of Task 2.3 named “D2.7 Datasets-Change detection and InSAR interferometry of assets” and it is included in Work Package 2 (WP2).

It appears important to improve landslide forecasting and hazard management, which includes hazard identification, hazard assessment and hazard information. In particular, monitoring can be an important tool for these purposes, because it can be used to identify failure potentials, to understand their mechanisms and to find reliable correlations between movement events and their triggering factors.

Figure 39 shows a complete view of the movements in the area and of their mean velocity retrieved from a PSI (Permanent Scatters Interferometry) analysis. The figure shows the mean velocity of the area in four different directions: descending Line of Sight (LOS), ascending LOS, East-West and Vertical. In the background, a map of estimated landslides from ISPRA (http://www.geoservices.isprambiente.it/arcgis/services/IFFI/Progetto_IFFI_WMS_public/MapServer/WMSServe) is shown.

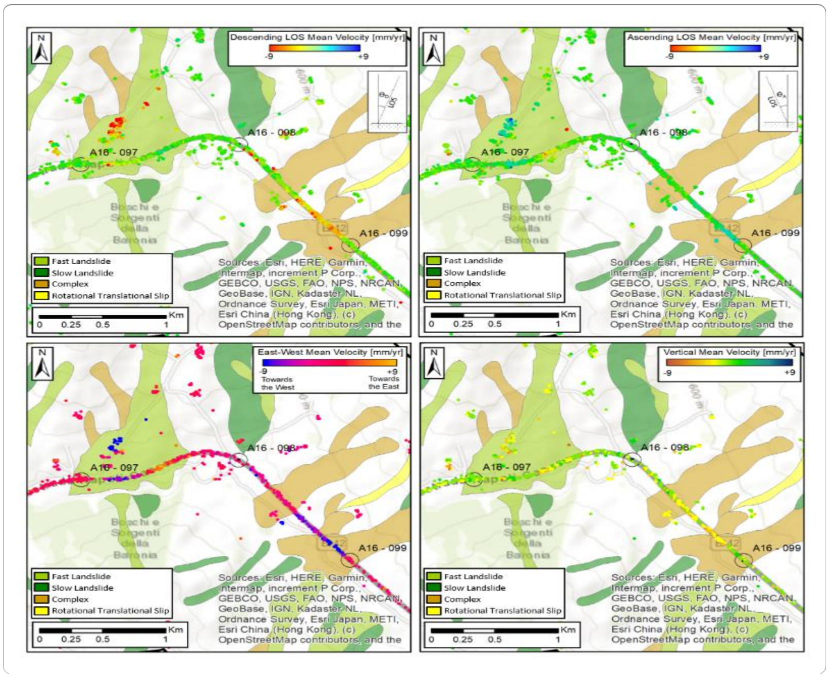

Figure 39. Descending, ascending, East-West and vertical mean velocity between Km. 97-99 (from D.2.7)

The application to CS#2 is of particular importance as validation as it includes not only data from satellite observations, but they are complemented by data from instrumental geotechnical regular monitoring (inclinometers and piezometers data), the timeframe covering the period 2012-2019.

It is of the utmost importance to integrate different sources of data as it has been made possible for the example at hand. In this way the level of confidence increases and more reliable and accurate models may be fit to describe phenomena/risks, for both large areas, linear elements and specific structures.

In the deliverable D.2.7 it is highlighted how the data from an inclinometer showing significant ground movement are strongly correlated with the data from the nearest Satellite (PSI) measurement (Figure 40). The area between km.97-99 has therefore been chosen for a more focused analysis.

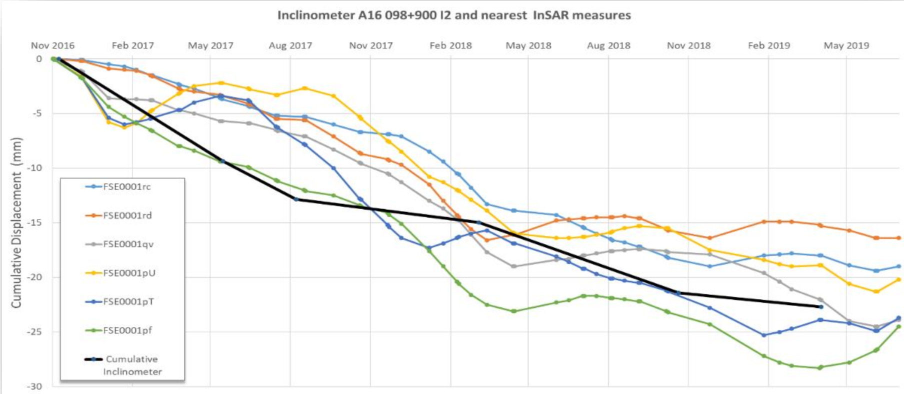

Figure 40. Comparison of the cumulative displacement detected by the inclinometer 098+900 I2 and six PSs from the PSI analysis. The scale is in the East West direction, positive values are moving to the East and negative values are moving West

The Virtual Modelling platform and asset failure prediction, described **in deliverable D.2.8 [16]¡Error! No se encuentra el origen de la referencia.**, integrates both (in situ) terrestrial and satellite data, GIS, and numerical modelling to predict failure of assets, considering rainfall a triggering factor. This would be extremely valuable from the point of view of preventing/managing emergency situations.

The main output, of the model validation is represented in the following

Figure 41 where most of the failures predicted to occur before the observed failure are near the road, where more information is available, while failures further away from the road tend to be modelled after the observed event. This may be relevant for managing purposes (for both preventative actions, due to the location of the "expected failure", or for emergency procedures)

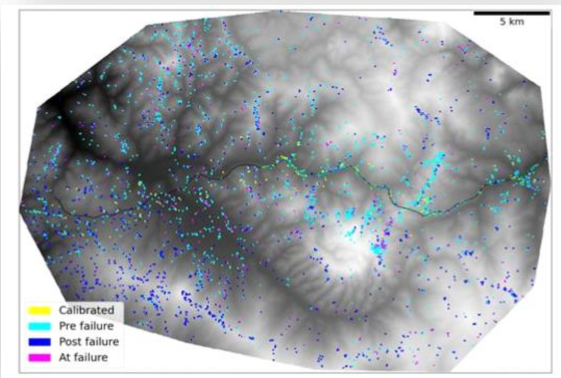

Figure 41. Map of calibrated points, alongside validation points. Calibration points are concentrated along the road. "At failure" means predicted failure within a window 25 days before observed failure. Post failure points concentrate at higher elevations far from the road.

It is clear that it is possible to find also points whose predicted failure occurred after observed exceedance of ground motion.

The limited reliability of the proposed predictive model correlating landslides to rainfall (from pore pressure measures) might be improved by future acquisition of data.

It is observed in the deliverable that a "deep" failure mechanism and a "shallow" one have been found. The first one should require a long build-up of pore pressure through multiple rainstorms, possibly better observed with radar satellites while the "shallow" failure mechanism is sensitive to intense rainfall.

For the purposes of validation, ermanent monitoring systems have been installed to validate the predictive models for hazard management. The real time acquisition rate of the permanent monitoring system, fundamental for alerts purposes, complements the rate of acquisition of InSAR data and it contributes to anchor to the ground the wide satellite images, both for shallow and in depth observed/predicted displacements.

In order to improve the precision of the models, a sensor for the monitoring of water vapour has also been installed on one of the bridges. Water vapour is correlated to rainfall a triggering factor for the landslide predictive model.

The final and comprehensive result from WP2 is the tool described under **deliverable D.2.9 [17]** which compares observed motion values against threshold failure values and thereby create a capability that issue alerts based on the comparison: "the goal of the tool here described is to generate RAG alerts over the different elements of a BIM corresponding to a critical infrastructure and to allow a 3D visualization of those alerts. Different level of alerts are raised in correspondence with the datasets of motion observed near or on each BIM element" .

The SHM BIM based alerting SAS is based on dynamic site data (satellite, in situ sensors, landslide failure prediction model), providing the motion observed on the infrastructure and its surroundings and static data, providing information on the infrastructure (BIM, motion thresholds). These two sets of data are combined and linked, and RAG alerts are raised for each BIM element. A 3D visualization of the alerts along the critical infrastructure is also provided.

The application of the SHM BIM to CS#2 has led to develop an application whose main steps are resumed in Figure 42.The main features are:

- Georeferenced representation of the territory and infrastructure,
- Internet based application,
- Possibility of links to open data software,
- Integration of different sources of data, with different rates of acquisition,
- Structural geometrical model on the infrastructure and its elements,
- Alerts thresholds based on structural considerations, for both maintenance and emergency situations,
- Alerts thresholds for landslide motion,
- Predictive models,
- Movements of the ground coupled with infrastructure' s displacements.

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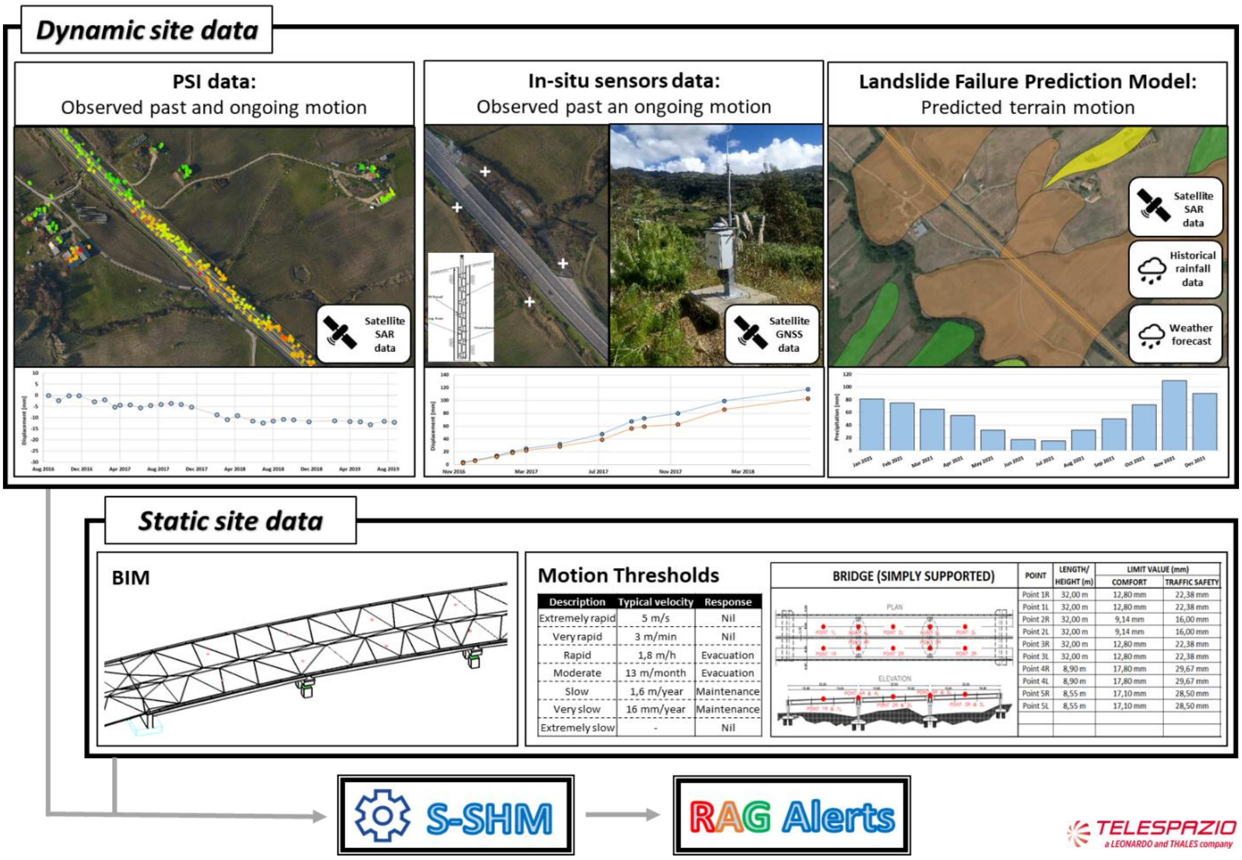

Figure 42. Schema on S-SHM Algorithm.

S-SHM validation using GNSS data from monitoring system

At the end of the summer of 2021, some GNSS data sensors were installed over two of the bridges in CS#2. These sensors measure displacement and provide the measurement automatically through an API. Figure 43 shows the location of these sensors over the two bridges. The red triangle indicates the reference point.

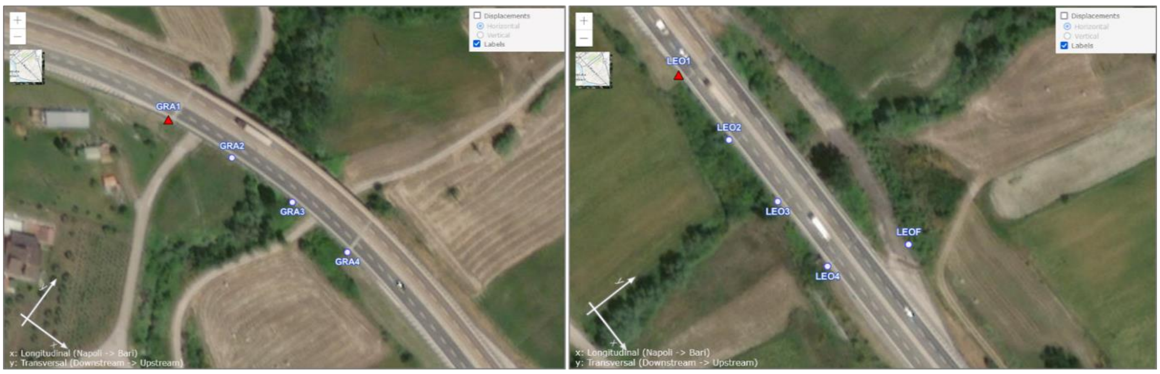

Figure 43. Location of the GNSS over the two bridges In CS#2.

In the framework of WP6, S-SHM tool (D2.9) has been modified to include these new GNSS sensors. There are two main goals for this integration: to allow a smooth validation of the tool and to provide updated information on the bridge's status.

Unlike the other type of measurements, the GNSS data is provided through an API (https://cloud.geoguard.eu). Therefore, TPZ-UK developed a new module inside S-SHM to allow the ingestion of data from external APIs.

As for the other type of measurements already integrated in S-SHM, the tool ingests the location of each GNSS sensor and evaluates which BIM elements are near each measurement point. After that, the recorded displacements are compared with the motion thresholds table in order to raise Red, Amber or Green alerts.

FORESEE toolkit **¡Error! No se encuentra el origen de la referencia.**gives access to the results provided by TPZ-UK's API. The S-SHM tool is only available for CS#2, as is the only area with InSAR results. The toolkit allows access to the 3D visualisation and to the alerts table.

Figure 44 shows and screenshot of the 3D visualisation, where the area can be navigated. The BIM is coloured in Red-Amber-Green according with the alert level. In the bottom of the screen, there is a time slide that can be moved in order to see the progress of the alerts along time. When an element is clicked, the list of alerts along time over this element are showed on the right side of the screen.

Figure 45 shows a screen of the table of alerts provided by TPZ-UK's API through FORESEE's toolkit. The alerts can be filtered by date, level or location. The example showed in the figure is the first lines of the results of filtering alerts older than 1st September 2021. As can be seen, the only sensors generating alerts after that date are the GNSS sensors.

Figure 44. Example of 3D visualisation of the alerting system over one of the bridges in CS#2. The BIM is coloured by RAG (Red-Amber-Green) alert values.

DISCUSSION

<u>The results from the project are in line with what is known in the Company.</u>

The **Virtual Modelling platform and asset failure prediction** investigated the possibility of creating a predictive model of landslides that may impact an infrastructure, based on historical displacement data, data from satellite interferometry and/or on-site monitoring (i.e. inclinometers), related to rainfall recorded data and consequent increase in interstitial pressures, to identify warning thresholds, exceeded which, it is expected for a landslide to trigger or to reach an appreciable velocity.

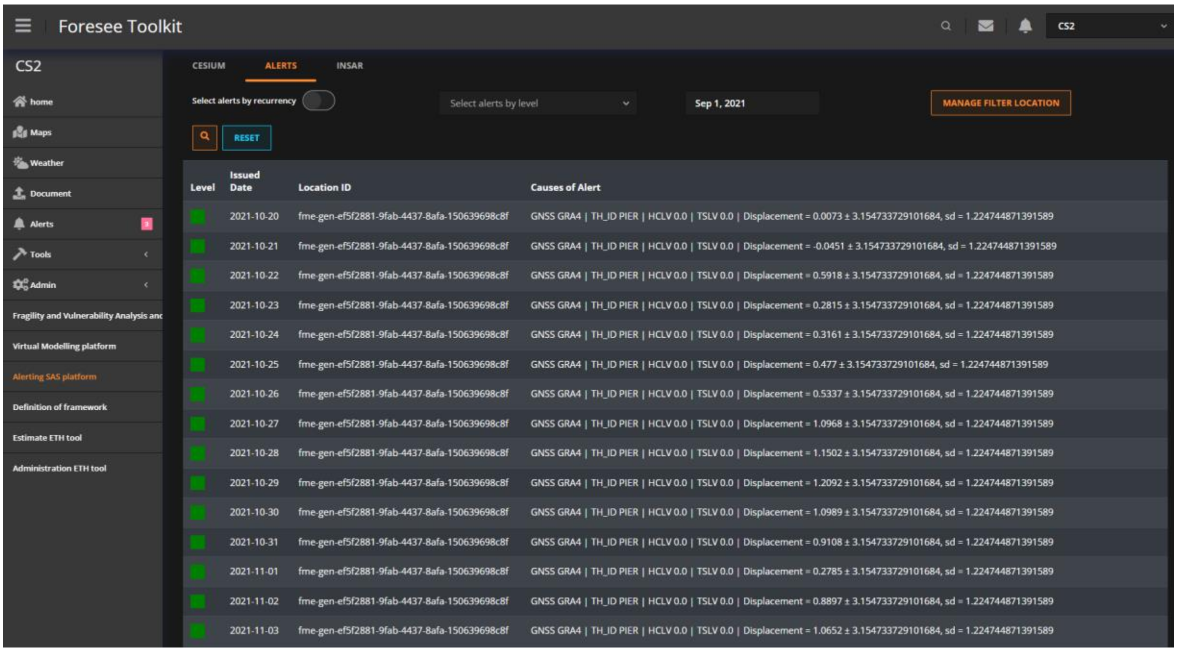

Figure 45. Example of alerts provided by the tool after Sep 1, 2021.

Such a system would certainly be useful for the safe management of the infrastructure.

Thresholds values should be discussed in deep in cooperation with infrastructure owners and operators, matched with their daily operation and mobility management and re-calibrated after a period of observation and collection of data from on-site monitoring and satellite interferometry.

An untimely alert would still risk causing damage to the infrastructure and/or users with consequent social/economic consequences. An excessively early warning would produce unnecessary limitations on the use of the infrastructure, always with economic/social impacts.

It is not easy to overcome this aspect as the triggering conditions of a phenomenon depend on multiple "local" factors which would therefore require a detailed study of the area of interest, to complement the large-scale approach.

The use of satellite interferometry data is very useful for reconstructing the historical series and therefore identifying landslide events that occurred in the past (and recording the present). However, they can only detect movements on the surface and not "in real time" and, for "early warning" purposes, they should be associated with instrumentation with GPS antennas (continuous) and/or inclinometers, possibly continuous, to obtain information on the displacement of the ground in depth.

In this way, once the trigger thresholds have been identified, it is possible to devise an alert system for managing the landslide risk on the infrastructure, again for localized areas / works.

As it regards the in-depth correlation between the rainfall data, interstitial pressures and triggering of landslides, probably the section under study (A16) is not very suitable as it crosses formations of fine/cohesive soils with landslide movements with deep sliding surfaces on which the influence of the increase in interstitial pressures, although significant, occurs over long times, due to the scarce permeability of the formations, and therefore not easily correlated to the rain data detected and to the management of an alert system based on them.

It could be interesting to re-evaluate the method in the medium term, following further monitoring data detected by the systems in place on the network (continuously) or by the rainfall data that we could detect from instruments to be installed suggested by the studies in progress on the hydrogeological instability on the network .

As for the **SHM BIM based alerting SAS platform**, the BIM model of the infrastructure as a whole, therefore comprising different structures with totally different behaviors/stiffnesses, is very interesting.

In this way, the identification of warning thresholds, based on the displacements that the infrastructure is able to undergo, in the absence of damage or with acceptable damage, would be much more reliable, reducing the risk of an estimate that is too conservative or too little.

The development of BIM for the earthworks (embankments / trenches) should be pursued, if possible in parametric form or in greater detail to make it as reliable as possible, according to a realistic behavior prediction, always for the identification of reliable warning thresholds.

The accuracy of the development of BIM for structural components, such as bridges, should be verified, always for the same reasons (detailed structural modeling, safety checks, etc.).

Different types of risks should be integrated in the same tool.

Question	**Impact**
Was this type of analysis made before FORESEE? How it was made?	Activities have been/are carried out both at local and central level in the Company along the network , for the relevant sites, that is kept under control both visually and instrumentally, even continuously, with sets of alerts. An integrated internet tool is not available to manage all the aspects linked to the hydrogeological risk.
How does FORESEE improve the results/analysis previously made?	The proposed tools integrates the Company's strategy of digitalization. Internet based tools for management of alerts are gaining importance, however the key factor is the rate of acquisition of data on site from permanent monitoring systems.
How does this FORESEE result improve your infrastructure's management	o It may integrate AGE-Autostrade Google Earth where the entire network is represented with all it elements and related functions o It may be made available to Company's Command and Control Centres and Local branches for the surveillance and monitoring of the infrastructure o It may be used to evaluate the performance of the infrastructure over time o It may be used to program and design interventions. o The BIM model of the infrastructure as a whole, comprising different structures with totally different behaviors/stiffnesses, is an added value to keep under control the entire infrastructure and its elements.
If it was not made, How does this FORESEE result improve your infrastructure's management ?	The timely warning of potential events has a positive impact on mobility and safety. The identification of warning thresholds, based on the displacements that the infrastructure is able to undergo, in the absence of damage or with acceptable damage, will be much more reliable, thus increasing resilience of the infrastructure.
What cost/resource efficiencies you expect these tools/results to have on your day-to-day business? (e.g. 10%-20% decrease in working hours over the first year; reduction of maintenance costs (20%-25%), Return on Investment (ROI) – 10-15%, increase in productivity 25-30%)	Benefits are in terms of: o optimised use of economic resources, o increase efficacy of maintenance inventions, o reduced impact of traffic flow due to the reduction in the number of subsequent interventions. o reduced impact on mobility for emergency situations

Table 17. Questions and impacts for WP2

6.4 FRAGILITY FUNCTIONS, VULNERABILITY FUNCTIONS

Risk and resilience-based approaches play a central role in all the phases of the infrastructure lifetime from design to operation and maintenance in order to correctly measure and set target service levels and enable safe and optimal decision making. Within the approach promoted in FORESEE, asset management must be coupled with the concept of the management of the transport infrastructures across all the phases in its lifetime (D.3.8) [18][19]

Two possible approaches are available within FORESEE: the indicators method and the simulation method. In the best scenario, these two approaches are applied both to the transport infrastructure, to have a first resilience screening and then a fully detailed resilience assessment. However, the choice of measurements could depend on the importance and specific problems to be addressed, the time and budget at disposition, the data and knowledge available and at the end the expertise to conduct the analysis.

For a complete approach to implement the Fragility and Vulnerability Analysis and Decision Support Toolkit, (Figure 46), a description of the different assets of the infrastructure and of the possible hazard scenarios would be the basis for the assessment of performance indicators expressed in the form of risk or damage probability indexes, loss indications for different hazard scenarios and resilience estimation both at asset and network level.

As far as it concerns the application to CS#2 two different type of assets have been analysed:

a. bridges,
b. road segments.

In addition to information on the infrastructure, information on traffic on the route in question was also provided to integrate with the traffic module to arrive to optimal decisions even from an economic point of view.

Figure 46. Data to be considered in the analysis

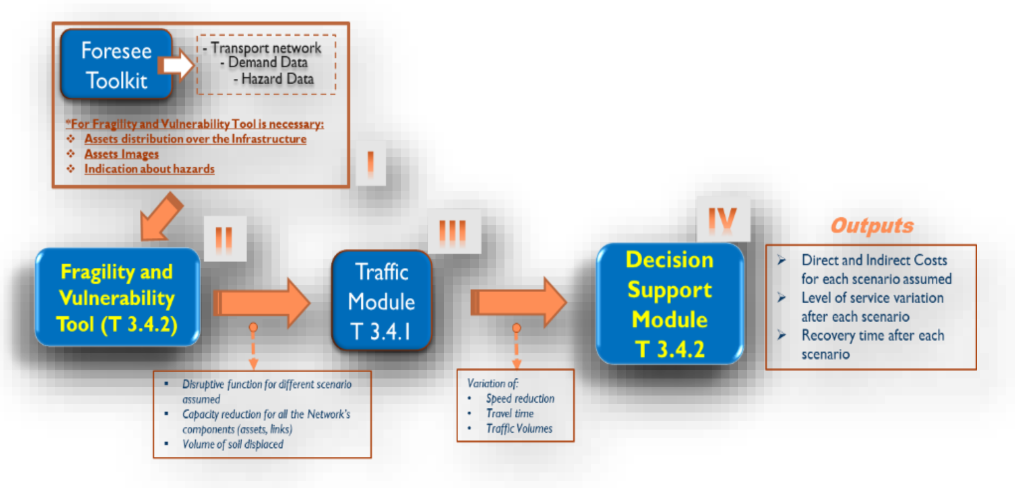

Figure 47. Main flow chart of the tool

Figure 48.-The analysed section of the A16

The assessment is based, in addition to the analysis of the individual road sections, also on the analysis of the structures along the specific section. The diagram of the road segment used for the analyses is shown below as well as the bridges.

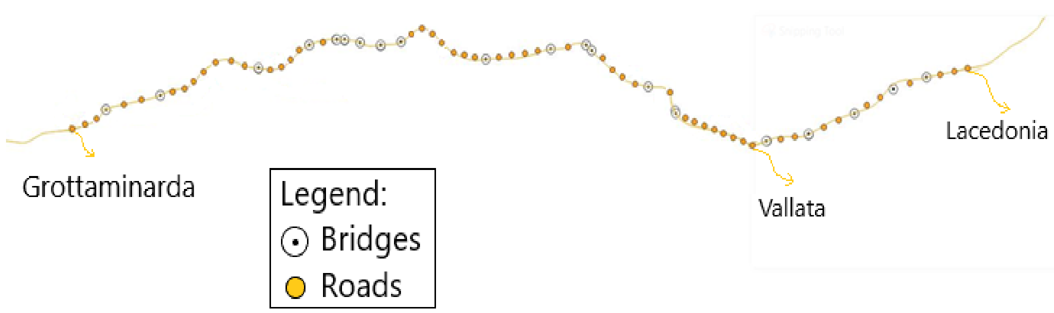

Figure 49. Distribution of elements along the analysed section of the A16

For the specific application, the induced hazard due to landslide has been computed considering two different triggering factors: earthquake and rainfall event.

For each of the road sections, databases have been created containing information relating to the ID, length and position. The database for the bridges, on the other hand, was set up with information relating to ID, length, position and structural details relevant for the analysis (provided by AISCAT). In addition to information on the infrastructure, information on traffic on the route in question was also provided. The information obtained concerns the average daily traffic divided by vehicle class (heavy and light).

The induced hazard curve is computed by combining the hazard and fragility at the slope level where the hazard of the main event represents the Mean Annual Frequency (MAF) of occurrence of a certain Intensity measure (IM) while the fragility of the slope is represented by the probability that the considered intensity (earthquake or rainfall) will trigger a landslide. The necessary information (maps of seismic, elevation (DTM), geological and rainfall hazard) has been resumed by public sources by the tool developer (RINA).

In output, two different information were obtained, related to the same phenomenon: the volume of the landslide (used for the assessment on road segments) and the height of the front of the landslide (used for the assessment on bridges).

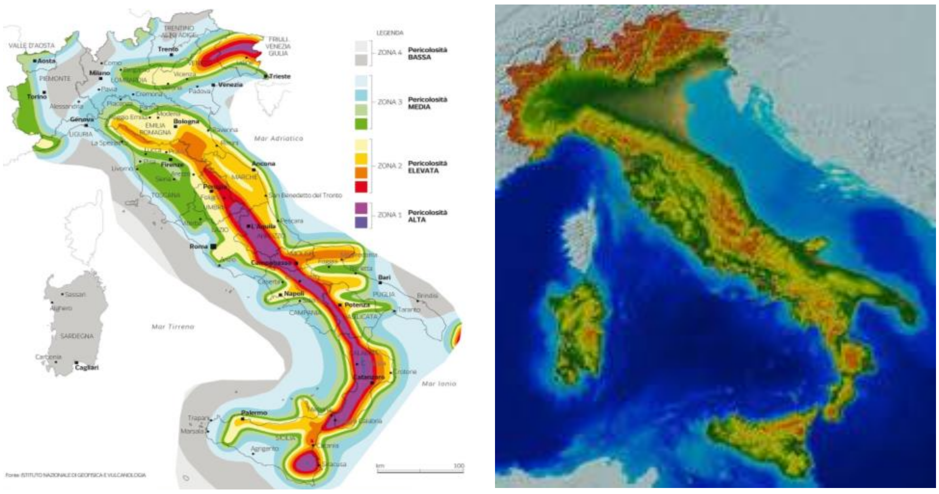

Figure 50. Available maps (earthquakes, geology-DTM)

Two different levels of damage are considered: direct linked to the loss of functionality and indirect or post-event linked to the loss of service and its impacts on traffic.

The first component of the damage analyzed is directly associated with the direct damage to which the infrastructure is subject: cost of removing the landslide , directly related to the volume of the landslide, the cost of infrastructure rehabilitation, related to the loss of functionality (obtained from table values) and the value of the asset itself.

Damage State	Roadways		Highway Bridges		Highway Tunnels	
	Mean (Days)	σ (days)	Mean (Days)	σ (days)	Mean (Days)	σ (days)
Slight/Minor	0.9	0.05	0.6	0.6	0.5	0.3
Moderate	2.2	1.8	2.5	2.7	2.4	2.0
Extensive	21	16	75.0	42.0	45.0	30.0
Complete			230.0	110.0	210.0	110.0

Table 18. Damage states

The second component of the damage is due to the indirect damage associated with the loss of service in the post event.

The loss of functionality (disruption functions) for the different scenarios, representing the most critical relations between events and infrastructure and the corresponding LoS before and after the event is determined in order to view the effects of the event on the traffic conditions of the different elements of the case study. Each event corresponds to a different temporary configuration of the network, which will return to full operation in a given period of time.

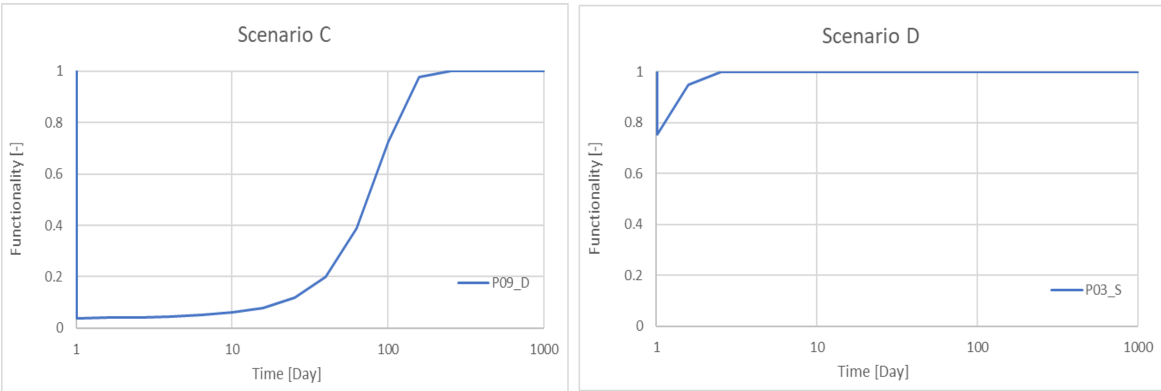

Figure 51. Critical scenarios – Disruption functions

For an evaluation at network level, it is necessary to include the traffic module and the simulation of travel demand[3]

The starting data used for modelling the network of A16 Highway. In particular, this study concerned a detailed analysis of travel demand in different alternatives scenarios of network development for various hazard. The transport network has been derived from the OSM (Open Street Map) data.

[3] Vehicle kilometres, Total time, Average travel speed on the network, Average criticality level, calculated as the flow-weighted average of the degree of saturation of each segment, following and event up to the restoration of the original conditions.

At network level 4 indicators were calculated for each of the scenarios described for the analysis of the circulation conditions:

1. Vehicle kilometres, quantified as the total sum of the kilometres travelled by vehicles moving on the network,
2. Total time, i.e. the total time spent by the vehicles to complete the journey from the point of origin to the point of destination,
3. Average travel speed on the network, the average of the real speeds calculated over each arc of the network under the simulated traffic conditions,
4. Average criticality level, calculated as the flow-weighted average of the degree of saturation of each arc.

Four different scenarios have been simulated for each one of the critical situations that could arise from the occurrence of a hazardous event from the scenario representing the current situation (without criticality) to the in scenario where a lane of a road arch is closed, therefore the capacity of the arches is halved and the speed T0 is set equal to 60Km / h; to the scenario where an entire carriageway is closed and traffic is diverted to the other carriageway and the vehicles proceed in one lane in each direction of travel; the arcs of the open roadway become bidirectional, the capacity and speed of the arc decreases; finally down to the situation where the highway is closed, so vehicles have to take alternative routes.

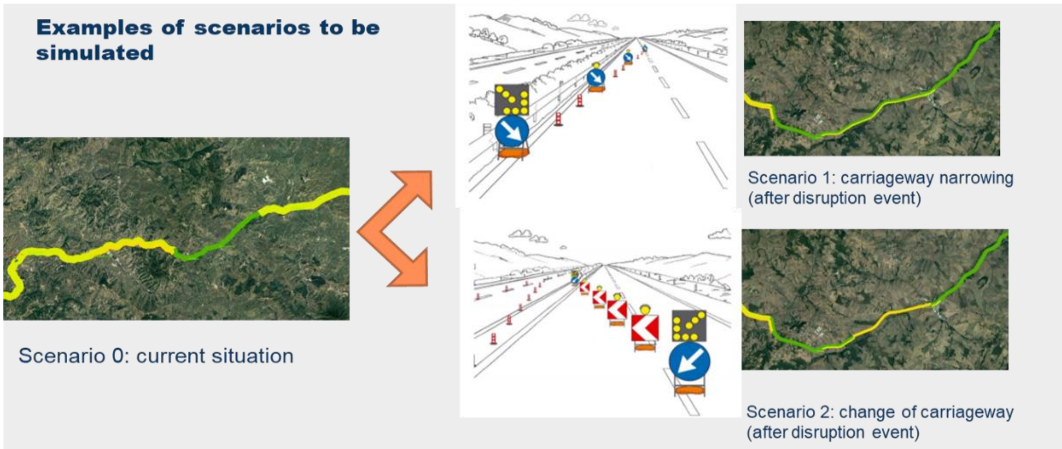

Figure 52. Traffic scenarios

Below it is shown an example of the result of the various indicators in the various scenarios, relating only to the rush hour, for a possible event that may occur on the A16 motorway. The example of the result of network indicators is close to the available real observed data.

	vehicle*km	average travel speed	VOC	Total Time	
Scenario 0	150473.86	74.5	0.64	22.9	
Scenario 1	150502.89	74.2	0.65	23.3	
Scenario 2	150582.98	73.3	0.66	23.6	
Scenario 3	207738.22	35.8	01.47	41.0	

Table 19. Values for the indicators

DISCUSSION

When extreme events occur, infrastructures ability to provide normal functionalities can be diminished. Thus, defining and measuring required service levels is nowadays a fundamental starting point for asset management, in order to control these operativity reductions.

The approach presented within this framework, tries to generate a flexible and innovative instrument that gives an overview of the infrastructure condition in terms of risks, possible losses and resilience assessment for different kind of hazards.

The instrument produced could be very helpful in the decision making process that infrastructure managers have to undertake for the infrastructure's level of safety control.

This tool allows to have different pictures before and after a possible event's impacts, regarding the above-mentioned parameters (e.g. LoS modification after the event).

Question	**Impact**
Was this type of analysis made before FORESEE? How it was made?	An integrated internet tool is not available to managers. Evaluation of the conditions of the network is/has been carried out and s the basis of actions to undertake.
How does FORESEE improve the results/analysis previously made?	This tool allows to have different pictures before and after a possible event's impacts, regarding the above-mentioned parameters (e.g. LoS modification after the event). It gives an overview of the infrastructure condition in terms of risks, possible losses and resilience assessment for different kind of hazards.
How does this FORESEE result improve your infrastructure's management	As result of the application of the tools, improved traffic flow and increased mobility are expected.
If it was not made, How does this FORESEE result improve your infrastructure's management ?	The instrument produced could be very helpful in the decision making process that infrastructure managers have to undertake for the infrastructure's level of safety control.
What cost/resource efficiencies you expect these tools/results to have on your day-to-day business? (e.g. 10%-20% decrease in working hours over the first year; reduction of maintenance costs (20%-25%), Return on Investment (ROI) – 10-15%, increase in productivity 25-30%)	Optimization of costs for operation and reduce maintenance and restoration costs.

Table 20.-Questions and impacts for D.3.8

7. FORESEE SUMMARY

The functioning of society depends on the transportation of goods and people and the infrastructure is built to ensure that this can be done in specific ways, that is, it is built to provide the required levels of service. Service reductions such as those due to natural events can have a significant social impact, and transport infrastructure managers have a mandate to minimize these risks.

It is therefore necessary for transport infrastructure managers:

1. to have a clear idea
   a. of the service the infrastructure is providing and
   b. an understanding of its resilience,
2. to understand how the resilience of a network can be modified:
   a. to counteract loss of service following an event,
   b. to provide specific levels of service during and after the occurrence of extreme events.

The Company has therefore participated in FORESEE to better understand the issues relating to the assessment of service levels and resilience of infrastructures and to share different managerial approaches and experience with the other infrastructure owners and operators active in the project.

Starting from the development of a harmonized methodology for assessing the level of service and resilience of the networks and/or its components, passing through the modeling of the various risk scenarios, also for forecasting and alert management purposes, FORESEE allows to define strategies and "adaptive" systems for the mitigation of risks and their consequences in the short-long term (protocols for the management of emergencies in order to ensure mobility during an event and/or strategies for surveillance, monitoring and preventive maintenance).

All the above supported by the development of a toolkit, a multifunctional software dedicated to the management of the infrastructures which includes the different outputs of the project, that, in perspective, could be commercialized.

<u>As it regards the case study on the ASPI network</u>, a section of the A16, on the TEN-T network, was chosen, due to the presence of numerous structural components and to the peculiarities of the territory, the extreme event being represented by the hydrogeological risk.

The application of the Guidelines to measure levels of service and resilience in infrastructures" and the "Guidelines to set target levels of service and resilience for infrastructures", has led, in a structured and coherent way, to the identification for the "extreme event (scenario a)" the relevant indicators for each component of the Infrastructure (physical, environment and organization) with impact on service and resilience.

For instance, as it regards the component linked to the organization, the most relevant parameters were: the presence of a monitoring strategy, the presence of a maintenance strategy, and the extension of the works carried out before the event.

As indicated in the guidelines, it is possible, through an incremental cost-benefit analysis, to evaluate where to intervene, setting targets/objectives to be achieved for the indicators, to obtain the maximum impact on resilience and service, also considering on which indicators it is possible for the manager act (for example it is not possible to affect the frequency of landslides or earthquakes, but it is possible to intervene on the state of conservation of the infrastructure).

Starting from the output of the calculation of the service level and resilience, a mathematical model and an algorithm were developed to optimize the preventive intervention programs in order to reduce the impacts in case of an event. The application of the algorithm indicates, as an optimal intervention, the improvement of the emergency operational plan, followed by the improvement of the maintenance strategy.

The assessment of service levels and resilience is part of the broader integrated approach proposed by the project, in particular they must be seen in association with the so-called "Situation Awareness System", developed in the project, for monitoring infrastructures located in areas with risk, also for the purposes of warning management, which was applied to the highway section and gave results in line with what is known to the Company.

The system is based on the acquisition of data from terrestrial (in situ) and satellite surveys and supported by GIS/BIM mapping technologies.

In the targeted section, two bridges have been identified on which two GNSS monitoring systems have been installed for the validation/calibration of the forecast models of displacements, for the assessment of the (future) landslide risk, according to the forecast atmospheric precipitation, integrated into the Situation Awareness System.

The monitoring systems installed represent, as part of a resilient approach to the infrastructure, a factor that increases the level of service and the resilience of the infrastructure, as also identified by application of the guidelines. The monitoring systems will remain active beyond the end of the project.

In addition to the assessment of service and resilience levels using indicators, in a "more expeditious" approach, the assessment of risk and resilience scenarios was developed within the project, starting from the assessment of the fragility and vulnerability of the network elements and the modeling of traffic flows (simulation method).

The Framework, Design and Operational and maintenance plans would t complements the risk management carried out in the Company. The tools, with their guided" and "objective" approach could complement the actual procedures and allow comparison among different risk scenarios; different territorial needs, different time steps, taking into consideration public socio-economic objectives.

The tools, guidelines and procedures developed and validated by the tool-developing partners of the project as well as the infrastructure manager of CS#2 have shown that a number of important results have been achieved that could be integrated or could complement the actual practice.

- **How does FORESEE improve the results/analysis previously made?**

  FORESEE gives an overview of the infrastructure condition in terms of risks, possible losses, resilience assessment for different kind of hazards.

  The proposed approach, based, as a first step, on the assessment of the level of service and resilience of the infrastructures, an approach that it is transversal to all developed tools, offers a new perspective (and new solutions) to design, operation and management as actually carried out and it complements current practice which takes into account codes, standards, public economic and political objectives and users' aspirations and needs.

  The different tools may be used separately or as a whole to improve asset management: i.e identifying the areas where to focus attention (new monitoring systems, new Internet-based alert system, novel network representation via GIS/BIM, fragility and vulnerability analysis), or to concentrate economic effort to increase service and resilience for design, maintenance and operation purposes.

- **How does this FORESEE result improve your infrastructure's management?**

  The deeper insight of the level of service that the infrastructure is providing; the understanding of its resilience, as affected by natural hazards, and how to counteract the loss of service would result in improved traffic flow and increased mobility are expected.

- **If it was not made, How does this FORESEE result improve your infrastructure's management**

  The guidelines and methodology allow to providea unique measure, also toward the other stakeholders also public, and a tool for governance to understand actions to take and where to improve service and reduce negative impact.

  The instrument produced could be very helpful in the decision making process that infrastructure managers have to undertake to control infrastructure's safety.

  The timely warning of potential events has a positive impact on mobility and safety and the identification of warning thresholds, based on the displacements that the infrastructure is able to undergo will be much more reliable, thus increasing resilience of the infrastructure.

- **What cost/resource efficiencies you expect these tools/results to have on your day-to-day business?**

  Main expected benefits may are in the:
  - optimised use of economic resources, with an allocation of resources according to the results of the application of FORESEE tools and guidelines,
  - increase efficacy of maintenance inventions,
  - reduced impact of traffic flow due to the reduction in the number of subsequent interventions,
  - reduced impact on mobility for emergency situations.

The following table summarizes the questions and impacts of the different available tools , as for CS#2.

Task	**7.1**	**7.2**	**7.3**	**1.1**	**1.2**	**2.2**	**2.4**	**2.5**	**T 3.4.2**
Deliv.	**D.7.1**	**D.7.5**	**D.7.6**	**D.1.1**	**D.1.2**	**D.2.7**	**D.2.8**	**D.2.9**	**D3.8**
Description	Framework use cases, risk scenarios and analysis of impact	Design, construction & remediation plans	Operational & maintenance plans	Resilience Guidelines to measure Level of Service & Resilience	Set Targets	Risk Mapping	Virtual modelling Platform	Alerting SAS platform	Fragility and Vulnerability Analysis & Decision Support Module
Was this type of analysis made before FORESEE? How it was made?	It complements Risk management carried out in the Company. It integrates current design standards and permissions procedures. It gathers consensus from the different stakeholders. As for operation & maintenance, they could be used to improve the level of service.			It is expected to include measures of service and resilience of elements and infrastructure in the daily and long term management of the assets to comply with national regulation.		An integrated internet tool is not available to manage all the aspects linked to the hydrogeological risk, even if activities are carried out for surveillance, monitoring and assessment			An integrated internet tool is not available to managers. Evaluation of the conditions of the network is/has been carried out and s the basis of actions to undertake
How does FORESEE improve the results/analysis previously made?	The proposed approach could be used to guide the definition of framework resilience plans for design and for operation & maintenance purposes in compliance with the risk strategies, objectives and management procedures of the organization			The resilience target system makes it possible to better correlate the infrastructural condition with the quality of the service. It identifies the areas where provided to concentrate activities		Internet based tools for management of alerts are gaining importance, however the key factor is the rate of acquisition of data on site from permanent monitoring systems.			It gives an overview of the infrastructure condition in terms of risks, possible losses, resilience assessment for different kind of hazards
How does this FORESEE result improve your infrastructure's management	As result of the application of the tools, improved traffic flow and increased mobility are expected.			To have a clear idea of the service that the infrastructure is providing and an understanding of its resilience, if it is affected by natural hazards, and how to counteract the loss of service		The proposed tools integrates the Company's strategy of digitalization and it may be used: ○ by Company's Command and Control Centres and local branches for surveillance and monitoring of the infrastructure, ○ to evaluate the performance of the asset over time, ○ to program and design interventions.			As result of the application of the tools, improved traffic flow and increased mobility are expected.
If it was not made, How does this FORESEE result improve your infrastructure's management	The tools, with their guided" and "objective" approach could complement the actual procedures and allow comparison among different risk scenarios; different territorial needs, different time steps, taking into consideration public socio-economic objectives.			The guideline s and methodology allow to provide : ○ a unique measure, also toward the other stakeholders also public, ○ a tool for governance to understand actions to take and where to improve service and reduce negative impact.		The timely warning of potential events has a positive impact on mobility and safety and the identification of warning thresholds, based on the displacements that the infrastructure is able to undergo will be much more reliable, thus increasing resilience of the infrastructure.			The instrument produced could be very helpful in the decision making process that infrastructure managers have to undertake to control infrastructure's safety.
What cost/resource efficiencies you expect these tools/results to have on your day-to-day business?	In general, an optimization of resources (economic, personnel, safety and travel time) is expected. For the operation & maintenance, it can be seen that a clear reduction of costs is possible both for safety ad interventions. As it is a tool that may be used at "high level" to assess a strategy to approach risk and resilience, a positive ROI is expected.			It is expected an optimization of costs meaning there is an improved allocation of resources among the different needs and actions to be undertaken rather than a saving of some sort.		Expected benefits in terms of: ○ optimised use of economic resources, ○ increase efficacy of maintenance inventions, ○ reduced impact of traffic flow due to the reduction in the number of subsequent interventions, reduced impact on mobility for emergency situations			Optimization of costs for operation and reduce maintenance and restoration costs

Table 21. Overview by impacts of the different Foresee tools

8. POTENTIAL IMPROVEMENTS OF THE TOOLKIT FOR REAL COMMERCIALISATION

The FORESEE Response, Mitigation and Adaptation Toolkit offers a comprehensive approach towards critical infrastructure and introduces a validated, evidence-based method to support infrastructure assessment throughout its full life-cycle.

The introduction of resilience concepts represents an added value in the definition and achievement of long-term strategies and objectives.

The benefits would not been obtained immediately and require time for its improvement in terms of quality and cost efficiency.

Benefits from the application of the toolkit would be in the field of management and operation of networks (Improved service/resilience of networks; improved response to hazards); risk reduction; increased transport fluidity (improved safety and security of mobility, reduced number of congestions, and alert and emergency management).

The Toolkit integrates the different tools, guidelines and plans that have been developed under FORESEE and that at this stage do not all presents the same level of maturity. Therefore additional effort should be spent to have an" homogeneous level" .

The TOOLKIT would need to be updated in order to remain relevant in the market and will require further development past project's end. Being an innovative solution requires time for implementation in the market.

Some of the tools could/are stand-alone products, such as:

- the guidelines of WP1: D1.1 and D1.2 fill a large gap in the market, as no guidelines are available that help transport infrastructure managers to develop their own indicators in a way that they can use the values of these indicators to prioritize resilience enhancing measures,
- the Data acquisition system integrating satellite and terrestrial Data and GIS/BIM based alerting Situation Awareness system (SAS) platform is designed specifically for structural health monitoring of structures in 3D and includes the incorporation of InSAR derived insight into the building information model. it will help in monitoring the infrastructure both for operation and emergency management,
- resilience-targeted operational and maintenance plans for risk management,
- new management and contingency plans.

Being a multi-purpose, multi-infrastructure type and, multi-risk the holistic approach must be customized for the specific infrastructure manager and specific problems and needs. Some of the proposed indicators or parameter cannot be universally applied.

On the other hand, the toolkit should cover the different types of risks and solutions be extended the different parts of the infrastructure (tunnels, embankments….) and be affordable for the different dimensions of infrastructure managers (public/private, local, national, …).

To be more effective, the toolkit should also be interfaced or connected into a "unique web platform" with the other tools currently used by the different organizations.

9. REFERENCES

[1] DOA-Description of Action

[2] Deliverable D.6.1 FORESEE testing strategy & Plan

[3] Estimating, and setting targets for, the resilience of transport infrastructure- Bryan T. Adey[a], Claudio Martani[a], Clemens Kielhauser[a], Ignacio Urqulijo Robles[b], Natalia Papathanasiou[a], Marcel Burkhalter[a], Iñaki Beltran-Hernando[c]

[4] Deliverable D.1.1 Guideline to measure Levels of Service and resilience in infrastructures

[5] Deliverable D.1.2 Guideline to set target levels of service and resilience for infrastructures

[6] Deliverable D.7.1-Framework based on use cases, risk scenarios and analysis of impacts

[7] Deliverable D.7.5 Design, construction and remediation plans

[8] Deliverable D.7.6 Operational and Maintenance Plan

[9] Importance of measuring the resilience and prioritizing interventions in relatively short time and with limited information available (4th SRG webinar on January 21st, 2021)

[10] Deliverable D.2.1 Design of Satellite Data Acquisition Program

[11] Deliverable D.2.2 Strategies for Change Detection and Surface Movement through Satellite Technology

[12] Deliverable D.2.3 Datasets-Regional change detection and InSAR interferometry from one case study

[13] Deliverable D.2.4 GIS risk analysis platform generating prioritised ranked site/asset risk map

[14] Deliverable D.2.5 Datasets/maps hot spots, risks and impact ranking

[15] Deliverable D.2.7 Datasets – Change detection and InSAR interferometry of assets

[16] Deliverable D.2.8 Virtual Modelling platform and asset failure prediction

[17] Deliverable D.2.9 SHM BIM based alerting SAS platform

[18] Deliverable D.3.8 Fragility Functions, Vulnerability Functions and Decision Support Module (DSM

[19] FORESEE TOOLKIT Response, Mitigation and Adaptation toolkit

ANNEX 1 TOOL VERIFICATION BY TOOL DEVELOPERS

In order for the consortium to develop the proposed solutions and toolkit and in order to validate them a wide range of data and information have been made available to partners under WP1, WP2, WP3, WP4, WP5, WP6,WP7:

- Original design,
- Operational & Maintenance plan:
  - Maintenance interventions (parametric, even if not on the same bridges or highway section).
  - Procedures and protocols for the management of events and emergencies.
- Surveillance:
  - Visual inspections (on a 3-month basis),
  - Drone's flights,
  - Instrumental geotechnical monitoring data for the relevant highway section
  - Results from NDT testing on similar structures,
  - SHM has been installed on 2 bridges-2 bridges,
  - Satellite data from WP2.
- Highway data:
  - GIS elements in Google earth all the elements of the network are georeferenced,
  - Cartography (+LIDAR),
  - Traffic data,
  - Data on events (accidents, etc…),
  - Role and actions of the Traffic Management Centre. Each local branch of the Company has its own Control and Command Centre to constantly monitor the highway and the traffic and for the management of operations and events.

The expected event is the triggering of a landslide, due to surface instability (slow surface deformations or to deep instability phenomena), supposed to hit the infrastructure in presence of normal traffic and/or in case of heavy traffic (works, accidents).

The objective is to evaluate the possibility of undertaking preventative measures (maintenance and/or emergency measures) aimed at minimising the direct impact on user casualties) and indirect consequences (i.e. closure of the highway).

A second scenario will be based on data from past events to increase the comprehension of all the relevant elements or factors affecting the specific event and to assess the possible consequences and actions to be undertaken. First, FORESEE's deliverables D1.1 "Guideline to measure levels of Service and resilience in infrastructures" and D1.2 "Guideline to set target Levels of service and resilience for infrastructures" will be adapted and implemented to CS#2 by the ETHZ together with ASPI and other partners.

The indicators and target values will be specially selected to answer to landslides. As a result of this, the CS will count with a set of indicators and target values that will be later used to be compared with the simulated situations. For CS#2 the level of service will be also measured through the simulation methodology from RINA. Moreover, the installation of two monitoring system on the two bridges on the A16 has been done to validate and improve the results from WP2: the monitoring data will be integrated into S-SHM and the RAG alerts will be updated based on field data.

ANNEX 1.1 TOOL VERIFICATION BY TOOL DEVELOPERS WP1

Estimating the resilience of, and targets for, a transport system using expert opinion [4]

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Abstract
To ensure that transport infrastructure provides acceptable levels of service with respect to extreme events, the resilience of the infrastructure needs to be estimated and targets for it need to be set. Recent work in the European research project FORESEE- Future proofing strategies FOr RESilient transport networks against Extreme Events (Adey et al., 2020) has shown how this can be done in situations with a wide range of available data, a wide range of available time frames for the estimation, and a wide range of expertise available.

This paper gives an example of how an infrastructure manager can use the guideline to estimate the resilience of, and set resilience targets for, a transport system in a relatively short period of time, even in the case of limited expertise in all the relevant areas and limited knowledge and information on all the basic input variables. The example is fictive, but realistic. It is based on the transport system consisting of a section of the A16 highway, in Italy, where a potential landslide could discharge enough material to damage road sections and bridges. The resilience is estimated using resilience indicators with differentiated weights. The resilience targets are set using cost-benefit analysis.

1. INTRODUCTION

The functioning of society depends on the transportation of goods and persons. The infrastructure required to enable transportation is built to ensure that this can happen in specified ways, i.e. built to provide specified levels of service. As reductions in service due to natural hazards, e.g. floods, earthquakes, heavy snow falls, can have significant societal consequences, transport infrastructure managers have the mandate to minimise this risk, i.e. the probability of having consequences if a natural hazard occurs multiplied by the consequences if it occurs.

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[4] Martani C, Adey BT, Robles I et al. Estimating the resilience of, and targets for, a transport system using expert opinion. Infrastructure Asset Management, https://doi.org/10.1680/jinam.20.00029

In order to do so, however, it is necessary for transport infrastructure managers to: (i) on the one side, have a clear idea of the service the infrastructure is providing and an understanding of its resilience, if it is affected by natural hazards, and (ii) on the other, to understand how the resilience of a network can be modified to counteract the loss of service following an hazard and to provide specified levels of service during and following the occurrence of extreme events, i.e. to set resilience targets.

A methodology to measure[5] the resilience of a transport infrastructure[6] with respect to a defined service, and set resilience targets have been proposed in the European research project FORESEE- Future proofing strategies FOr RESilient transport networks against Extreme Events (Adey et al., 2020).

Adey et al, 2020 define service as the ability to perform an activity in a certain way. This definition can be operationalised, for example, as the ability to transport from A to B the required goods and persons, within a specific amount of time, and for goods without being damaged, while for persons without being hurt or losing their lives. They define resilience as the ability to continue to provide service if a hazard event occurs. Resilience, with this definition, is measured, using each measure of service deemed relevant, in order to assess how service is being affected, and the cost of the interventions required to ensure that the infrastructure once again provides an adequate service. When considering natural hazards, resilience is therefore measured as the difference between: (i) the service provided by the infrastructure if no hazard event occurs and the service provided by the infrastructure if a hazard event occurs, and (ii) the costs of intervention if no hazard event occurs and the costs of interventions if a hazard event occurs.

Adey et al, 2020 consider it possible to set targets on the maximum decrease in service / increase in intervention costs from the beginning to the end of the hazard event, the service restoration time, the shape of the restoration curve and the total reduction in service / increase in intervention costs. The targets can be set simply using the opinions of experts or using cost-benefit analysis.

This article demonstrates how the guidelines presented in (Adey et. al, 2020) are to be used, using a fictive, but realistic example transport system based on the A16 highway, in Italy, which could be exposed to hazards causing severe landslides. The remaining of the article is organized as it follows. Section 2 contains a description of the hypothetical case study situation. Section 3 contains the definition of the transport system. Section 4 and 5 contain explanations as to how service and resilience are measured. Section 6 contains an explanation as to how the resilience indicator targets are sets. Section 7 contains the conclusions.

[5] To measure - To assess the importance, effect or value of (something)

[6] Transport infrastructure is considered to be all infrastructure to enable travel, e.g. road infrastructure and rail infrastructure or combinations of both.

2. SITUATION

The example is developed using a section of the highway A16. The Autostrada A16, is a highway connecting Napoli to Canosa, before merging with the A14 (Figure 53). The road is also known as "Autostrada dei Due Mari" (Motorway of the Two Seas) because it connects Napoli, on the Tyrrhenian coast, with Candela, on the Adriatic coast, playing a strategic role for the connectivity of the Country.

Figure 53. Location and development of the A16 highway[7]

The highway passes through areas of a high geomorphological hazard zone which renders it subject to landslides of medium to severe intensity. It is considered, for the purpose of the paper, to focus on the 30.1 km section connecting Grottaminarda and Lacedonia. Moreover, it is assumed that the infrastructure manager has registered the hazard events occurred in the past and has realized from the records that the potential event that is associated to the most severe consequences is a landslide of a magnitude of up to 19.3 kN/m, which occurs with a frequency of 1/20 years[8].

In light of the importance of such an event, the infrastructure manager wishes to estimate the resilience of the transport system for the interested section with respect to a landslide of this magnitude, and set resilience targets to optimally balance the cost of preventive interventions and increasing resilience. The three measures of service to be used are the travel time, safety, and the socio-economic impact of people and goods not being able to travel. The infrastructure manager, in addition to the many different activities carried out to provide the required service, are assumed to takes care of surveillance and maintenance of the infrastructure, as well as the planning and exercise of the emergency plans in case a hazard occurs.

According to Adey et al., 2020, for this paper, it is considered that the infrastructure manager has decided to a) estimate the resilience of the transport infrastructure using indicators with differentiated weights, and, b) set resilience indicator targets with cost benefit analysis. The decisions are motivated by the fact that:

[7] Source: https://it.wikipedia.org/wiki/Autostrada_A16_(Italia)

[8] It is to be noticed that both the intensity and the frequency of the event here considered are invented by the authors in order to define a precise hazard, against which measuring the resilience. As such, the event is fictive and does not reflect the real situation of the highway.

- given the dimension of the infrastructure and the complexity of the service considered, it would be computationally too intense to estimate the resilience using simulations.
- using indicators the infrastructure manager wishes to estimate the resilience with the highest possible accuracy, therefore the effort will be made to use the differentiated weights, i.e. an individual weight will be defined for each indicator to express the impact that each indicator has on each service considered.
- the infrastructure manager wants to set the targets based on a general idea of what might be the optimal balance between costs and benefits.

3. TRANSPORT SYSTEM

Before the service provided by, and the resilience of, the transport infrastructure are measured and the targets set, it is necessary to define the parts of the transport system to be considered. The transport system is considered to have three main components, namely

1. the infrastructure, i.e. the physical assets that are required to provide the service,
2. the environment, i.e. the physical environment in which the infrastructure is embedded that might affect the provision of service, and the organisational environment in which the infrastructure management organisation is embedded that might affect the provision of service, and,
3. the organization, i.e. the organisation(s) responsible for ensuring that the infrastructure provides service.

Infrastructure

The A16 has a total length of 172,300 km that mainly consists of double-lane road sections, which are predominately on the ground, but occasionally, due to the conformation of the valley, on viaducts and in tunnels (Figure 54). The portion of the A16 analyzed in this work is the section connecting Grottaminarda and Lacedonia. The main physical characteristics of the transport infrastructure are listed in Table 22.

Figure 54. Images of the double-lines road A16 highway[9].

Table 22. Proposed infrastructure characteristics (the data are invented by the authors and does not reflect the actual situation of the infrastructure)

Inputs [units]	Symbol	Value
Length of the infrastructure [m]	Li	30’100
Average width of the infrastructure [m]	$Width$	21
Average height of the infrastructure [m]	$High$	0-3
Average condition of the infrastructure	CS	CS2-Very good

[9] Source: https://www.quotidianomotori.com/sicurezza-stradale/a16-napoli-canosa-chiusura-notturna-e-regolamentazione-del-traffico/

The infrastructure - i.e. the road sections, viaducts and tunnels - is characterized by some features that influence positively and some negatively the resilience of the transport system. Some features are assumed that positively contribute to resilience include:

- The infrastructure is on average in very good condition as well as the slopes around it, that have been designed to comply with the slope stability design code.
- The highway is equipped with warning systems both fixed (road signs) and dynamic (digital signs) used to warn drivers of the presence of landslides, which are in relatively good condition, and of protective structures, i.e. barriers to prevent landslides to hit the road.
- There are existing ways to deviate vehicles, as well as the possibility of using another means of transport, to satisfy transport demand, in case the traffic on the highway is interrupted, i.e. as an alternative to the A16.
- In case a landslide occurs, there are emergency measures to help evacuate people trapped on bridges and tunnels.

To negatively influence resilience, some features are assumed as follows:

- Despite its very good condition, the infrastructure is not designed to withstand all landslide events without consequences. It is, indeed, expected that following the reference landslide both the infrastructure and the protection barriers will be out of service and in need of rehabilitation.
- There are currently neither alert systems, i.e. systems able to detect signals of landslides through environmental monitoring, nor safe shut down systems, i.e. systems able to trigger an immediate blockage of road as soon as a landslide starts.
- In the most part of the chosen section, there are no possibilities to build any nearby temporary alternative route for vehicles in case a landslide damages the highway.

Environment

The A16 covers a diversified set environmental conditions that range from a flatter landscape at the two ends and a green hilly - and even mountainous - one in the central part. The soil along the highway is mainly characterized by a clay-sand component (low permeability), with rare calcareous or lithoid intercalations. In 2005, the section crossing Lacedonia - next to Avellino - has been hit by a landslide that has moved the road embankment at the km 122.5, forcing the closure of the road for several days. During those days traffic was diverted in Grottaminarda.

It is assumed that a landslide of the reference magnitude has occurred in the past with a frequency of circa 1/20 years and it is consider plausible that: (i) it will have a similar frequency in future, and (ii) that it may affect other sections of the highway. The risk on traffic and on the safety due to these events is not negligible, as there is a relatively large traffic flow on the highway. The main physical and traffic characteristics of the environment are listed in Table 23 and 24 respectively.

Table 23. Proposed environment characteristics (the data are invented by the authors and does not reflect the actual situation of the infrastructure)

Type	Inputs	Symbol	Landslide [_l]
Physical	Landslides severity [m/s]	Ls	20
	Landslides frequency	Lf	1/20 years
	Soil type	*Soil*	Clay and sand
	Expected amount of material to hit the infrastructure [m^2]	Eam	700
	Expected force with which it will hit the infrastructure [kN/m3] - dry and saturated	Efm	15.3 - 19.3
Traffic	Speed limit (average among weather conditions) [km/h]	Sl	120
	No. of people traveling per day	P	5'000
	No. of people traveling for work in a day	Pw	3'000
	No. of people traveling for leisure in a day	Pl	2'000
	Amount of goods travelling per day [trucks]	G	1'000
	Vehicle transporting dangerous goods [% of the total trucks]	$TRdg$	5

Organization

The route is managed by an infrastructure manager that, among the many different activities carried out to provide the service required, takes care of surveillance and maintenance of the infrastructure. The activities performed by the infrastructure manager include conducting periodic monitoring of the condition states, executing maintenance when required, ensuring the functioning of emergency plans to react to hazard events and, when needed, preparing and managing tendering procedures for the extra-ordinary interventions, e.g. after the event the section has been completely rebuilt with a double-curved variant, due to the difficulty in restoring the damaged viaduct. The main physical characteristics of the organization are listed in Table 24.

Table 24. Proposed organisation characteristics (the data are invented by the authors and does not reflect the actual situation of the infrastructure)

Inputs	Symbol	Value
Annual cost of regular maintenance [€/m]	Cm	0.06
Days to recover in case of the reference landslide	D	9
Cost of intervention after the reference landslide [€/m]	Ci	400
Restoration plans	-	Existing
Average time required for the submission of tenders to repair damaged infrastructure*	Tt	1 year

* The time to tender refers to the required time for selecting the tender to undergo major interventions that cannot be held by the infrastructure manager himself (e.g. the reconstruction of a bridge). It is to be noticed that this does not refers to the time the infrastructure is out of service, which is instead given by the parameter *D*.

4. MEASURES OF SERVICE

The service provided by the transport system is measured as the ability of road users to travel from Grottaminarda to Lacedonia on the A16 highway within a specific amount of time (travel time) and without having their property damaged or being hurt or losing their lives (safety), and the inhabitants of the area to be able to ship and have shipped goods on the highway (socio-economic activities).

The service provided by the infrastructure (in absence of any landslide) is measured as shown in Table 25, where in the last column it is shown how the annual service is estimated, using inputs on the infrastructure, environment and organization (Table 22-4) and the variables affecting the service. Table 25 should be read as follows: the measure of travel time (€18’068’000) is estimated as the amount of minutes a vehicle spend on average on the road, which is computed as the ratio of length of the infrastructure in km (Li = 30’100/1’000) and the speed limit (Sl = 120km/h) and converted in minutes (i.e. multiplied by 60 min/h), multiplied by the cost of that time for the users in one year, estimates as the sum of the average number of people traveling for work in a day (Pw = 3’000) for the cost of work time (Cwt = 0.9 €/min) and the average number of people traveling for leisure in a day (Pl = 2’000) for the cost of leisure time (Clt = 0.3 €/min), for 365 days. This number is used as reference number to measure deviations that are caused due to the reference landslide. It is not a measure of the value of the road. The formulas to estimate the costs for safety and socio-economic activities reported in Table 25 follow a similar logic. In total the measures of service have a value of 24.6 million €.

Table 25. Measure of the service provided in one year assuming there is no landslide

Type of service	Measure	Annual estimate [10^3€]	Estimated as
Travel time (Stt)	The travel time for all the people travelling between on the viaduct	18’068	$\left(\left(\left(\frac{\left(\frac{L_i}{1'000}\right)}{(S_l)}\cdot 60\right).\left((P_w.C_{wt})+(P_l.C_{lt})\right)\right).365\right)$
Safety (Ss)	The cost of repairing damaged property, the number of injuries and deaths due to people travelling on the viaduct	941	$\left(\left(\left(\left(\frac{Pdp_0}{100}\right).P.PDp_0\right)+\left(\left(\frac{Pi_0}{100}\right).P.Ip\right)+\left(\left(\frac{Pd_0}{100}\right).P.Dp\right)\right).365\right)$
Socio economic activities (Ssc)	The socio-economic activity facilitated by persons and goods travelling.	5’475	$\left(\left((P.Dpud_0.SEC_p)+(G.Dpud_0.SEC_g)\right).365\right)$
Total		24’543	$(Stt+Ss+Ssc)$

Table 26. Assumed values of variables used to measure service (the data are invented by the authors and does not reflect the actual situation of the infrastructure)

Variable	Symbol	Value
Daily injury probability assuming no landslide [%]	Pi_0	0.15
Daily death probability assuming no landslide [%]	Pd_0	0.01
Daily property damage probability assuming no landslide [%]	Pdp_0	0.15
Delay per unit (person or truck) per day assuming no landslide [min/p.u.]	$Dpud_0$	6
Property damage per person in case of no accident [10^3€/p.p.]	PDp_0	0.5
Socio economic costs per person, i.e. the cost of one minute delay of one passenger to the wither society [€/min/p.p.]	SEC_p	0.1
Socio economic costs for goods, i.e. the cost of one minute delay of one truck to the wither society [€/min/truck]	SEC_g	2
Impact of injuries per person [10^3€/p.p.]	Ip	10
Impact of death per person [10^3€/p.p.]	Dp	5’000
Cost of work time [€/min]	Cwt	0.9
Cost of leisure time [€/min]	Clt	0.3

5. RESILIENCE INDICATORS

The infrastructure manager determined that there were 42 relevant indicators for the example transport system and defined their possible ranges of values (Table 27).

The indicators were selected to give an indication of the difference between the intervention costs and the service provided if no landslides occurs and if the reference landslide occurs, from the start of the landslide to the time when service is again provided at the level it was before the landslide. The indicators were grouped at the highest level as infrastructure, environment or organization indicators.

Infrastructure indicators (Table 27) are considered those related to the physical man-made parts of the transport system. They consisted of condition state, protective measure, and preventive measure indicators. Protective measure indicators pertained to how well the physical man-made parts of the transport system can protect the infrastructure providing the service. Preventive measure indicators pertained to how well the physical man-made parts of the transport system can withstand the reference hazard. Condition indicators pertained to how well the physical man-made parts of the transport system can provide the service it was originally designed to provide.

Environment indicators (Table 28) were those related to the physical natural parts, and the non-physical man-made parts of the transport system. An example of the former is the exposure to hazards. An example of the latter would be the available budget.

Organisation indicators (Table 29) are those related to non-physical man-made parts of the transport system, i.e. the activities of the organisation managing the infrastructure. They consisted of pre-event and post-event activities indicators, whereas pre-event and post-event referred to the start of the landslide.

The values of all indicators were taken as averages for the entire 30 km road section, and were thought of only in general terms (Table 27 - Table 29). For example, the condition of the infrastructure was expressed as an average of the condition states of all objects that comprise the A16. If desired, the condition state of each category of objects (e.g. road sections, bridges and tunnels), could be treated separately. For example, if the age of the warning system (1.3.1) along the A16 highway is on average 10 years, and its expected lifetime is 25 years, the indicator value is 2. The relevancy check was used to identify if intervention costs and each measure of service were affected by variation in the values of each indicator. For example, the presence of an emergency plan, has no effect on the safety measure of service, but it does on the travel time measure of service.

Table 27. Proposed infrastructure resilience indicators

Type	ID	Indicator	Possible values (the current value is underlined)
Protective measure	1.1.1	The possibility of building a temporary alternative route for vehicles, reduces the consequences on infrastructure users.	0 - No alternative path; 1 - 1 alternative path; 2 - Multiple alternative paths
	1.1.2	The possibility of using another means to satisfy transport demand - reduces the consequences of an infrastructure being out of service.	0 - No alternative means; 1 - 1 alternative mean; 2 - Multiple alternative means
	1.1.3	The number of possible existing alternative ways to deviate vehicles reduces the consequences of an infrastructure being out of service.	0 - No alternative ways; 1 - 1 alternative way; 2 - Multiple alternative ways
	1.1.4	The presence of a warning system allows users to bypass a road section in case of danger, which reduces the consequences of a landslide.	0 - No warning systems; 1 - 1 warning system; 2 - Multiple warning systems
	1.1.5	The presence of a safe shutdown system to prevent users from using a damaged road section reduces the consequences of a landslide	0 - No safe shut down system; 1 - 1 safe shut down system;
	1.1.6	The presence of emergency / evacuation paths allows users to escape in case of danger, which reduces the consequence of a landslide	0 - No emergency path; 1 - 1 emergency path; 2 - Multiple emergency paths
	1.1.7	The presence of special measures to help evacuate persons (e.g. helicopter) allows users to escape in case of danger, reduces the consequence of a landslide.	0 - No extraordinary measures; 1 - 1 extraordinary measure; 2 - Multiple extraordinary measures
Preventiv e	1.2.1	Compliance with the current slope stability design code, increases the likelihood that no landslide will occur and if it does decreases the extent of the landslide.	0 - Below current regulation, e.g. designed according to an older design; 1 - According to current regulation; 2 - Above current regulation
	1.2.2	The presence of protection barriers prevents the infra. From being hit	0 - No protection; 1 - Protection
	1.2.3	The adequacy of protection barriers (e.g. adequately dimensioned and located) prevent the road section from being hit by a landslide.	0 - Not adequate; 1 - Adequate
Condition	1.3.1	The age / age of replacement of the warning system affects the probability of accidents due to a lack of signalling in case of a landslide.	0 - > 80% of min. service life achieved; 1 - > 50%,< 80% of min. service life achieved; 2 - > 20%,< 50% of min. service life achieved; 3 - < 20% of min. service life achieved
	1.3.2	The condition of the infrastructure providing service affects the probability of the infrastructure being damaged in a landslide	0 - highly likely to collapse; 1 - No information is available; 2 - moderately likely to collapse; 3 - unlikely to collapse; 4 - very unlikely to collapse; 5 - extremely unlikely to collapse.
	1.3.3	The condition of protection barriers affects the probability that they can provide the level of service for which it was designed during and following the occurrence of a landslide and the harder to repair it if damaged in a landslide.	0 - highly likely to collapse; 1 - No information is available; 2 - moderately likely to collapse; 3 - unlikely to collapse; 4 - very unlikely to collapse; 5 - extremely unlikely to collapse.
	1.3.4	The condition of the assistance alert systems affects the probability that it can provide the level of service for which it was designed during and following the occurrence of a landslides and the harder to repair it if damaged in a landslide	0 - highly likely to collapse under normal traffic loads; 1 - No information is available; 2 - moderately likely to collapse under normal traffic loads; 3 - unlikely to collapse under normal traffic loads; 4 - very unlikely to collapse under normal traffic loads; 5 - extremely unlikely to collapse
	1.3.5	The expected condition of infrastructure providing service after a landslide affects its ease of repair.	0 - Collapsed, requires rebuilding; 1 - Out of service, requires repair/rebuilding; 2 - In service but repairs are necessary; 3 - In service and no repairs necessary
	1.3.6	The expected condition of the protective barriers after a landslide affects the likelihood that they will not function as intended after a landslide.	0 - Collapsed, requires rebuilding; 1 - Out of service, requires repair/rebuilding; 2 - In service but repairs are necessary; 3 - In service and no repairs necessary
	1.3.7	The expected condition of assistance alert systems after a landslide, affects the likelihood that they will not function as intended after a landslide	0 - Out of service, requires repair/rebuilding; 1 - In service but repairs are necessary; 2 - In service and no repairs necessary

Table 28. Proposed environment resilience indicators

Type	ID	Indicator	Possible values (the current values are underlined)
Physical	2.1.1	The height of the infrastructure providing service affects the consequences of an accident	0 - > 3 meters; 1 - < 3 meters; 2 - At the same level
	2.1.2	The accessibility of the infrastructure affects the ability and time required to restore it	0 - Accessible with telescopic crane; 1 - Accessible with truck mounted crane; 2 - Accessible with steps; 3 - Accessible without equipment
	2.1.3	The presence of persons/property below the infrastructure affects the consequences if a landslide occurs	0 - Yes; 1 - No
	2.1.4	The extent of past damages due to landslides indicates the likelihood of future damages	0 - Collapse; 1 - Serious damage; 2 - Minor damage; 3 - Aesthetic damages
	2.1.5	The hazard zone affects the likelihood of future landslides	0 - High; 1 - Medium; 2 - Low
	2.1.6	The frequency of past landslides affects the likelihood of future landslides	0 - Location in a <1-year landslide zone; 1 - Location in a >1, <5-years Landslide Zone; 2 - Location in a >5, <15-years Landslide Zone; 3 - Location in a >15-years Landslide Zone
	2.1.7	The severity of past landslides affects the probability of restoration interventions / service interruptions	0 - Collapse; 1 - Serious damage; 2 - Minor damage; 3 - Aesthetic damages
	2.1.8	The expected frequency of future landslides affects the probability of restoration interventions / service interruptions	0 - Location in a <1-year landslide zone; 1 - Location in a >1, <5-years Landslide Zone; 2 - Location in a >5, <15-years Landslide Zone; 3 - Location in a >15-years Landslide Zone
	2.1.9	The expected severity of future landslides affects the probability of restoration interventions / service interruptions	0 - Strong increase; 1 - Soft increase; 2 - Soft decrease; 3 - Strong decrease
	2.1.10	The land type affect the likelihood of future landslides and the probability of restoration interventions / service interruptions	0 - Rock mass; 1 - Clayey; 2 - Loose rocks; 3 - Sandy
	2.1.11	The terrain type affects the likelihood of future landslides and the probability of restoration interventions / service interruptions	0 - Rugged; 1 - Hilly; 2 - Flat
	2.1.12	The extent of vegetation affects the likelihood of future landslides and the probability of restoration interventions / service interruptions	0 - Limited; 1 - Light; 2 - Middle; 3 - Dense
	2.1.13	The amount of traffic affects the consequences of a landslide	0 - >80% of capacity; 1 - >50%,<80% of capacity; 2 - >20%,<50% of capacity; 3 - <20% of capacity
	2.1.14	The amount of hazardous goods traffic affects the consequences of an accident	0 - Frequent dangerous goods; 1 - Rare dangerous goods; 2 - No dangerous goods
	2.1.15	The amount of flammable goods traffic affects the consequences of an accident	0 - Yes; 1 - No
Non-physical	2.2.1	The budget availability affects the likelihood that speed of restoration	0 - Enough for <50% of the interventions; 1 - Enough for >50%,<100% of the interventions; 2 - Enough for >100% of the interventions

Table 29. Proposed organisation resilience indicators

Type	ID	Indicator	Possible values
pre-event activities	3.1.1	The presence of a monitoring strategy raises the awareness of the state of the road and is likely to increase their preparedness to react when necessary	0 - No condition monitoring; 1 - Periodic condition monitoring; 2 - Constant condition monitoring
	3.1.2	The presence of a maintenance strategy increases the likelihood that the infrastructure will be in a condition to resist a landslide	0 - No intervention strategy; 1 - Only responsive interventions conducted; 2 - Preventive interventions strategies is conducted
	3.1.3	The extent of interventions executed prior to the landslide affects the likelihood that the infrastructure will be in a condition to resist a landslide	0 - <50% of the benchmark budget; 1 - >50%,<80% of the benchmark budget; 2 - > 80% of the benchmark budget
post-event activities	3.2.1	The presence of an emergency plan reduces the time between the occurrence of a landslide and the moment a manager reacts.	0 - No plan; 1 - Generic plan; 2 - Operative plan (with tasks, resources, ...)
	3.2.2	The practicing of the emergency plan affects the ability of the manager to use it when needed, reducing the time for execution.	0 - No exercise; 1 - 1 exercise every > than 2 years; 2 - 1 exercise every 2 years; 3 - 1 exercise every year; 4 - 1 exercise every 6 months
	3.2.3	The time since the last review/update of the emergency plan affects the likelihood that it will be fit for purpose	0 - >5 years ago; 1 - <2 years ago; 2 - <5 years ago
	3.2.4	The expected time for tendering affects the time required to restore service	0 - > 1 year; 1 - > 8 months and < 1 year; 2 - > 4 months and < 8 months; 3 - < 4 month
	3.2.5	The expected time for demolition of damaged infrastructure affects the time required to restore service	0 - > 1 year; 1 - > 8 months and < 1 year; 2 - > 4 months and < 8 months; 3 - < 4 month
	3.2.6	The expected time for construction affects the time required to restore service	0 - > 1.5 year; 1 - > 1 year and < 1.5 year; 2 - > 6months and < 1 year; 3 - < 6 month

6. RESILIENCE

6.1 ESTIMATION

The measures of resilience used were the cumulative differences in interventions costs and the reductions in service if each indicator had its worst and current values. This was determined by first estimating the maximum restoration intervention costs and reductions in service (Table 30) considering the transport system characteristics (Table 22 - Table 24), and the additional assumptions listed in Table 31, and then the expected intervention costs and reductions in measures of service if each indicator had worst possible value (Table 32). An example of the former is the maximum reduction in the travel time for work measure of service (€2.4 million), which is estimated by multiplying the number of workers traveling per day (3’000), by the average delay per person per day (100 minutes), by the cost of working time (0.9 €/min) by the average number of days in which the traffic is delayed due to the restoration interventions (9). An example of the latter is that the value of the safety measure of service between the age of warning system indicator (1.3.1) having its worst value is €14.6 million, which is 26% of the maximum expected reductions in safety if all indicators have their worst possible values, i.e. €54 million. The total measure of resilience is €70 million. The age of the warning system is expected to have no effect on the restoration intervention costs or on the travel time measure of service.

Table 30. Maximum expected restoration intervention costs and reductions in service

Intervention costs / Measure of service	Description	Costs [10^3€]		
		Estimate	Equation	Estimate
Intervention costs (Ii)	The impact of executing restoration interventions	12'040	$(Ci \cdot Li)$	12'040
Travel time (Itt)	The impact of travel condition in terms of time lost the impact of travel condition on the vehicle cost for work and leisure	**2'430**	$(Pw \cdot Dpud \cdot Cwt \cdot D)$	2'970
		540	$(Pw \cdot Dpud \cdot Clt \cdot D)$	
Safety (Is)	The impact due to the user being involved in an accident divided by property damage, injury, deaths	3'000	$\left(\left(\frac{Ppd}{100}\right) \cdot PDp \cdot P\right)$	**54'000**
		1'000	$\left(\left(\frac{Ppd}{100}\right) \cdot Ip \cdot P\right)$	
		50'000	$\left(\left(\frac{Ppd}{100}\right) \cdot Dpp \cdot P\right)$	
Socio-economic activities (Ise)	The impact of people and goods not being able to travel	450	$(P \cdot Dpud \cdot D \cdot SECp)$	1'260
		810	$(G \cdot Dpud \cdot D \cdot SECg)$	
Total		70'270	$(Ii + Itt + Is + Ise)$	**70'270**

Table 31. Assumptions required to estimate how service would be affected by the reference landslide (the data are invented by the authors and does not reflect the actual situation of the infrastructure)

Variable	Symbol	Value
Delay per unit (person or truck) per day after the reference landslide [min/p.u.]	$Dpud$	100
Injury probability given occurrence of the reference landslide [%]	Pi	2
Death probability given occurrence of the reference landslide [%]	Pd	0.2
Property damage probability given occurrence of the reference landslide [%]	Ppd	30
Property damage per person in case of accident [10^3€/p.p.]	PDp	2

Table 32. Expected intervention costs and reductions in measures of service if each indicator had worst possible value

Indicator	Costs and reductions in service [10^3€]					Weight total[1]
	Inter. costs	Measures of service			Total	
		Travel time	Safety	Socio-econ.		
1.1.1 - The possibility of building a temporary alternative route for vehicles	-	1'931	-	819	2'750	65%
1.1.2 - The possibility of using another means to satisfy transport demand	-	2'079	-	882	2'961	70%
1.1.3 - The number of possible existing alternative ways to deviate vehicles	-	1'149	-	488	1'637	39%
1.1.4 - The presence of a warning system	-	2'138	-	907	3'046	72%
1.1.5 - The presence of a safe shutdown system	-	1'961	-	832	2'792	66%
1.1.6 - The presence of emergency / evacuation paths	-	1'040	-	441	1'481	35%
1.1.7 - The presence of special measures to help evacuate persons	-	802	-	340	1'142	27%
1.2.1 - Compliance with current slope stability design code,	8'910	2'198	39'960	932	52'000	74%
1.2.2 - The presence of protection barriers	10'118	2'496	45'381	1'059	59'054	84%
1.2.3 - The adequacy of protection barriers	7'465	1'841	33'480	781	43'567	62%
1.3.1 - The age / age of replacement of the warning system	-	-	14'273	333	14'606	26%
1.3.2 - The condition of the infrastructure providing service	12'040	2'970	54'000	1'260	70'270	100%
1.3.3 - The condition of protection barriers	9'391	2'317	42'120	983	54'811	78%
1.3.4 - The condition of the assistance alert systems	2'190	540	9'824	229	12'783	18%
1.3.5 - The expected condition of infrastructure	11'799	2'911	52'920	1'235	68'865	98%
1.3.6 - The expected condition of the protective barriers	7'585	1'871	34'020	794	44'270	63%
1.3.7 - The expected condition of assistance alert systems	690	170	3'095	72	4'028	6%
2.1.1 - The height of the infrastructure	-	-	14'925	-	14'925	28%
2.1.2 - The accessibility of the infrastructure	3'367	-	-	-	3'367	28%
2.1.3 - The presence of persons/property below the infrastructure	-	-	44'280	-	44'280	82%
2.1.4 - The extent of past damages	6'104	-	-	-	6'104	51%
2.1.5 - The hazard zone	9'632	2'376	43'200	1'008	56'216	80%
2.1.6 - The frequency of past landslides	-	1'735	31'552	736	34'024	58%
2.1.7 - The severity of past landslides	-	1'723	31'320	731	33'773	58%
2.1.8 - The expected frequency of future landslides	-	2'228	40'500	945	43'673	75%
2.1.9 - The expected severity of future landslides	-	2'228	40'500	945	43'673	75%
2.1.10 - The land type	4'236	-	18'998	-	23'234	35%
2.1.11 - The terrain type	3'251	802	14'580	340	18'973	27%
2.1.12 - The extent of vegetation	722	178	3'240	76	4'216	6%
2.1.14 - The amount of traffic	10'170	2'509	45'612	1'064	59'355	84%
2.1.15 - The amount of hazardous goods traffic	-	-	17'280	-	17'280	32%
2.1.16 - The amount of flammable goods traffic affects	-	-	14'252	-	14'252	26%
2.2.1 - The budget availability	6'863	1'693	30'780	718	40'054	57%
3.1.1 - The presence of a monitoring strategy	1'588	392	7'121	166	9'267	13%
3.1.2 - The presence of a maintenance strategy	5'687	1'403	25'508	595	33'193	47%
3.1.3 - The extent of interventions executed prior to the landslide	9'693	2'391	43'475	1'014	56'574	81%
3.2.1 - The presence of an emergency plan	-	2'020	-	857	2'876	68%
3.2.2 - The practicing of the emergency plan affects the ability of the manager to use it when needed, reducing the time for execution.	-	936	-	397	1'333	32%
3.2.3 - The time since last review/update of the emergency plan affects the likelihood that it will be fit for purpose	-	743	13'500	315	14'558	25%
3.2.4 - The expected time for tendering	5'418	1'337	-	567	7'322	45%
3.2.5 - The expected time for demolition of damaged infrastructure	3'251	802	-	340	4'393	27%
3.2.6 - The expected time for construction	4'575	1'129	-	479	6'183	38%

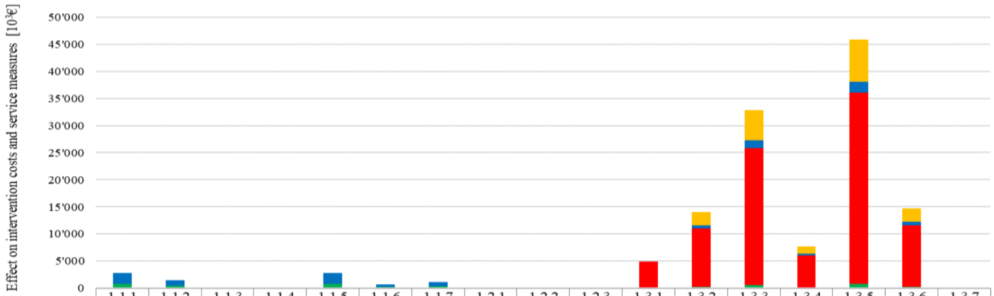
[1] *The expected intervention costs and reductions of service due to the indicator having its current values / the maximum expected intervention costs and reductions of service multiplied by 100.*

6.2 MEASURES OF RESILIENCE PER INDICATOR

The measures of resilience per indicator were computed as the expected intervention costs and reductions in the measures of service taking into consideration the value of the indicator (Table 27 - Table 29, and Table 32). They are shown in Figure 55, 4 and 5 for all indicators. The exact numbers are shown for a subset of these in Table 33 in terms of both the maximum possible value, the actual expected value and the difference between the two. The figures show, for example, that the measures of resilience of the condition of the infrastructure (1.3.2) in terms of intervention costs, and the travel time, safety and socio-economic measures of services using the worst indicator value (0/5), i.e. the Max measures, are €12, €3, €54 and €1.3 million, and using the actual indicator value (4/5), are €2.4, €0.6, €10.8 and €0.25 million. The former of these values mean that if the condition of the infrastructure indicator had its worst possible values the consequences of the reference landslide would be €12 million in restoration interventions, €3 million in additional travel time, €54 million in terms of injuries and fatalities, and €1.3 million for the regional economy. The latter of these values mean that in the actual situation, the consequences of the reference landslide would be €2.4 million in restoration interventions, €0.6 million in additional travel time, €10.8 million in terms of injuries and fatalities, and €0.25 million for the regional economy. The maximum and actual values of the measures of resilience of the condition indicator in terms of the intervention costs and all measures of service are €269.6 and €120.2 million respectively.

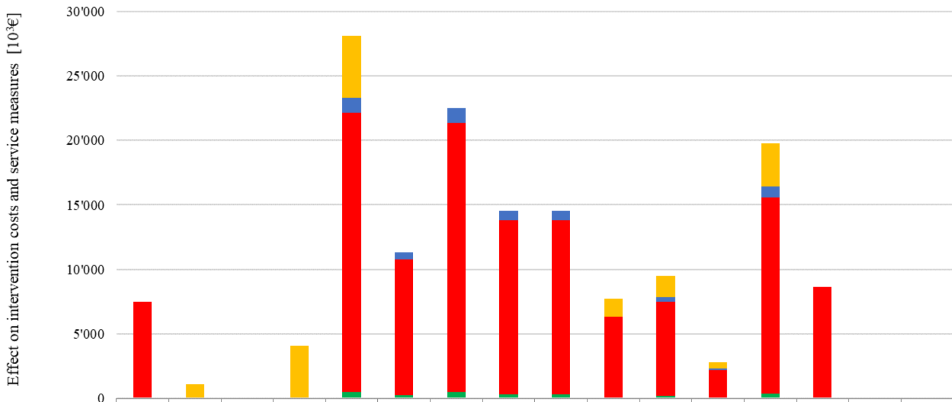
Table 33. Infrastructure: Measures of resilience per condition indicator (1.3)

Indicator	Item	Measures of resilience (10^3€)				
		Intervention cost	Reductions in service			Total
			Travel time	Safety	Socio-econ.	
1.3.1 - The age / age of replacement of the warning system	Max	Not relevant	Not relevant	14'273	333	14'606
	Actual			4'758	111	4'869
	Difference			9'515	222	9'737
1.3.2 - The condition of the infrastructure providing service	**Max**	**12'040**	**2'970**	**54'000**	**1'260**	**70'270**
	Actual	**2'408**	**594**	**10'800**	**252**	**14'054**
	Difference	**9'632**	**2'376**	**43'200**	**1'008**	**56'216**
1.3.3 - The condition of protection barriers	Max	9'391	2'317	42'120	983	54'811
	Actual	5'635	1'390	25'272	590	32'886
	Difference	3'756	927	16'848	393	21'924
1.3.4 - The condition of the assistance alert systems	Max	2'190	540	9'824	229	12'783
	Actual	1'314	324	5'894	138	7'670
	Difference	876	216	3'929	92	5'113
1.3.5 - The expected condition of infrastructure	Max	11'799	2'911	52'920	1'235	68'865
	Actual	7'866	1'940	35'280	823	45'910
	Difference	3'933	970	17'640	412	22'955
1.3.6 - The expected condition of the protective barriers	Max	7'585	1'871	34'020	794	44'270
	Actual	2'528	624	11'340	265	14'757
	Difference	5'057	1'247	22'680	529	29'513
1.3.7 - The expected condition of assistance alert systems	Max	690	170	3'095	72	4'028
	Actual	0	0	0	0	0
	Difference	690	170	3'095	72	4'028
Total	Max	43'696	10'779	210'252	4'906	269'633
	Actual	19'751	4'872	93'344	2'178	120'146
	Difference	23'945	5'907	116'908	2'728	149'487



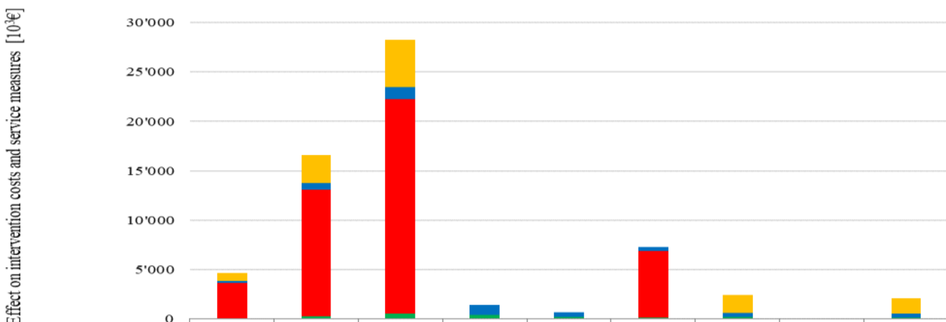
	1.1.1	1.1.2	1.1.3	1.1.4	1.1.5	1.1.6	1.1.7	1.2.1	1.2.2	1.2.3	1.3.1	1.3.2	1.3.3	1.3.4	1.3.5	1.3.6	1.3.7
Intervention	0	0	0	0	0	0	0	0	0	0	0	2'408	5'635	1'314	7'866	2'528	0
Travel time	1'931	1'040	0	0	1'961	520	802	0	0	0	0	594	1'390	324	1'940	624	0
Safety	0	0	0	0	0	0	0	0	0	0	4'758	10'800	25'272	5'894	35'280	11'340	0
Socio-economic	819	441	0	0	832	221	340	0	0	0	111	252	590	138	823	265	0

Figure 55. Infrastructure: Measures of resilience for each indicator, using the actual value of all indicators, by intervention costs and each measure of service



	2.1.1	2.1.2	2.1.3	2.1.4	2.1.5	2.1.6	2.1.7	2.1.8	2.1.9	2.1.10	2.1.11	2.1.12	2.1.13	2.1.14	2.1.15	2.2.1
Intervention	0	1'122	0	4'069	4'816	0	0	0	0	1'412	1'625	482	3'390	0	0	0
Travel time	0	0	0	0	1'188	578	1'148	743	743	0	401	119	836	0	0	0
Safety	7'462	0	0	0	21'600	10'517	20'880	13'500	13'500	6'333	7'290	2'160	15'204	8'640	0	0
Socio-Economic	0	0	0	0	504	245	487	315	315	0	170	50	355	0	0	0

Figure 56. Environment: Measures of resilience for each indicator, using the actual value of all indicators, by intervention costs and each measure of service



	3.1.1	3.1.2	3.1.3	3.2.1	3.2.2	3.2.3	3.2.4	3.2.5	3.2.6
Intervention	794	2'844	4'847	0	0	0	1'806	0	1'525
Travel time	196	701	1'196	1'010	468	371	446	0	376
Safety	3'561	12'754	21'738	0	0	6'750	0	0	0
Socio-Economic	83	298	507	428	199	158	189	0	160

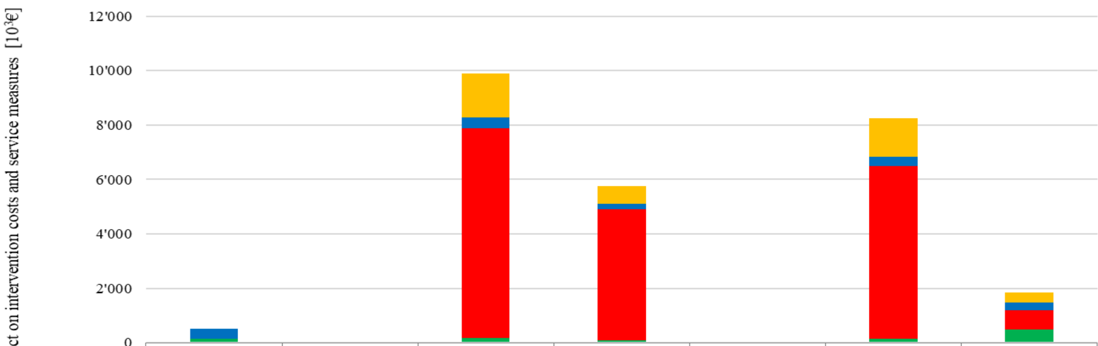
Figure 57. Organisation: Measures of resilience for each indicator, using the actual value of all indicators, by intervention costs and each measure of service

Estimating the measures of resilience for intervention costs and each measure of service in this manner, provides an infrastructure manager with an idea of which of these is the most problematic and where to focus efforts on improving resilience.

It can be seen from the measures of resilience shown in this section, for example, that the safety measure of service is significantly more important than intervention costs, and the travel time and socio-economic measures of service. The safety measure of service accounts for 93% of the measure of resilience for the indicator's frequency of future hazards (2.1.8) and severity of future hazards (2.1.9) and 100% for the height of the infrastructure indicator (2.1.1). It can also be seen that the largest potential for improvement is by improving the value of the expected condition state of infrastructure indicator (1.3.5), which would result in an improvement of the measure of resilience by €46 million.

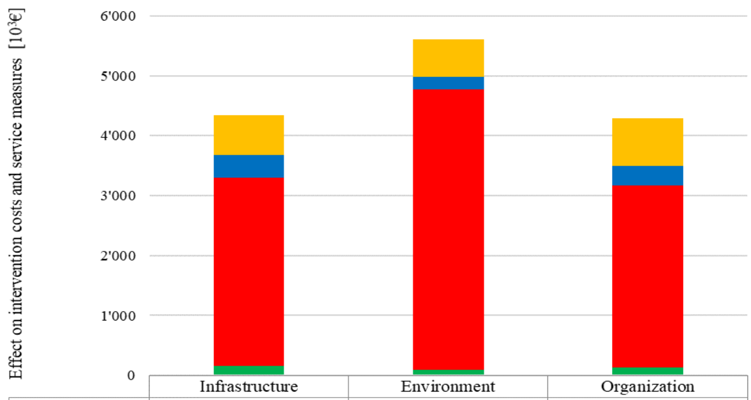
6.3 MEASURES OF RESILIENCE PER INDICATOR CATEGORY

The measures of resilience per indicator category are shown in Figure 58 and Figure 59. A measure of resilience for an indicator category is the ratio between the sum of the actual and the sum of the highest possible values of all indicators in the category multiplied by the average of the values of their individual measures of resilience. For example, the measure of resilience of the indicator category 1.3 "Condition" with respect to intervention costs was given by the sum of the actual values of indicators 1.3.1 to 1.3.7 (i.e. 15) (Table 33) divided by the sum of their highest possible values (i.e. 26), multiplied by the average of the expected intervention costs due to indicators 1.3.1 to 1.3.7 (i.e. €2.8 million). The measure of resilience for the indicator category 1.3 with respect to intervention costs and all measures of services was €1.6 million.



	Protective measures	Preventive measures	Condition state of the infrastructure	Physical	Non-physical	Pre-event activities	Post-event activities
Intervention	0	0	1'628	640	0	1'414	359
Travel time	372	0	402	218	0	349	288
Safety	0	0	7'693	4'809	0	6'342	728
Socio-economic	158	0	180	92	0	148	477

Figure 58. Measures of resilience for the condition state, protection measures, preventive measures, physical and non-physical environment, and pre- and post-event activities indicator categories



	Infrastructure	Environment	Organization
Intervention	664	624	799
Travel time	374	212	322
Safety	3'138	4'684	3'030
Socio-economic	162	90	137

Figure 59. Measures of resilience for the infrastructure, environment and organisation indicator categories

It can be seen from Figure 58, that there is the most potential to improve resilience by improving the values of the condition state of the infrastructure indicators, the pre-event activities indicators, and the physical environment indicators, which have measures of resilience of €9.9, €8.3 and €5.8 million respectively, and that improvements to their values would have the largest impact on the safety measure of service, followed by intervention costs, with very little of the resilience related to travel time or socio-economic impact.

Figure 59 shows that the environment indicators are the largest contributor to resilience, with a value of €5.6, compared to €4.34 and €4.3 million for the organisation and infrastructure indicators. It has to be kept in mind that these values do not, of course, say anything about the ease with which the indicators can be reduced even if it is possible. This is discussed in section 7.

6.4 MEASURES OF RESILIENCE FOR THE TRANSPORT SYSTEM

The measures of resilience for the whole transport system are shown in Figure 60. The measure of resilience for the intervention costs and all measures of service was €4.8 million, i.e. the sum of the expected intervention cost (€0.7 million), and expected reductions in the travel time, safety and socio-economic measures of service (€0.3, €3.7, and € 0.13 million) if the reference landslide occurs. The measures of resilience for the transport system were obtained with the same logic as for the indicator categories explained in section 6.3. For example, the safety measure of resilience was the sum of the actual values of indicators 1.1.1 to 3.2.6 (i.e. 60) divided by the sum of their highest possible values (i.e. 104), multiplied by the average measures of resilience per indicator (i.e. €7.34 million).

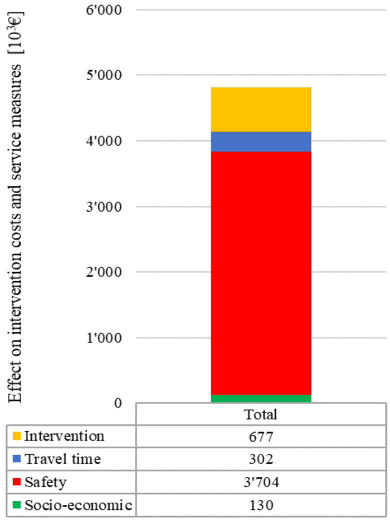


Figure 60. Measures of resilience for the transport system

6.5 DIFFERENCE BETWEEN MEASURES OF RESILIENCE USING WORST AND ACTUAL VALUES OF INDICATORS

The differences between the measures of resilience using the worst and actual values of indicators are shown in Figure 61 for the whole transport system and the infrastructure, environment and organisation categories using intervention costs and all measures of service. Figure 62 shows the resilience indicators for the infrastructure, environment and organisation categories using intervention costs and each measure of service. Figure 63 shows the safety measures of service for the indicator categories condition state, protection measures, preventive measures, physical and non-physical environment, and pre- and post-event activities. While Figure 64 show the example of the specific expected condition state of protective barriers indicator (1.3.6). Through these figures, an infrastructure manager obtains an idea of how much better and how much worse resilience can be.

For example, although the measure of resilience of the transport system is €4.8 million (Figure 61), which is arguably a high number, it is less than half of what it could be, i.e. €14.4 million. Although alone, even this might not be much information, it would be very useful if being used to track resilience over time. It can also be seen quickly where little or no additional improvements in resilience can be achieved. For example, the protective measures indicator category (Figure 63) is not relevant with respect to safety so if safety is of concern no improvements are possible through the improvements of these measures. As well, improvements are not possible by improving the values of the preventive measures indicators, as they all already have their best values. On the contrary, improvements are possible by improving the values of the indicators, such as the expected condition state of protective barriers indicator (Figure 64).

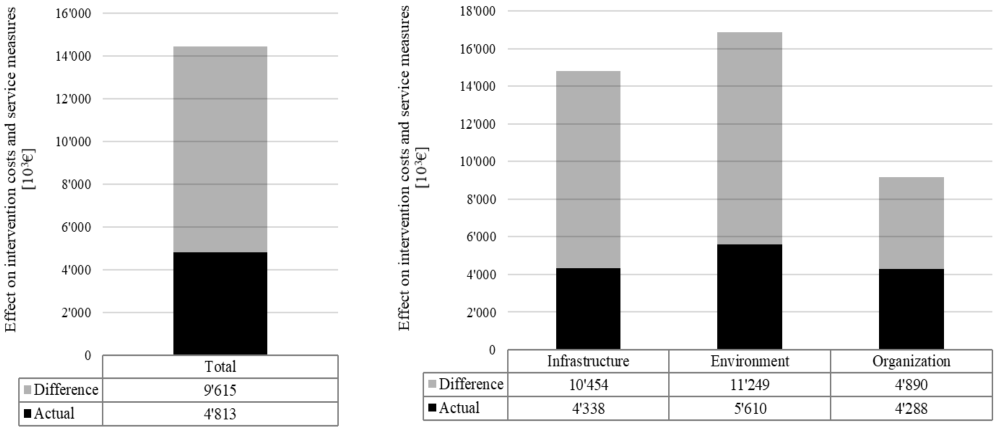


Figure 61. Difference between measures of resilience for a) the transport system, and b) the infrastructure, environment and organisation categories

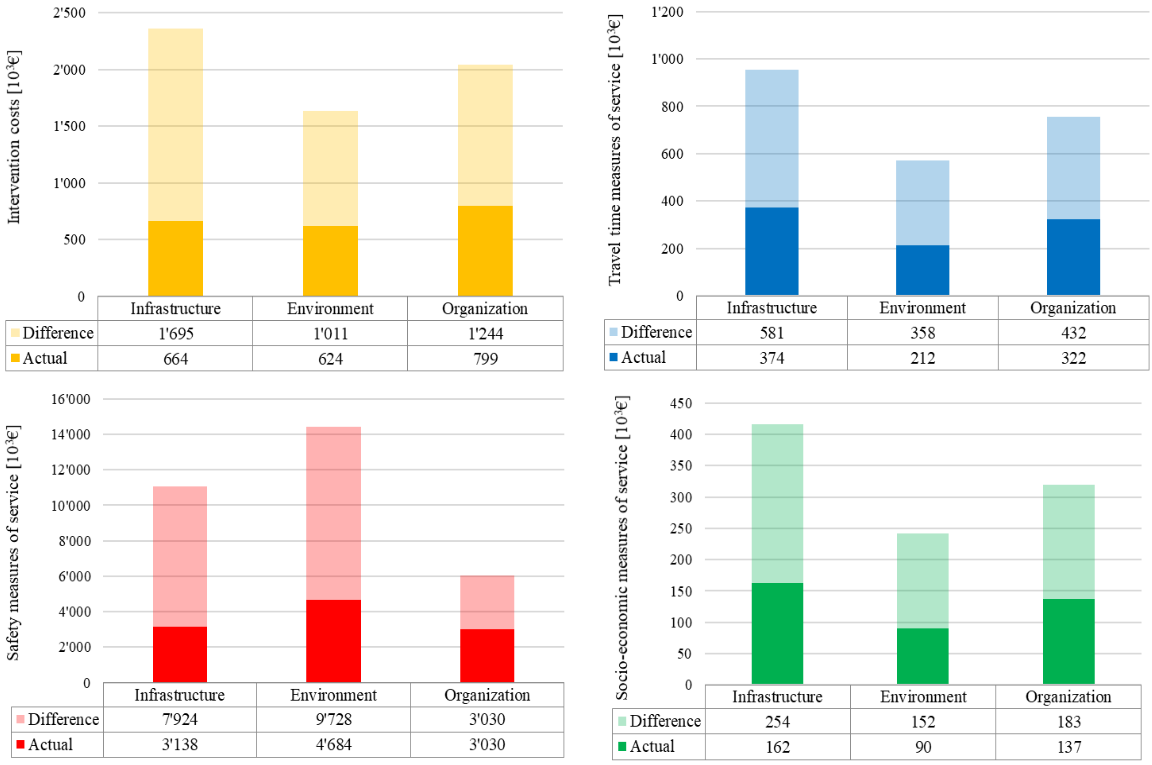


Figure 62. Difference between measures of resilience for the infrastructure, environment and organisation categories using only a) intervention costs, b) the travel time measure of service, c) the safety measure of service, and d) the socio-economic measure of service.

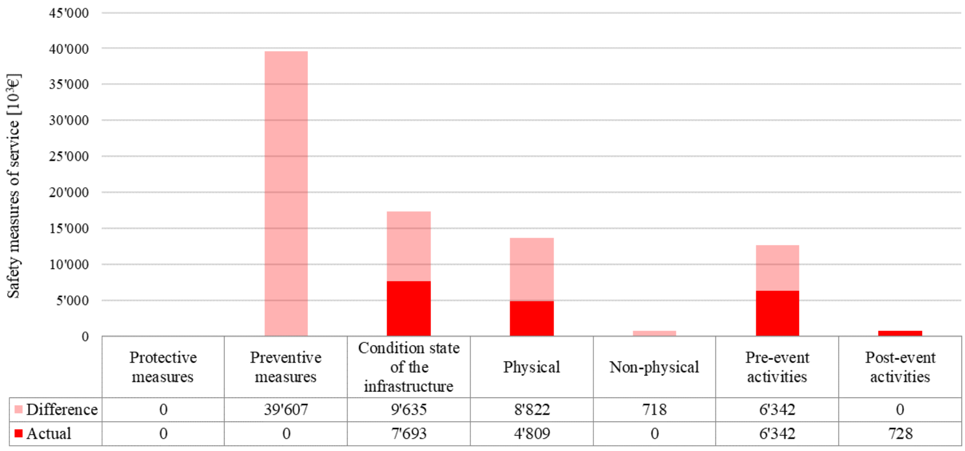


Figure 63. Difference between measures of resilience for the indicator categories condition state, protection measures, preventive measures, physical and non-physical environment, and pre- and post-event activities

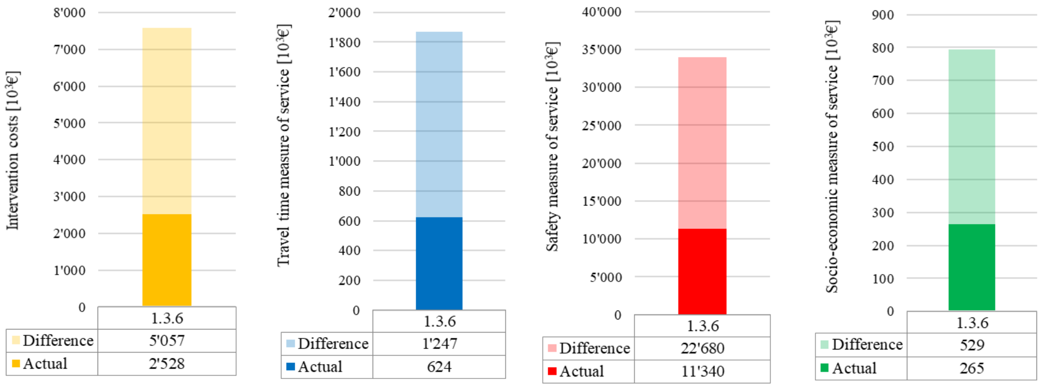


Figure 64. Difference between measures of resilience for the indicator expected condition state of protective barriers (1.3.6)

6.6 SUMMARY

The resilience of the transport system is relatively good (€4.8 million compared to the maximum possible value of €14.4 million (only 33.3%). The greatest contributor to the €4.8 million is that of the environment, followed by the organization, and the infrastructure, with measures of resilience of €5.6, €4.34, and €4.3 million. This is mainly due to the fact that, for the example, the infrastructure is assumed to be out of service, and the protection barriers moderately likely collapsed following the occurrence of a reference landslide. Although both the infrastructure and the barriers are designed to withstand reference landslides, they are still expected to be severely damage if they occur, and consequently significant repair or even a replacement is likely to be required.

These facts can be clearly seen by looking closely at the indicator categories and indicators themselves. Looking at the indicator categories, it can be seen that the greatest contributors in terms of indicator categories are the infrastructure condition indicators, the pre-event activities indicators, and the physical environment indicators, with measures of resilience of €9.9, €8.3 and €5.8 million, respectively. Looking at the specific indicators, the greatest contributors are the expected condition of infrastructure (1.3.5), €46 million, the condition of protection barriers (1.3.3), €33 million, the extent of interventions executed prior to the landslide (3.1.3), €28.3 million, and the hazard zone (2.1.5), with €28.1 million.

With the goal of improving resilience, i.e. decreasing the measure of resilience for the transport system, the infrastructure manager should focus his attention in improving the values of the above indicators. It should be kept in mind from the beginning on though that some of these are relatively easy to modify, i.e.: the expected condition of infrastructure (1.3.5), currently 1/3; the condition of the protection barriers (1.3.3), currently 2/5; and the extent of interventions executed prior to the landslide (3.1.3), currently 1/2, and another that is impossible to modify, i.e. the hazard zone of the infrastructure (2.1.5). Once clarity is achieved on the measures of resilience, the infrastructure manager can proceed with setting targets on the values of the indicators taking into consideration the ease with which values can be improved.

7. TARGETS

The resilience indicators targets for the example infrastructure were set for the indicators that were considered to be in the control of the infrastructure manager (31 out of the 42). In general, the infrastructure manager should first identify both the legal requirements and his own, as well as the owners', requirements, i.e. the things that they empirically know had to be done. He then systematically estimated the approximate costs and benefits of improving the values of each of the indicators, with respect to the likely restoration costs and the likely reductions in service with respect to the reference landslide. Finally, he then selected the target values that were likely to give the maximum net-benefit, while satisfying all of the requirements. Each of these steps is explained in the following sections in more detail, though in this example it was considered that no requirements, i.e. neither legal nor stakeholders' requirements, bounded the decision. So the process to set the targets starts directly with the estimate of the net-benefit.

7.1 NET-BENEFIT

Beyond the requirements for the indicator values, the targets were determined using incremental cost-benefit analysis, i.e. for each indicator estimating the approximate net-benefit from the lowest acceptable level to the level where the incremental net-benefit of a further increase is negative (which is equivalent to the benefit/cost ratio being less than 1.0). An example of how this was done using the condition of the protective barriers (1) is shown in Table 34, where

- The indicator was first assumed to have its worst possible value (0) and the likely intervention costs and reductions in service (€54.8 million) that would follow the occurrence of the reference landslide were estimated (listed as the maximum values for the intervention costs (€9.4 million), and the reductions in service (€2.3 million - travel time, €42 million - safety, and €1 million – socio-economic).

- The cost of improving the value of the indicator by one unit and the expected benefit in terms of avoided intervention costs, and reductions in service, were then estimated, incrementally, assuming the indicator had the value of 1, 2, 3, 4 and 5. For example, the cost of moving the value of the condition of the protective barriers indicator from 1 to 2 was estimated in €5 million and the expected avoided intervention costs and reductions in service in €11 million, yielding a net benefit of €14 million and a B/C of 2.19, which indicates that the target should be moved to 2 from 1. The costs of improvement of the value of this indicator were assumed to increase non-linearly, while the reductions in service were assumed to increase linearly.
- The target for the indicator was selected as the last value before the incremental net-benefit becomes negative or the highest value possible, which in this case is 5, and 5 is above the legal requirement of 2.

Following this logic targets were set for 31 resilience indicators out of the 42 presented in **Table 27**-8, i.e. 11 of the 42 indicators of the transport system have no targets. This is because they refer to situations that cannot be modified by the infrastructure manager (e.g. hazard zone) and therefore no target can be set on these. The targets for all 31 indicators are given in Table 35.

Table 34. Setting targets based on net-benefit for the condition state of the protective barriers

Possible values	Costs (10^3€)	**Target**	Max/ per value	Measures of resilience (10^3€)						Net benefit (10^3€)
				Avoided intervene-tion costs	Avoided reductions in service				B/C	
					Travel time	Safety	Socio-econ.	Total		
		5	*Max*	*9'391*	*2'317*	*42'120*	*983*	*54'811*	*N/A*	N/A
0	0		0	0	0	0	0	0	0.00	0
1	3'000		1	1'878	463	8'424	197	10'962	3.65	7'962
2	5'000		2	1'878	463	8'424	197	10'962	2.19	5'962
3	5'000		3	1'878	463	8'424	197	10'962	2.19	5'962
4	7'000		4	1'878	463	8'424	197	10'962	1.57	3'962
5	10'000		5	1'878	463	8'424	197	10'962	1.10	962

In Table 35 it can be seen that only 4 indicators have actual values below the target values, i.e. the condition state of protective barriers indicator (1.3.3), the expected condition state of infrastructure indicator (1.3.5), the presence of a maintenance strategy indicator (3.1.2), and the presence of an emergency plan indicator (3.2.1).

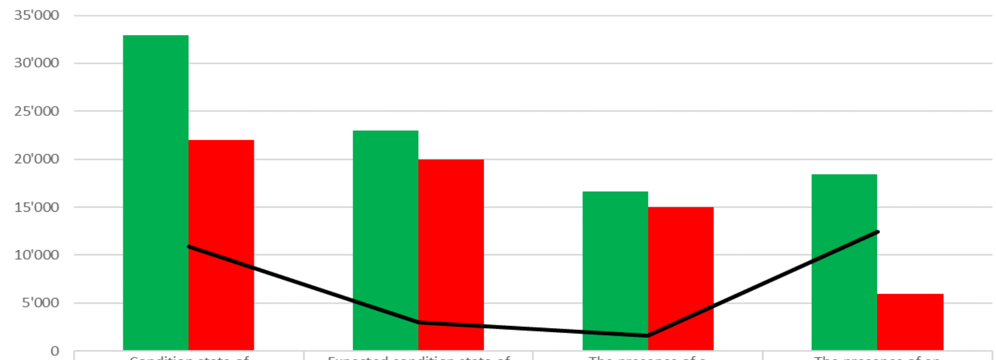
Table 35. Targets proposed for the 31 resilience indicators considered to be in the control of the infrastructure manager.

ID	Indicator	Scale	Actual value	**Target value**	Costs to reach target 10³€	Benefit of reaching target 10³€	B/C	Net benefit of reaching (10³€)
1.1.1	The possibility of building a temporary alternative route for vehicles	2	0	**0**	0	0	0.00	0
1.1.2	The possibility of using another means to satisfy transport demand	2	1	**1**	1'200	1'481	1.23	281
1.1.3	The number of possible existing alternative ways to deviate vehicles	1	1	**0**	0	0	0.00	0
1.1.4	The presence of a warning system	2	2	**2**	2'500	3'046	1.02	546
1.1.5	The presence of a safe shutdown system	1	0	**0**	0	0	0.00	0
1.1.6	The presence of emergency / evacuation paths	2	1	**1**	0	0	0.00	0
1.1.7	The presence of special measures to help evacuate persons	2	0	**0**	0	0	0.00	0
1.2.1	Compliance with the current slope stability design code	2	2	**1**	0	0	0.00	0
1.2.2	Presence of protection barriers	1	1	**0**	0	0	0.00	0
1.2.3	Adequate protection barriers	1	1	**1**	2'000	43'567	21.78	41'567
1.3.1	Age / Age of replacement of the warning system	3	2	**0**	0	0	0.00	0
1.3.2	Condition of infrastructure	5	4	**3**	0	0	0.00	0
1.3.3	Condition of protective barriers	5	***2***	**5**	30'000	54'811	1.10	24'811
1.3.4	Condition of assistance alert systems	5	2	**1**	2'500	2'557	1.02	57
1.3.5	Expected condition of infrastructure	3	***1***	**2**	35'000	45'910	1.15	10'910
1.3.6	Expected condition of protective barriers	3	2	**0**	0	0	0.00	0
1.3.7	Expected condition of assistance alert systems	2	2	**0**	0	0	0.00	0
2.1.12	Extent of vegetation cover	3	1	**0**	0	0	0.00	0
2.1.13	Traffic	3	2	**0**	0	0	0.00	0
2.1.14	Hazards goods traffic	2	1	**0**	0	0	0.00	0
2.1.15	Flammable goods traffic	1	1	**0**	0	0	0.00	0
2.2.1	Budget availability	2	2	**1**	20'000	20'027	1.00	27
3.1.1	The presence of a monitoring strategy	2	1	**0**	0	0	0.00	0
3.1.2	The presence of an maintenance strategy	2	***1***	**2**	25'000	33'193	1.11	8'193
3.1.3	The extent of interventions executed prior to the event	2	1	**1**	20'000	28'287	1.41	8'287
3.2.1	The presence of an emergency plan	2	***1***	**2**	9'000	36'912	3.08	27'912
3.2.2	Practice of the emergency plan	4	2	**1**	3'000	3'021	1.01	21
3.2.3	Review/update of the emergency plan	2	1	**1**	5'000	9'268	1.85	4'268
3.2.4	Expected time for tendering	3	2	**2**	14'000	23'175	1.05	9'175
3.2.5	Expected time for demolition	3	3	**3**	520	2'929	4.58	3'773
3.2.6	Expected time for construction	3	2	**1**	10'000	14'177	1.42	4'177

* The grey shaded actual values highlight the ones that are below the target.

Of these 4 indicators (Figure 65), it seems that the greatest net-benefit (€12.5 million) would be developing and improving the operative emergency plan, i.e. replacing the current generic emergency plan with one where specific tasks, resources and responsibilities are defined; the second best would be improving the condition state of the protective barriers (€10.9 million), i.e. replacing the deteriorated nets and piles; the third would be achieved by improving the expected condition of the infrastructure following the occurrence of the reference landslide event(€3 million), i.e. reinforcing the pillars and girders of the bridges that are currently expected to have significant damage when affected by the reference landslide (e.g. as the bridge that was moved away by the landslide of the 7th of March, 2005); and the fourth would be improving the maintenance strategy (€1.6 million) to ensure a solid preventive maintenance throughout the whole infrastructure.

This means that if only one thing can be done developing an operative emergency plan should be prioritized, requiring €6 million. If all are to be done approximately €63 million would be required.



	Condition state of protective barriers	Expected condition state of infrastructure	The presence of a maintenance strategy	The presence of an emergency plan
Total benefit	32'886	22'955	16'597	18'456
Total costs	22'000	20'000	15'000	6'000
Net benefit	10'886	2'955	1'597	12'456

Figure 65. Total benefit, total costs and net benefit to align the current four indicators out of target to their targets

7.2 SUMMARY

The targets have been set for 31 out of the 42 resilience indicators, while for the 11 indicators that the infrastructure manager has no power to modify, no target have been set. Out of the 31 targets set, only 4 indicators currently have a value that is below the target value: the condition state of protective barriers indicator, the expected condition state of infrastructure indicator, the presence of a maintenance strategy indicator, and the presence of an emergency plan indicator. Moving these indicators from their current values to the targets is expected to provide a relatively large total benefit (indicated here to be in the order of €91 million) and is expected to cost in the order of €63 million.

Although, more exact numbers would require more detailed analysis, these give a good idea that it is worthwhile to undertake the efforts, i.e. reinforce the bridges that are currently expected to have significant damages when affected by the reference landslide, replace the deteriorated protection barriers, develop maintenance strategies for all assets on the highway, and develop an operative emergency plan to be followed in the case of a landslide.

8. CONCLUSION

In this paper, it is shown that the FORESEE guidelines (Adey et al., 2020) provide a systematic way for infrastructure managers to obtain an idea of the resilience of their transport systems, and an idea of how to set resilience targets, when infrastructure managers want to assess resilience, but do not yet know where to concentrate their efforts. It is also shown that for some resilience enhancing actions, these initial results are perhaps sufficient to take action, whereas others point to where more investigation is required, which is part of the iterative process that all infrastructure managers should following in risk assessment (Adey et al., 2016).

The use of the guideline helps ensure that infrastructure managers define service and resilience clearly and consistently, and that they are systematically considered when evaluating the resilience of the transport system, as well as obtaining an idea of how to improve resilience. The example shows that this is possible, with relatively little input and effort. Of course, if the results of such an analysis are not sufficient to plan risk-reducing interventions, they can also be used to focus more detailed future analysis.

Future work should be focused on developing more examples with different types of infrastructure, different types of hazards and different organisations. This work could lead to organisations to develop more specific guidelines as to how they would like to measure service and resilience to enable them to make the best decisions possible.

It may also lead to the development of country or region specific guidelines that would allow the fair comparison of the resilience of multiple transport systems, which would aid to the efficient distribution of limited resources. Additionally, future work should focus on investigating the accuracy of using resilience indicators when compared to results that come from detailed analysis. It is anticipated that in the framework of the FORESEE project simulations using real data will be run to demonstrate the applicability of the guidelines.

9. ACKNOWLEDGEMENTS

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10. DISCLAIMER

The work presented in this article is a mere exercise, for which the vast majority of inputs have been set based on authors' assumptions, i.e. the inputs are realistic, but fictive and as such does not reflect the current situation of the highway chosen for the present application. Therefore the results cannot be in any way connected to the actual resilience of the real transport infrastructure. For a real assessment of the resilience of the infrastructure, the current inputs should be replaced with the actual data on the highway and relevant indicators considered. It is expected to conduct such simulation in the framework of the FORESEE project to demonstrate the applicability of the guidelines

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ANNEX 1.2 TOOL VERIFICATION BY TOOL DEVELOPERS WP2

Dynamic Landslide Failure Prediction Model Using Remote Sensing Data

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Telespazio VEGA UK Ltd and the University of Edinburgh are developing an operational methodology for determining the probability of slope failure (as 'factor of safety') from rain events by developing a remotely sensed, rainfall driven landslide
model approach to slope failure management. The goal is to develop a technical system designed to progress the current science of predicting rain-induced natural slope failure. It creates a Digital Twin of a physical environment utilising Earth Observation datasets, on which various rainfall scenarios can be run to simulate the landscape behaviour.

The Geo Information business unit of Telespazio VEGA UK is leading the development. The University of Edinburgh and specifically its School of Science has adapted the landslide model for remote sensing data ingestion and has been in charge of performance and testing. The method is being applied to railway network landslide risk and rail network operators have shown interest in further development.

INTRODUCTION

Slope movement occurs when forces acting down slope exceed the strength of the earth materials that compose the slope. Causes include factors that increase the effects of downslope forces or factors that contribute to low or reduced strength of the slope material. Landslides can be initiated in slopes already on the verge of movement by rainfall, snowmelt, changes in water level, stream erosion, changes in ground water, earthquakes, volcanic activity, disturbance by human activities, or any combination of these factors. However, the most common cause for landslide initiation is rainfall. Infiltrating rainwater alters the pore pressure within the slope, which leads to instability. The heavy-laden slope materials overcome the strength of the slope, succumb to gravity and the slope failure occurs. Landslides are deadly natural disasters that kill an estimated 4,600 people a year, with disastrous events that can take the lives of thousands in a single event. Landslides can also have a sizeable economic cost when infrastructure is damaged or destroyed.

The global risk of landslides is significant as almost any slope has the potential to slide, given the correct conditions. Figure 1 shows landslide risk around the world.

Identifying the location and timing of landslides remains a key challenge in natural hazard research and mitigation. Predicting slope failure is complex, but slope failure prediction models can be successful where the study area is data rich, with all required geophysical characteristics of the slope. However, there is a lack of sufficiently detailed and real-time measurements of slope characteristics such as soil, rock-mass, ground water conditions and slope angle, to allow accurate landslide monitoring over large areas [ref. 1]. This lack of data is due to both economic limitations and limited accessibility in risk areas.

A number of different landslide types exist. Some are shallow, with slope failure in the upper one or two meters of slope materials and occur with little warning.

Others have deep failure surface that may feature precursory movement.

In both cases we seek to find rainfall onditions that may trigger failure [ref. 1].

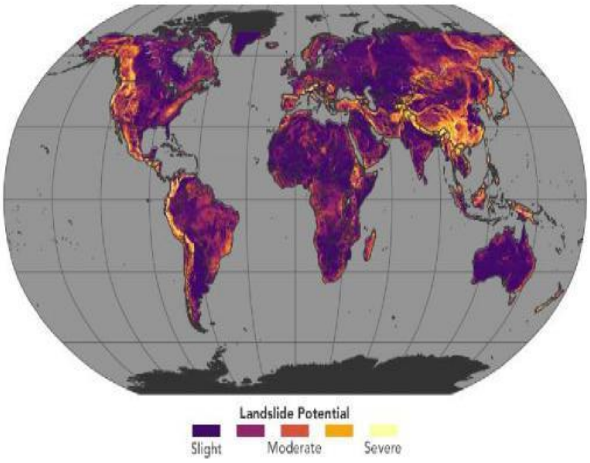

Figure 1 – Landslide potential risk world map [ref. 1]

Earth Observation satellites provide remote, non-invasive, repeated monitoring services over vast areas in a single image. For example, the European Space Agency's Copernicus satellite Sentinel-1, can acquire images that are 250 km wide with a pixel size of 20 by 5 meters [ref. 2]. There are a range of satellite missions with different kind of sensors that provide a variety of data, image sizes and spatial resolutions (pixel size), ranging from MODIS with multispectral images size of over 2000 km and spatial resolution of 250 m [ref. 3] to COSMO-SkyMed, which provides SAR images with a spatial res.olution of up to 1 m [ref. 4]. The spatial and temporal resolution of satellite remote sensing products make them useful in the study of landslide behaviour. The imagery and data from satellites, however, only records the surface and does not provide the geophysical datasets needed to model the internal mechanics of slopes.

The majority of satellite remote sensing for landslides has been used for post failure detection and monitoring. The ability to revisit a study area and monitor changes has been used to classify areas of slope failure and help mitigation efforts.

Landslide prediction is complex and satellite monitoring has been used as an additional dataset to add to in-situ instrumentation for example using InSAR to monitor the slopes surface movement.

However, the work presented here develops a landslide prediction model that only uses satellite data, so that landslides around the world can be predicted without the need of in-situ instrumentation.

The objective of this work is to develop an operational methodology for determining slope failure (using a factor of safety approach) from rain events by developing a remotely sensed, rainfall driven landslide model that can be used in slope failure management. One main component of this goal is to derive geophysical parameters of the slope using multiple types of satellite data and machine learning. Once these geophysical parameters are constrained, the data is ingested into a landslide prediction model.

In this study we have used the transient pore pressure model of Iverson [ref. 5]. This simulates how subsurface pore pressure responds to a time series of rainwater infiltration, and subsequently calculates the factor of safety of the slope materials as a function of both depth below the surface and time. This model requires a number of inputs: the initial depth of the water table, the cohesion and friction angle of the slope material, the hydraulic conductivity and diffusivity of the slope material, and the background vertical infiltration rate. These parameters are both challenging and expensive to measure in the field. Our approach is to use satellite observations of ground motion to tune these parameters rather than measure them directly.

METHODOLOGY

The methodology presented here is mainly based on two techniques:

- Persistent Scatters Interferometry (PSI), which is used to generate the observation data; and

- Failure Landslide Prediction Models, which ingest the PSI data and generate the final output.

The following subsections give an overview on the PSI, highly documented in several references, and give details on how the Failure Landslide Prediction Model has been adapted to the ingestion of PSI data.

Persistent Scatters Interferometry
Persistent Scatters Interferometry (PSI) is an effective remote sensing technique able to map Earth's surface displacement along time. PSI is a technique based on radar images that belongs to the group of Differential Interferometric Synthetic Aperture Radar (DInSAR) techniques [ref. 6].

DInSAR techniques are based in the use of interferograms, which are the combination of the phase of two SAR images acquired over the same area at different times and with slightly different viewing angles. These phase differences are related to the topography of the observed scene as well as to its terrain displacement. If the topography is known and subtracted, then a differential interferogram is obtained, in which the main component of signal is the terrain displacement that has occurred between the two SAR acquisitions. Differential interferograms can also contain a component of distortion due to the delay imposed on the microwave phase signal when travelling through the atmosphere. This component can be more or less relevant depending on the atmospheric conditions and on the magnitude of the observed displacement, see Figure 2.

DInSAR techniques have been widely exploited since the 90's in several applications including subsidence [ref. 7], landslides [ref. 8], [ref. 9], seismology [ref. 10], [ref. 11],volcanology [ref. 12], [ref. 13].

On the other hand, PSI techniques, thanks to the combination of numbers of differential interferograms generated with several SAR images over the same area, are able to derive displacement evolution along time with millimetric precision.

The use of several differential interferograms allows the identification of Persistent Scatterers (PS), Distributed Scatterers (DS) and the estimation of atmospheric effects in the phase signal allowing to achieve millimetric precision in displacement time series. Currently, there are tens of different PSI approaches which main differences are the interferograms configurations, the measurement pixels criterion selection and the deformation model application [ref.13]-[ref.30].

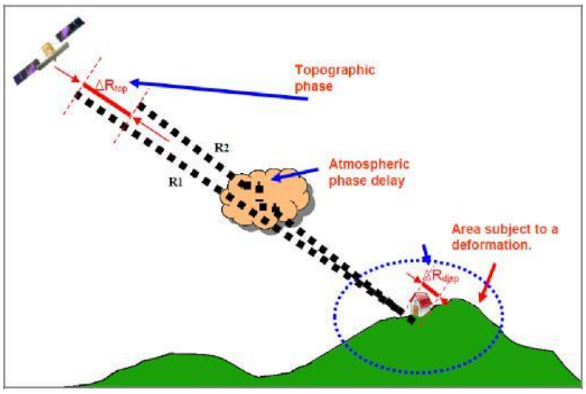

Figure 2 – Schema of interferometric acquisition. Topographic component is due to the different position of the sensor when the images are acquired. Deformation component is due to the displacement of the target between the two acquisitions. Finally, changes on the atmospheric conditions between the two acquisitions introduce differing phase delays that can interfere in the measurement of both the topography and the displacement unless this atmospheric phase delay is compensated.

The work here presented uses PSI results obtained with two different techniques:

- PSP-IFSAR (Persistent Scatterer Pairs Interferometry). This technique was developed and maintained by e-GEOS, an Italian Space Agency (ASI) and Telespazio Company. The PSP method is characterized by the fact of exploiting only the relative properties of neighbouring pairs of points for both detection and analysis of persistent scatterers (PSs). Thanks to the pair-of-point approach, the PSP technique is intrinsically not affected by artefacts that vary slowly in space, such as those depending on atmosphere or orbits. Moreover, by exploiting a very redundant set of pair-of-point connections, the PSP approach guarantees extremely dense and accurate displacement and elevation measurements, both in correspondence of structures and when the backscattering is weak or distributed as in the case of natural terrains. In all cases, the measurements keep the full resolution of the input SAR images [ref.31].

- ISBAS (Intermittent Small BAseline Subset). This technique is an adapted version of the established low resolution SBAS DInSAR time series algorithm. It has been designed to improve the density and spatial distribution of survey points to return measurements in vegetated areas where DInSAR processing algorithms habitually struggle. This technology was developed at the Nottingham Geospatial Institute of the University of Nottingham [ref.32].

Landslide Failure Prediction Models

The numerical transient pore pressure model of Iverson [5] calculates pore pressure as a function of depth with:

$$\frac{\psi}{z}(Z, t \le T) = \beta\left(1-\frac{d}{z}\right)+\frac{I_Z}{K_Z}[R(t^*)] \qquad (1a)$$

$$\frac{\psi}{z}(Z, t > T) = \beta\left(1-\frac{d}{z}\right)+\frac{I_Z}{K_Z}[R(t^*)-R(t^*-T^*)] \qquad (1b)$$

Where i is the pressure head, *Z* is a vertical coordinate, *z* is a coordinate normal to the surface, *d* is the water table depth measured normal to the ground surface, I_z is the vertical infiltration rate, K_z is the vertical hydraulic conductivity, (3 is a constant set by:

$$\beta = \cos^2\alpha - \left(\frac{I_Z}{K_Z}\right)_{steady} \qquad (2)$$

Where a is the slope angle, *t** and *T** are non-dimensionalised versions of time (*t*) and the duration of rainfall [ref. 7]:

$$t^* = \frac{t}{Z^2/\hat{D}} \qquad (3a)$$

$$T^* = \frac{T}{Z^2/\hat{D}} \qquad (3b)$$

Where:

$$\hat{D} = 4D_0\cos^2\alpha \qquad (4)$$

And *D0* is a hydraulic diffusivity, and *R* is a response function for rainfall:

$$R(t^*) = \sqrt{t^*/\pi}\exp\left(-\frac{1}{t^*}\right) - \operatorname{erfc}(1/\sqrt{t^*}) \qquad (5)$$

Once pore pressure is calculated, the factor of safety is calculated with:

$$FS = F_f + F_w + F_c \qquad (6)$$

With:

$$F_f = \frac{\tan\varphi}{\tan\alpha} \qquad (7a)$$

$$F_w = \frac{-\psi(Z,t)\gamma_w\tan\varphi}{\gamma_s Z\sin\alpha\cos\alpha} \qquad (7b)$$

$$F_c = \frac{c}{\gamma_s Z\sin\alpha\cos\alpha} \qquad (7c)$$

Where tan 9 is the friction angle of the slope material, *c* is the soil cohesion, and γ_s and γ_w are the unit weights of soil and groundwater, respectively. When the factor of safety is less than 1, the slope is predicted to be unstable. Based on these equations, the following parameters are required by the model:

- Precipitation data (in dimensions of length per time) to simulate the transient pore pressure evolution in the modelled soil column.
- Hydraulic parameters from the modelled soil: the hydraulic diffusivity (*D0*), the Hydraulic conductivity (*Ksat*), the steady-state infiltration rates (*Iz/Kz*).

- The depth of the water table and of the substrate.
- The mechanical soil properties: soil cohesion (soil capacity to resist motion), friction angle, weight of soil and weight of water.
- Topographic slope of the landscape (a).

Parameter calibration

For a specific site, we cannot directly calculate parameter values from either remote-sensed or in-situ data. We therefore run the model using a Monte Carlo sampling schemes on range of possible parameters. In the case of testing the model against in-situ data, ranges of parameters are determined by different mechanical and hydraulic tests. Calibration is achieved using satellite-derived observations of ground motion. In the case of testing the model against remote-sensed constraints, the ranges of parameters are determined using values reported in the literature and calibrating failures are recorded from InSAR data that detect ground motion.

Successful model runs are defined as most closely matching field observations of ground motion, ideally observed landslide data. Due to the lack of recorded landslides in the region of interest, this has been substituted by a threshold of motion recorded from InSAR data. Only ground motion distances exceeding the threshold are considered landslides.

The calibrated points are chosen to be close to the road, as they are the ones most likely to impact infrastructure.

The remaining points are used to validate model parameters; all points are driven by the same rainfall time series at our test site due to the spatial resolution of the rainfall data. Each point, driven by both calibrated parameter values and the rainfall time series, includes a predicted time of failure.

Machine Learning Model

In addition to the physics-based model, we have explored the potential of a data driven approach to landslide prediction.

This approach relies on the availability of observed data for each of the points, including ground motion and rainfall time series. We include fixed parameters for each of the data points including the topographic slope and the distance to the road. Each point is thus uniquely identified.

Based on an initial performance analysis, a k-Nearest Neighbour method is the preferred model for this task.

After performing a Forward Chaining cross validation, the final model predicts a ground motion time series for each spatial point of interest.

RESULTS

This section describes the preliminary results obtained from the methodology described above in a specific area of study.

Site Description

Our primary test site is a region in Italy along 30 km of a motorway to the East of Naples. The highly clayey nature of the area soils strongly influences the stability of the slopes, and the study area has previously experienced slope motion.

Input data

The results here presented are based in two PSI results:

- Sentinel-1 data analysis. This data was processed with ISBAS technique and included 186 Sentinel-1 images over the area of interest acquired in ascending geometry.
- COSMO-SkyMed data PSP-IfSAR analysis over the area of interest in two geometries. The first analysis considered 30 images in descending geometry and covered from September 2016 to August 2019. The second analysis considered 30 images in ascending geometry from November 2016 to July 2019.

Existing piezometers data has been used for the calibration of the model. Those piezometers are all located near the road.

Failure Model Parameters

Based on observations on-site and literature values, the ground motion threshold for failure is set to 80 mm/yr. Figure 3 depicts the spatial distribution of failures above this threshold.

Most of the failures predicted to occur before the observed failure are near the road, which is expected since calibrated instances gather around that area.

Failures further away from the road (particularly to the southwest) tend to be modelled after the observed event, whereas failures predicted beforehand may be caused by higher sensitivity of near-road points to smaller precursor motions in the ground (as can be seen in Figure 4).

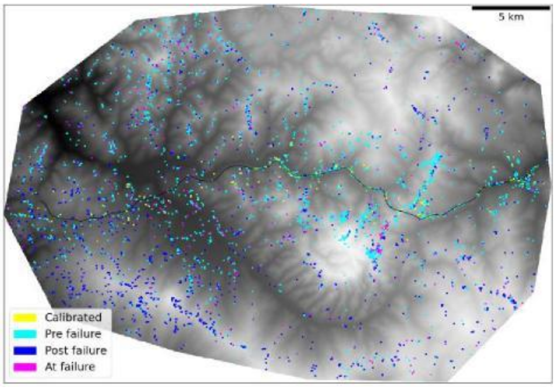

Figure 3 - Distribution of predicted failures. The map shows the distribution of calibrated points along with failures predicted before observations (Pre failure), after the observations (Post failure) and within a 25-day window of the observed failure (At failure).

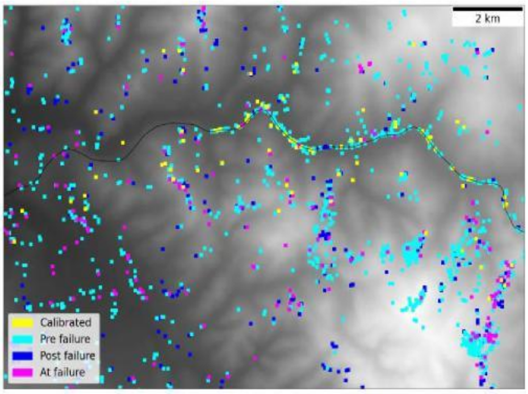

Figure 4 – As Figure 3; close-up of the central segment of the road.

Figure 5 shows the performance of the temporal component of the model. The observed and modelled failure times are recorded, starting on 1st January 2014 for a time span of 5 years. Based on the normalised probability distribution function, the overall shape of the distribution is similar in the model and observations. The model overestimates the number of failures early in the rainfall time series, and under predicts failures later in the time series.

The model calibration attempts to constrain the model parameters that result in failure under a given time series of precipitation. But similar precipitation events, or more intense rainfall, may occur prior to observed failure.

This will skew the predicted failure events to have a probability distribution that peaks earlier than the observed distribution.

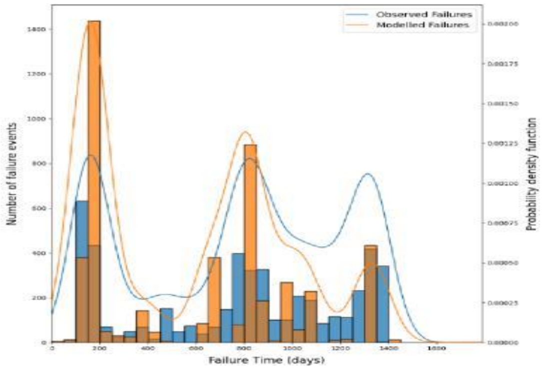

Figure 5 – Temporal distribution of observed and modelled failure times.

Preliminary results from the machine learning approach are shown in Figure 6. The model is trained on data from 2014 to 2017 and tested with data from 2018, sourced from both Sentinel-1 and COSMO-SkyMed satellites. The plot shows, for each predicted point, the predicted versus observed ground motion. The model is driven by rainfall inputs and a small number of slope properties (e.g., slope angle, distance from road). This approach can explain 82% of the variance in the predicted vs. observed ground motion.

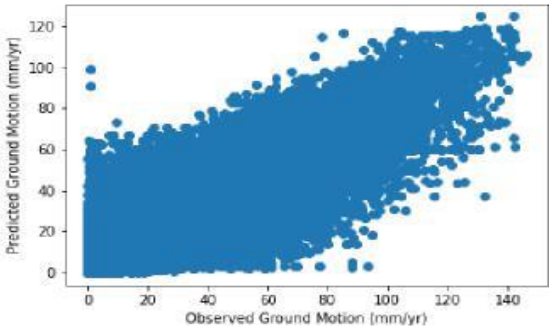

Figure 6 – Test data prediction results for ground motion data compared to the observed values.

Further work is planned following this approach to refine parameter tuning and data pre-processing. Additional data regarding geological and geomorphic variables will also be added to the training instances to improve the predictive power of the model.

CONCLUSIONS

This paper describes a methodology for determining the probability of slope failure (as a factor of safety) from rain events by developing a remotely sensed, rainfall driven landslide model approach to slope failure management.

The approach based on the pore pressure model responds to rainfall time series as expected and is able to broadly predict the distribution of failures in time. For infrastructure managers, predicting failure before and event is essential, and at our test site the predicted failure times are mostly prior to observed "failure" (which we define as a threshold of ground motion) along the road. The timing of failure predicted by the model has a spatial variation: locations far from the road, which have fewer calibration points, are not as well predicted by the model.

The data driven approach also shows promise: we are able to explain 82% of the variation in observed ground motion data. This approach may allow identification of potential areas of ground motion in advance of rainstorms that may be provided to infrastructure owners under different climate scenarios.

This approach based on remote sensing data can be extremely useful for foreseeing slope failure. This prediction will help in the predictive management and mitigation tasks allowing pre-event actions to increase safety and to decrease repair cost. It uses the concept of creating 'virtual models' of a physical environment and its characteristics from space observations, mainly PSI data.

Without the need of in-situ data, this product can accurately predict the landslide risk and failure of slopes across a significantly larger spatial extent than current landslide monitoring methods, using space based remote sensing satellites.

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[ref. 31] Costantini, M., Falco, S., Malvarosa, F., Minati, F., Trillo, F., Vecchioli, F., 2014. Persistent Scatterer Pair Interferometry: Approach and Application to COSMOSkyMed SAR Data. J. Select. Top. Appl. Earth Obs. Remote Sens. 7 (7), 2869– 2879.

[ref. 32] Sowter A., Bateson L., Strange P., Ambrose K., Syafiudin M., 2013. DInSAR estimation of land motion using intermittent coherence with application to the South Derbyshire and Leicestershire coalfield. Remote Sensing Letters, 4(10), 979-987

ANNEX 1.3 TOOL VERIFICATION BY TOOL DEVELOPERS WP7 (D.7.5)

In the following the description of the different tools as defined under Task 7.1 and applicable or applied to CS#2 is resumed:

- Risk Mapping tool
- Virtual modelling platform
- SHM BIM based Alerting SAS Platform
- New Slope Stabilization-Protection System
- Guidelines for the Adoption of Sustainable Drainage Systems (SDS)
- Fragility and Vulnerability Functions and Decision Support Module
- Risk-Reducing and Restoration Programs
- Updated Structural Health Monitoring (SHM) Algorithms

RIKS MAPPING TOOL					
Task	T2.1	**Leader**	UC	**Deliverable(s)**	D2.5
Name					
Risk mapping tool					
Description					
GIS-based methodology providing strategic areas where to implement measures to mitigate the impacts of extreme natural events.					

MAIN CHARACTERISTICS	
Category	Research and learning
Location	On the infrastructure and surrounding area
Asset	All
Hazard	Flooding, landslide, earthquake
Life-cycle phase	Planning

RESILIENCE				
Resilience Stage				
Pro-action	**Preventive**	**Preparation**	**Response**	**Recovery**
x				

Resilience-Principle Performance		
Performance Indicator Related	Score	
Robustness	0	
Resourcefulness	0	
Rapid Recovery	0	
Adaptability	3	

WP1 Resilience indicator related		
Indicator	Category	Part
Presence and frequency of monitoring	Pre-event measures	Organization
Presence and adequacy of hazard effect reduction system	Preventive measures	Infrastructure
Indirect: Presence of an emergency plan	Post-event measures	Organization
Indirect: Practice of the emergency plan	Post-event measures	Organization

VIRTUAL MODELLING PLATFORM					
Task	T2.4	**Leader**	UEDIN	**Deliverable(s)**	D2.8
Name					
Virtual Modelling Platform					
Description					
A numerical model that ingests rainfall data, ground motion data, and topographic data and then calibrates a physics-based slope stability model based on these inputs.					

MAIN CHARACTERISTICS	
Category	Research and learning
Location	On the infrastructure and surroundings
Asset	The whole asset
Hazard	Landslides
Life-cycle phase	Operation and Maintenance

RESILIENCE				
Resilience Stage				
Pro-action	**Preventive**	**Preparation**	**Response**	**Recovery**
X	X	X		

Resilience-Principle Performance	
Performance Indicator Related	Score
Robustness	2
Resourcefulness	3
Rapid Recovery	1
Adaptability	1

WP1 Resilience indicator related		
Indicator	Category	Part
Condition state of the infrastructure (pre-event)	Condition State	Infrastructure
Expected condition state of infrastructure (post event)	Condition State	Infrastructure
Extent of past damages	Physical	Environment
Frequency of past hazard	Physical	Environment
Severity of past hazards	Physical	Environment
Expected frequency of future hazards	Physical	Environment
Expected severity of future landslides	Physical	Environment
Terrain type	Physical	Environment

SHM BIM BASED ALERTING SAS PLATFORM						
Task	T2.5	**Leader**		TPZ UK	**Deliverable(s)**	D2.9
Name						
SHM BIM BASED ALERTING SAS PLATFORM						
Description						
This tool generat RAG (Red-Amber-Green) alerts over infrastructures by comparing observed motion against threshold failure values. The tool ingest: (i) Motion data from satellites (from PSI technique), (ii) Predicted landslides failure points (from D2.8), (iii) In-situ sensors measurements and (iv) Critical threshold asset failure values. The output is a table with the raised alerts and a 3D visualisation of the infrastructure BIM RAG-coloured showing the alerts values.						
MAIN CHARACTERISTICS						
Category	Monitoring					
Location	On the infrastructure and surroundings					
Asset	The whole asset					
Hazard	Landslides and other sources of displacement					
Life-cycle phase	Operation and Maintenance					
RESILIENCE						
Resilience Stage						
Pro-action	**Preventive**	**Preparation**	**Response**	**Recovery**		
x	x	x				
Resilience-Principle Performance						
Performance Indicator Related	Score					
Robustness	2					
Resourcefulness	3					
Rapid Recovery	1					
Adaptability	0					
WP1 Resilience indicator related						
Indicator	Category	Part				
Direct: Presence/age warning system	Protection measures	Infrastructure				
Direct: Presence of a monitoring strategy	Pre-event measures	Organizational				
Indirect: Condition state of infrastructure	Condition State	Infrastructure				
Indirect: Expected condition state of infrastructure	Condition State	Infrastructure				
Indirect: extent of past damages	Physical	Environment				
Indirect: severity of past damages	Physical	Environment				
Indirect: expected frequency of future hazard	Physical	Environment				
Indirect: expected severity of future hazard	Physical	Environment				

NEW SLOPE STABILIZATION-PROTECTION SYSTEM					
Task	T3.2	**Leader**	UC	**Deliverable(s)**	D3.6
Name					
NEW SLOPE STABILIZATION-PROTECTION SYSTEM					
Description					
Designt of a slope stabilization-protection system with integrated primary (resistant) and secondary (closing gaps) membrane with the aim of reducing the in-situ installation time					

MAIN CHARACTERISTICS	
Category	Robust design
Location	On the infrastructure
Asset	Slope
Hazard	Rockslides or landslides
Life-cycle phase	Design

RESILIENCE				
Resilience Stage				
Pro-action	**Preventive**	**Preparation**	**Response**	**Recovery**
x	x			

Resilience-Principle Performance	
Performance Indicator Related	Score
Robustness	3
Resourcefulness	1
Rapid Recovery	1
Adaptability	0

WP1 Resilience indicator related		
Indicator	Category	Part
Condition state of the infrastructure	Condition State	Infrastructure
Expected condition state of infrastructure after event	Condition State	Infrastructure
Compliance with current design code	Preventive Mesaures	Infrastructure
Adequacy of hazard effect reduction system	Preventive Mesaures	Infrastructure
Presence of protection barriers	Preventive Mesaures	Infrastructure

GUIDELINES FOR THE ADOPTION OF SUSTAINABLE DRAINAGE SYSTEMS (SDS)					
Task	T3.3	**Leader**	CEM	**Deliverable(s)**	D3.2
Name					
Guidelines for the adoption of sustainable drainage systems					
Description					
A set of strategies for adapting current drainage designs to the sustainable drainage concept: 1) a methodology to predict new precipitation patterns taking into account the effects of climate change; 2) a GIS-based procedure to assist users in the identification of areas where SDS could be implemented and 3) methodology for comparative assessment among feasible SDS					
MAIN CHARACTERISTICS					
Category	Design strategy				
Location	On the infrastructure and surroundings				
Asset	Roads and railways				
Hazard	Flooding				
Life-cycle phase	Design				
RESILIENCE					
Resilience Stage					
Pro-action	**Preventive**	**Preparation**	**Response**	**Recovery**	
x	x				
Resilience-Principle Performance					
Performance Indicator Related		Score			
Robustness		3			
Resourcefulness					
Rapid Recovery					
Adaptability		2			
WP1 Resilience indicator related					
Indicator	Category	Part			
Expected condition state of infrastructure after an event	Condition State	Infrastructure			
Compliance with current design code	Preventive measures	Infrastructure			
Presence drainage system	Preventive measures	Infrastructure			
Adequate dimensioning of drainage systems	Preventive measures	Infrastructure			
Adequate systems to reduce flooding	Preventive measures	Infrastructure			
Expected severity of future hazards	Physical	Environment			

<table>
<tr><th colspan="6">FRAGILITY AND VULNERABILITY FUNCTIONS AND DECISION SUPPORT MODULE</th></tr>
<tr><td>Task</td><td>T 3.4.2</td><td>Leader</td><td>RINA-C</td><td>Deliverable(s)</td><td>D 3.8</td></tr>
<tr><td colspan="6">Name</td></tr>
<tr><td colspan="6">Fragility and Vulnerability Functions and Decision Support Module</td></tr>
<tr><td colspan="6">Description</td></tr>
<tr><td colspan="6">The principal aim of the tool is to make available an helpful instrument to the infrastructure managers and owners in addressing the economic resources in the achievement of the transport infrastructure safety levels required</td></tr>
<tr><th colspan="6">MAIN CHARACTERISTICS</th></tr>
<tr><td colspan="2">Category</td><td colspan="4">Design strategy</td></tr>
<tr><td colspan="2">Location</td><td colspan="4">On the infrastructure</td></tr>
<tr><td colspan="2">Asset</td><td colspan="4">Transport infrastructure (bridges, tunnels, roads)</td></tr>
<tr><td colspan="2">Hazard</td><td colspan="4">Earthquake</td></tr>
<tr><td colspan="2">Life-cycle phase</td><td colspan="4">Maintenance</td></tr>
<tr><th colspan="6">RESILIENCE</th></tr>
<tr><td colspan="6">Resilience Stage</td></tr>
<tr><td>Pro-action</td><td>Preventive</td><td colspan="2">Preparation</td><td>Response</td><td>Recovery</td></tr>
<tr><td>x</td><td>x</td><td colspan="2">x</td><td>x</td><td>x</td></tr>
<tr><td colspan="6">Resilience-Principle Performance</td></tr>
<tr><td colspan="4">Performance Indicator Related</td><td colspan="2">Score</td></tr>
<tr><td colspan="4">Robustness</td><td>1</td><td></td></tr>
<tr><td colspan="4">Resourcefulness</td><td>2</td><td></td></tr>
<tr><td colspan="4">Rapid Recovery</td><td>2</td><td></td></tr>
<tr><td colspan="4">Adaptability</td><td>2</td><td></td></tr>
<tr><td colspan="6">WP1 Resilience indicator related</td></tr>
<tr><td colspan="3">Indicator</td><td colspan="2">Category</td><td>Part</td></tr>
<tr><td colspan="3">Design resistance to hazard</td><td colspan="2">Preventive measure</td><td>Infrastructure</td></tr>
<tr><td colspan="3">Condition state</td><td colspan="2">Condition state</td><td>Infrastructure</td></tr>
<tr><td colspan="3">Seismic zone</td><td colspan="2">Physical</td><td>Environment</td></tr>
<tr><td colspan="3"></td><td colspan="2"></td><td></td></tr>
</table>

<table>
<tr><th colspan="6">RISK-REDUCING AND RESTORATION PROGRAMS</th></tr>
<tr><td>Task</td><td>T4.3</td><td>Leader</td><td>ETHZ</td><td>Deliverable(s)</td><td>D4.2 & D4.7</td></tr>
<tr><td colspan="6">Name</td></tr>
<tr><td colspan="6">Development of algorithms for the selection and definition of efficient and optimal actions</td></tr>
<tr><td colspan="6">Description</td></tr>
<tr><td colspan="6">The algorithm to determine the optimal risk reduction programs contains a description of all required inputs, a complete mathematical model and a search algorithm to be used to determine optimal risk reduction programs, for all objects in a network based on the maximization of the difference between risk reduction and intervention cost. The algorithms to determine optimal restoration programs contains a description of all required inputs, a complete mathematical model and multiple search algorithms to be used to determine optimal restoration programs, for all objects in a network following the occurrence of a hazard event.</td></tr>
<tr><th colspan="6">MAIN CHARACTERISTICS</th></tr>
<tr><td colspan="2">Category</td><td colspan="4">Maintenance & Management</td></tr>
<tr><td colspan="2">Location</td><td colspan="4">On the infrastructure</td></tr>
<tr><td colspan="2">Asset</td><td colspan="4">Railways and roads</td></tr>
<tr><td colspan="2">Hazard</td><td colspan="4">Any</td></tr>
<tr><td colspan="2">Life-cycle phase</td><td colspan="4">Design; Operation & management</td></tr>
<tr><th colspan="6">RESILIENCE</th></tr>
<tr><td colspan="6">Resilience Stage</td></tr>
<tr><td>Pro-action</td><td>Preventive</td><td>Preparation</td><td>Response</td><td colspan="2">Recovery</td></tr>
<tr><td>x</td><td>x</td><td></td><td>x</td><td colspan="2">x</td></tr>
<tr><td colspan="6">Resilience-Principle Performance</td></tr>
<tr><td colspan="4">Performance Indicator Related</td><td colspan="2">Score</td></tr>
<tr><td colspan="4">Robustness</td><td>3</td><td></td></tr>
<tr><td colspan="4">Resourcefulness</td><td>0</td><td></td></tr>
<tr><td colspan="4">Rapid Recovery</td><td>3</td><td></td></tr>
<tr><td colspan="4">Adaptability</td><td>0</td><td></td></tr>
<tr><td colspan="6">WP1 Resilience indicator related</td></tr>
<tr><td colspan="3">Indicator</td><td colspan="2">Category</td><td>Part</td></tr>
<tr><td colspan="3">Indirect: expected condition state of infrastructure after a disruption</td><td colspan="2">Condition State</td><td>Infrastructure</td></tr>
<tr><td colspan="3">Indirect: presence of an emergency plan</td><td colspan="2">Post event measures</td><td>Organizational</td></tr>
<tr><td colspan="3">Indirect: practice of the emergency plan</td><td colspan="2">Post event measures</td><td>Organizational</td></tr>
<tr><td colspan="3">Indirect: review/update of the emergency plan</td><td colspan="2">Post event measures</td><td>Organizational</td></tr>
<tr><td colspan="3"></td><td colspan="2"></td><td></td></tr>
</table>

UPDATED STRUCTURAL HEALTH MONITORING (SHM) ALGORITHMS					
Task	T4.5	**Leader**	TEC	**Deliverable(s)**	D4.4 and D4.9
Name					
DATA-DRIVEN, MODEL-BASED AND COMBINED SHM ALGORITHMS FOR DAMAGE DETECTION, QUANTIFICATION AND LOCATION					
Description					
SHM algorithms for bridge structures have been developed, tested and validated within T4.5, some leading to publications. These algorithms if integrated in a wider system could detect damage and quantify it by its severity or by a deviation from the characterized reference behaviour, thus they provide an insight of structural robustness before and after an event, and slightly contribute to resourcefulness, rapid recovery and adaptability, as they can quickly asses if an structure has not suffered damage or significative damage (so it can be used). As any other SHM algorithm, they do not imply physical actuation on the structure, only monitoring and quick assessment, which means a solid					

MAIN CHARACTERISTICS	
Category	Monitoring
Location	On the infrastructure
Asset	Bridge Structure
Hazard	Hazards that cause structural damage
Life-cycle phase	Operation and Maintenance

RESILIENCE				
Resilience Stage				
Pro-action	**Preventive**	**Preparation**	**Response**	**Recovery**
	x		x	x

Resilience-Principle Performance	
Performance Indicator Related	Score
Robustness	1
Resourcefulness	1
Rapid Recovery	1
Adaptability	1

WP1 Resilience indicator related		
Indicator	Category	Part
Condition state of bridge	Condition State	Infrastructure
Presence of monitoring strategy	Pre-event measures	Organisation

ANNEX 1.4 TOOL VERIFICATION BY TOOL DEVELOPERS WP7 (D.7.6)

RISK ASSESSMENT		Risk Id.
FLOODING	Flash flood.	1
	River flood.	2
	Groundwater flood.	3
	Coastal flood.	4
	Structural failure flood.	5
EARTHQUAKES	Tectonic Earthquakes.	6
	Volcanic Earthquakes.	7
	Explosion Earthquakes.	8
	Collapse Earthquakes.	9
LANDSLIDE	Landslides.	10
	Rockfalls.	11
	Flows.	12
	Lateral Spreads.	13
SNOW/ICE	Snowstorm.	14
	Snow cover.	15
	Snowslide/avalanche.	16
	Black ice/clear ice.	17
WIND	Gale.	18
	Storm.	19
	Hurricane.	20
FIRE/EXPLOSION	Wildfire.	21
	Electrical fire.	22
	Flammable/explosive material discharges fire.	23
	Vehicle fire.	24
	Terrorist attack.	25
CYBERATTACK	Internet connected vehicles attack.	26
	Traffic Control System / Centre Attack.	27

Id	Impact description	Impact values 1	2	3	4
A	Intangibles (media coverage and intervention of managers)	Punctual/Maintenance unit	Local/Maintenance manager	Regional/Stakeholders	Nacional/Investors, politicians
B	Damage to buildings, equipment and infrastructure	< 1 million €	< 50 million €	< 200 million €	>200 million €
C	Human damage	Minor damages	Multiple damage	One victim or multiple heavy damage	Multiple victims or multiple damages
D	Cuts of circulation due to maintenance	Puntual interruptions	Interruption T(h)< 12 h in one day	T(h)>12 h for more than one day	T(h)>12 h for more than one day
E	Reduction of transport capacity	Secondary road cut for many hours	Secondary road closed > 12 h o area during few horus	Secondary road closed > 24 h, primary road closed many hours or area > 12 h	Main road closed > 24 h or area > 48 h
F	Environmental deterioration	Temporary, minor	Temporary, heavy	Permanent, minor	Permanent, heavy

Risk probability	Value
Very high - Event occurs many times per year)	4
High - Event occurs in the local region	3
Moderated - Event occurs in the country	2
Low - Event never occured in the country	1

2. Analysis

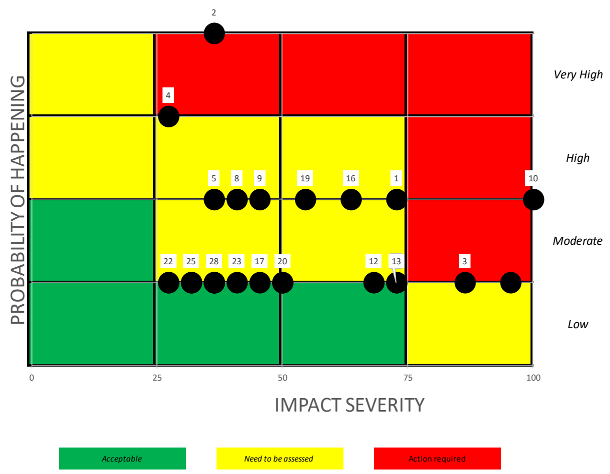


Figure 66. Risk assessment procedure for Operation and maintenance planning

INFRASTRUCTU	**ROADWAYS**
HAZARD	**LANDSLIDES**

				MAINTENANCE PLANNING					
ELEMENT	**ID**	**DAMAGE**	**DESCRIPTION**	**How is it measured/detected?**	**How is it monitorized?**	**How often?**	**How is it maintained?**	**How often?**	**FORESEE new tools/solutions/options**
STRUCTURAL ELEMENTS	ST.01	Loss of loading capacity.	Damaged estructure of tunnels, bridges, culverts, retaining walls...	Partial collapse of the structure during or after an extreme event. Reduction of service capacity.	Command and Control center can detect an important anomaly if a structure is damaged, in combination with SHM Algorithms.	Hybrid Data Assessment For Diagnosis & Prognosis provides the damage state of the structure once a flooding event is happened. The results will provide the degree of damage, and in combination with Decision Support Module stablishes a proper monitoring frequency after the flooding.	Proper design of the structure, and stablish a maintenance strategy to keep the resilience of the system as high as possible.	According to Governance Module outputs.	Command and Control can detect the collapse as an anomaly is raised. Hybrid Data Assessment to stablish the state of the structure after a landslide, depending on the magnitude of it. Governance Module to provide a fast decision-making support if collapse is reached. Decision Support Module to stabish the optimal monitoring frequency after a landslide. SHM Algorithms can early detect a structural damage by changes on the structural reponse.
STRUCTURAL ELEMENTS	ST.02	Cracking.	Structural cracking appear, being these superficial or structural due to differential movements.	Visible detection of cracking, mainly on the peak stressess direction.	Fissure meter devices to monitor the evolution of cracking.	Depending on the growing rate of cracking and the criticality of the structural element.	Two main types of cracking is identified: The superficial ones, due to retraction/contraction of the external layers of the material, can be repaired by adding coating material. Structural cracks are a signal of differential movements, meaning an action is required if these are not stable.	Algorithms for the selection and definition of efficient and optimal actions / Intervention & Mitigation can provide the actions to be performed in order to assess and intervent on this risk. If structural cracking is identified, a repairing action must be performed urgently prior to bigger damages. SHM algorithms in combination with Command and Control center can provide a continuous monitoring that reflects the evolution and affection rate of the cracking.	SHM Algorithms to evaluate the structural damages. Command and Control to detect anomalies caused by structural damage by cracking. Algorithms for selection of optimal actions can provide the actions to be performed or the inspection frecuencies.
STRUCTURAL ELEMENTS	ST.03	Collapse.	Collapse off different structural elements: bridges, retaining walls, tunnel structures, hub buildings, parking slots.... In addition to ground surface and geotechnical failures, bridges are vulnerable to complete structural collapse.	Collapse of the structure during or after an extreme event. Total lack of service capacity.	Command and Control center can detect an important anomaly if a structure collapses.	Hybrid Data Assessment For Diagnosis & Prognosis provides the damage state of the structure once a landslide event is happened. The results will provide the degree of damage, and in combination with Decision Support Module stablishes a proper monitoring frequency after the landslide.	Proper design of the structure, and stablish a maintenance strategy to keep the resilience of the system as high as possible.	According to Governance Module outputs.	Command and Control can detect the collapse as an anomaly is raised. Hybrid Data Assessment to stablish the state of the structure after a landslide, depending on the magnitude of it. Governance Module to provide a fast decision-making support if collapse is reached. Decision Support Module to stabish the optimal monitoring frequency after a landslide.
EMBANKMENT / CUTTING (SLOPES)	EC.02	Lack of stability.	An increase in pore pressure reduces strength of coarse granular material that might lead to failures.	SHM BIM based alerting SAS platform controls ground surface points movements after a landslide.	Fixed ground surface points movements detected by satellital control.	A measure is raised each time the satellite is passing over the area.	GIS risk analysis platform generating prioritised ranked site/asset risk map to detect the most critical slopes that need to be protected. New slope stabilisation systems can improve the reponse of the slope against landslide, or reduce the impact on the service of the transport system	After a landslide the embankments and slopes need to be evaluated.	SHM BIM based alerting SAS platform to control ground surface movement. GIS Risk Analysis plattform to detect the critical areas. New slope stabilization systems to improve the reponse of the slope after a landslide.

Figure 67. Maintenance planning

			OPERATION PLANNING					
ID	**IMPACT**	**DESCRIPTION**	**How is it measured?**	**How is it monitorized?**	**How often?**	**How is it managed?**	**How often?**	**FORESEE new tools/solutions/options**
OP.01	REDUCED TRAFFIC CAPACITY	Occasional / brief lane closure, but roads remains open. This impact includes lane obstruction due to snow, debris, fallen trees, rock falls, etc.)	By measuring the traffic flow of the road.	Counter vehicles devices / satellite monitoring / CCTV	Continuosly.	Traffic agents need to provide alternative routes to the traffic. SHM BIM based alerting SAS platform: Detection of a disruption from satellital information of land movements.	Prior to expected traffic demand peak	Governance module: To identify critical transport system sections, and define critical dates of peak demand Traffic module: Evaluation of affection of different scenarios SHM BIM based alerting SAS platform: Detection of a disruption from satellital information of land movements.
OP.02	TEMPORARY CLOSURE	Minor damages that result in temporary closure of road or in closing railway lines, from hours to weeks up to 60 days. Vehicles would be forced to reroute to other roads during rehabilitation works.	Interruption of the traffic in a section leads to diverged traffic flow to other areas.	SHM BIM based alerting SAS platform can raise an alarm as soon a congestion is detected in the traffic flow.	Continuously.	Preventive actions can be provided in order to avoid unexpected events that cause a temporary closure, as improved drainage systems. A continuous monitoring of the network is recommended to detect as soons as possible the irruption.	Needed actuation as soon as it happens.	Governance module: To identify critical transport system sections, and define critical dates of peak demand Traffic module: Evaluation of affection of different scenarios SHM BIM based alerting SAS platform: Detection of a disruption from satellital information or other source. Hybrid Data Assessment: Prediction of the performance of a temporary closure of a part of a transport network. Guidelines to the adoptation of suistanable drainage: To improve the drainage capabilities of a road, improving resilience of the transport system against floodings.
OP.03	COLLAPSE / LONGTIME CLOSURE	Total loss or ruin of asset. It implies immediate road/line closure and requires major repair or rebuild over an extended period of time.	Interruption of the traffic in a section leads to diverged traffic flow to other areas. Anomalies can be detected by Command and Control Center, using the predictive algorithms to avoid the collapse in conjunction with the SHM Algorithms.	SHM BIM based alerting SAS platform can raise an alarm as soon a collapse is detected in the network. Command and Control Center can detect an anomaly, in conjunction with SHM Algorithms.	Continiusly.	Alerts can be raised from predictive tools (Command and Control Center, SHM Algorithms) in order to perform an action prior to the collapse, or to be detected once these are trigered (SHM BIM based alerting SAS platform).	Needed actuation as soon as it is detected, any kind of anomaly or once it has been trigered.	Governance module: To identify critical transport system sections where to focus the continuous monitoring. Traffic module: Evaluation of affection of different scenarios, assessment of alternative routes. SHM BIM based alerting SAS platform: Detection of a disruption from satellital information or other source. Hybrid Data Assessment: Prediction of the performance of a diverged part of a transport network. Command and Control Center: To predict and detect any anomaly to prevent the collapse. SHM Algorithms: Perform a continuous monitoring of any signal of potential collapse.
OP.05	TRAVEL DELAYS	Delays due to congestion caused by speed reductions, lane closure, driver capabilities, slippery surfaces, etc.	By measuring the time employed of individual users to complete a route predefined.	Using traffic module simulations the travel delays can be simulated under different environments.	Once it is required	Traffic agents need to provide alternative routes to the traffic to the restricted vehicles. Slope flexible systems can prevent a landslide blocking the road. Traffic module can simulate the afection of this restriction to the transport network. SHM BIM based alerting SAS platform for detection of a disruption from satellital information of land movements.	During the event, management of the traffic to diverged routes. Prior an event, simulation and preparedness of the network is this event is trigered.	Traffic module: Evaluation of affection of different scenarios Slope flexible systems can prevent a landslide and block the road. SHM BIM based alerting SAS platform: Detection of a disruption from satellital information of land movements.
OP.06	INFRASTRUCTURE LIFESPAN DECREASE	Lifespan decrease due to infrastructure's damages	Routine inspections detect patologies at the infrastructure. Users may experience uncomodities.	SHM Algorithms can detect damages or deteriorations at the infrastructures.	Continuous monitoring is advised in critical infrastructures.	Command and Control Center detects the anomaly from the data collected employing SHM algorithms	Continuous monitoring is advised in critical infrastructures.	SHM Algorithms can detect structural behavour changes related to damages Command and Control Center detect the anomaly arisen from the data collected and raise an alert.
SF.02	ACCIDENTS (Objects)	Collisions caused by trees on the roads, rock falls, etc.	CCTV, traffic agents report, afections to the traffic flow.	Permanent surveying of the roads. Command and control center can detect an anomaly in the traffic flow in order to raise an alert.	Continiuisly.	An accident will lead to a reduction on the service of the road. Traffic aggents have to divert the traffic. Traffic module tool can simulate diferent accident scenarios, in order to predesign the alternative routes for different accident points on the road. Other strategy is clearing the margins of the roads from trees or any other elements, and New slope protection systems can prevent of a rock fall happening.	Prior to an accident, have a catalogue of alternative routes using Traffic module.	Traffic module: Evaluation of affection of different scenarios. Command and control center can detect any anomaly on the traffic flow to raise an alert. New slope protection systems to prevent a rockfall on the road. Flooding Methodology can identify the most sensitive areas to flooding, that can cause an accident.
SF.05	PASSAGE OBSTRUCTION	Presence of obstacles that hinder the passage (water, snow, debris, fallen trees, rock falls, etc...)	Traffic flow afection detected.	Command and control center can detect an anomaly on the traffic flow.	Continiuisly.	SHM BIM based plattform can raise alarms in case of excesive land movement that can arise to a passage obstruction. Slope protection systems can protect the slopes of rock/land obstacling the passage. Traffic module can define alternative routes.	Continuously, special attention during a flooding or prior of it is exepcted.	Command and control center to detect any anomaly. SHM BIM based plattform to detect an exceeding land movement. Slope protection systems to improve the slope stability. Traffic module to provide with alternative routes.
SF.07	VEHICLE INMOBILIZATION	Immobilitation of vehicles by being trapped by debris, water... SNOW/ICE - Heavy snowfall can immobilize a vehicle entirely, which may be deadly depending on how long it takes rescue crews to arrive. The clogging of a vehicle's tailpipe by snow may lead to carbon monoxide buildup inside the cabin.	During/after a landslide, report from involved agents.	Triggering of a landslide.	During/after a landslide.	Traffic module to stablish alternative routes in case of inmobilised vehicle blocks a passage. Shakemaps methodology to identify the critical areas that can be subjected to earth movements.	During the event, management of the traffic to diverged routes. Prior an event, simulation and preparedness of the network is this event is trigered.	Traffic module to provide with alternative routes. Shakemaps methodology to identify the most sensitive areas.
SS.01	DIRECT LOSS OF LIVES	Loss of life as a consequence of infrastructure collapse or failure	Infrastructure collapsed	SHM Algorithms can detect damages or deteriorations at the infrastructures. Command and control center can detect the anomalies in the data given by the algorithms.	For critical infrastructures, a continuous monitoring is advised.	Hybrid Data Assessment For Diagnosis & Prognosis can predict the operative of the infrastructure if damaged or collapsed. Preventive detection of patologies is mandatory.	For critical infrastructures, a continuous monitoring is advised.	SHM Algorithms can detect structural behavour changes related to damages. Command and Control Center detect the anomaly arisen from the data collected and raise an alert. Hybrid Data Assessment can predict the operative of the infrastructure if damaged or collapsed.
SS.02	INDIRECT LOFF OF LIVES	Indirect loss of life due to an inability to respond and/or to provide medical aid (impeded acces to hospital, evacuation areas)	Traffic flow afection detected, reducing efficiency of sanitary personal to the area.	Decision Support Module can provide an efficient support to manage the situation.	Prior to the accident.	Decision Support Module can provide an efficient support to manage the situation.	Prior to the accident.	Decision Support Module to stablish a minimum level of service to reduce this impact.
SS.03	DIFFICULTY FOR RESPONSE OPERATIONS	Difficulty for response operations due to the state of the road	Traffic flow afection detected, reducing efficiency of sanitary personal to the area.	Decision Support Module can provide an efficient support to manage the situation.	Prior to the accident.	Decision Support Module can provide an efficient support to manage the situation. Porous asphalt can provide a better resilience during an extreme event.	Prior to the accident.	Decision Support Module to stablish a minimum level of service to reduce this impact. Porous asphalt can provide a better resilience during an extreme event.
SO.02	LOSS OF REPUTATION	Loss of confidence of the public in the ability of the roadway/railway operator to deal with flooding/hazard.	Increase of the time required to perform a route.	Estimated/measured time to get from one point to the next.	During analysis.	Reason of losing transport service quality can be traffic restrictions. Traffic module can provide alternative routes to the public transport.	If lack of quality in operations is detected.	Traffic module to provide with alternative routes.
EC.01	MAINTENANCE COSTS	Increase in maintenance - replacement - rehabilitation cost	Increase of the economical maintenance costs of the infrastructure.	Governance module support the managers with finantial tools.	During operation of the infrastructure.	Algorithms for the selection and definition of efficient and optimal actions / Intervention & Mitigation can optimise the costs to be performed, reducing the costs associated. Additional solutions can be introduced, analysing the return of the investment period.	When a raising in the costs is detected.	Governance module to provide with finantial tools. Algorithms for the selection of optimal actions to reduce the costs.
SE.01	ISOLATION OF AREAS	Isolation of areas due to closure of roads and railway lines.	Traffic agents reports	Governance module can track this event if happens.	When hazard is triggered.	GIS Risk Analysis plattform support with the identification of the most sensitive areas that can be isolated. Provide alternative routes to access to these areas with Traffic module.	Prior to the isolation of the area.	Governance module analyse the area isolated and the impact on the level of service. GIS Risk analysis plattform gives the most possible areas to be isolated. Traffic module to provide alternative routes.
SE.02	REDUCED ACCESS TO DESTINATIONS	Reduced access to destinations served by the road/rail line: preventing or delaying people from reaching work / education / medical facilities / terminals	By measuring the traffic flow of the transport system.	Counter vehicles devices / satellite monitoring / CCTV	Once it is trigered.	Traffic agents need to provide alternative routes to the traffic to the restricted vehicles. Sustainable drainage systems deployed on a section can prevent the traffic restrictions during a flooding event. Traffic module can simulate the afection of this restriction to the transport network.	During the event, management of the traffic to diverged routes. Prior an event, simulation and preparedness of the network is this event is trigered.	Governance module: To identify critical transport system sections, and define critical dates of peak demand Traffic module: Evaluation of affection of different scenarios Sustainable Drainage Systems: Can provide a better resilience of the restricted area, reducing the duration of the restricted capacity.
SE.03	DISRUPTION OF ECONOMIC ACTIVITY	Reduced commerce in affected areas.	Economical reports on the studied areas, traffic restrictions.	Economical comertial performance of the area. Traffic counter devices.	Once a finantial disruption is detected.	Governance module can stablish the minimum level of service required to satisfy users.	Prior to the reduction of economic activity.	Governance module to identify critical transport system and areas.
EN.02	HAZARDOUS PRODUCTS RELEASE	Release of hazardous products as a consequence of accidents / derailments	Visual releases on the place of the accident.	Pollution measures after cleaning the area.	Depending on the size of the polutioned area.	Clearing the area after the accident. Compensative measures and biological solutions. Sustainable drainage solutions can help filtering the pollutants.	After an accident.	Suistainable drainage systems to help filtering the polution released.

Figure 68. Operation planning

			MAINTENANCE PLANNING					
ELEMENT	DAMAGE	DETAILS	**How is it measured/detected?**	**How is it monitorized?**	**How often?**	**How is it maintained?**	**How often?**	**FORESEE new tools/solutions/options**
STRUCTURAL ELEMENTS	Loss of loading capacity.	Damaged estructure of tunnels, bridges, culverts, retaining walls...	Partial collapse of the structure during or after an extreme event. Reduction of service capacity.	Command and Control center can detect an important anomaly if a structure is damaged, in combination with SHM Algorithms.	Hybrid Data Assessment For Diagnosis & Prognosis provides the damage state of the structure once a flooding event is happened. The results will provide the degree of damage, and in combination with Decision Support Module stablishes a proper monitoring frequency after the flooding.	Proper design of the structure, and stablish a maintenance strategy to keep the resilience of the system as high as possible.	According to Governance Module outputs.	Command and Control can detect the collapse as an anomaly is raised. Hybrid Data Assessment to stablish the state of the structure after a landslide, depending on the magnitude of it. Governance Module to provide a fast decision-making support if collapse is reached. Decision Support Module to stabish the optimal monitoring frequency after a landslide. SHM Algorithms can early detect a structural damage by changes on the structural reponse.
STRUCTURAL ELEMENTS	Cracking.	Structural cracking appear, being these superficial or structural due to differential movements.	Visible detection of cracking, mainly on the peak stressess direction.	Fissure meter devices to monitor the evolution of cracking.	Depending on the growing rate of cracking and the criticality of the structural element.	Two main types of cracking is identified: The superficial ones, due to retraction/contraction of the external layers of the material, can be repaired by adding coating material. Structural cracks are a signal of differential movements, meaning an action is required if these are not stable.	Algorithms for the selection and definition of efficient and optimal actions / Intervention & Mitigation can provide the actions to be performed in order to assess and intervent on this risk. If structural cracking is identified, a repairing action must be performed urgently prior to bigger damages. SHM algorithms in combination with Command and Control center can provide a continuous monitoring that reflects the evolution and affection rate of the cracking.	SHM Algorithms to evaluate the structural damages. Command and Control to detect anomalies caused by structural damage by cracking. Algorithms for selection of optimal actions can provide the actions to be performed or the inspection frecuencies.
STRUCTURAL ELEMENTS	Collapse.	Collapse off different structural elements: bridges, retaining walls, tunnel structures, hub buildings, parking slots.... In addition to ground surface and geotechnical failures, bridges are vulnerable to complete structural collapse.	Collapse of the structure during or after an extreme event. Total lack of service capacity.	Command and Control center can detect an important anomaly if a structure collapses.	Hybrid Data Assessment For Diagnosis & Prognosis provides the damage state of the structure once a landslide event is happened. The results will provide the degree of damage, and in combination with Decision Support Module stablishes a proper monitoring frequency after the landslide.	Proper design of the structure, and stablish a maintenance strategy to keep the resilience of the system as high as possible.	According to Governance Module outputs.	Command and Control can detect the collapse as an anomaly is raised. Hybrid Data Assessment to stablish the state of the structure after a landslide, depending on the magnitude of it. Governance Module to provide a fast decision-making support if collapse is reached. Decision Support Module to stabish the optimal monitoring frequency after a landslide.
EMBANKMENT / CUTTING (SLOPES)	Lack of stability.	An increase in pore pressure reduces strength of coarse granular material that might lead to failures.	SHM BIM based alerting SAS platform controls ground surface points movements after a landslide.	Fixed ground surface points movements detected by satellital control.	A measure is raised each time the satellite is passing over the area.	GIS risk analysis platform generating prioritised ranked site/asset risk map to detect the most critical slopes that need to be protected. New slope stabilisation systems can improve the reponse of the slope against landslide, or reduce the impact on the service of the transport system if a slope failure is triggered during or after the flooding.	After a landslide the embankments and slopes need to be evaluated.	SHM BIM based alerting SAS platform to control ground surface movement. GIS Risk Analysis plattform to detect the critical areas. New slope stabilization systems to improve the reponse of the slope after a landslide.

Figure 69. Risks maintenance

ID	IMPACT	DESCRIPTION	OPERATION PLANNING					
			How is it measured/detected?	**How is it monitorized?**	**How often?**	**How is it managed?**	**How often?**	**FORESEE new tools/solutions/options**
OP.01	REDUCED TRAFFIC CAPACITY	Occasional / brief lane closure, but roads remains open. This impact includes lane obstruction due to snow, debris, fallen trees, rock falls, etc.)	By measuring the traffic flow of the road.	Counter vehicles devices / satellite monitoring / CCTV	Continuosly.	Traffic agents need to provide alternative routes to the traffic. SHM BIM based alerting SAS platform: Detection of a disruption from satellital information of land movements.	Prior to expected traffic demand peak	Governance module: To identify critical transport system sections, and define critical dates of peak demand Traffic module: Evaluation of affection of different scenarios SHM BIM based alerting SAS platform: Detection of a disruption from satellital information of land movements.
OP.02	TEMPORARY CLOSURE	Minor damages that result in temporary closure of road or in closing railway lines, from hours to weeks up to 60 days. Vehicles would be forced to reroute to other roads during rehabilitation works.	Interruption of the traffic in a section leads to diverged traffic flow to other areas.	SHM BIM based alerting SAS platform can raise an alarm as soon a congestion is detected in the traffic flow.	Continuously.	Preventive actions can be provided in order to avoid unexpected events that cause a temporary closure, as improved drainage systems. A continuous monitoring of the network is recommended to detect as soons as possible the irruption.	Needed actuation as soon as it happens.	Governance module: To identify critical transport system sections, and define critical dates of peak demand Traffic module: Evaluation of affection of different scenarios SHM BIM based alerting SAS platform: Detection of a disruption from satellital information or other source. Hybrid Data Assessment: Prediction of the performance of a temporary closure of a part of a transport network. Guidelines to the adoptation of suistanable drainage: To improve the drainage capabilities of a road, improving resilience of the transport system against floodings.
OP.03	COLLAPSE / LONGTIME CLOSURE	Total loss or ruin of asset. It implies immediate road/line closure and requires major repair or rebuild over an extended period of time.	Interruption of the traffic in a section leads to diverged traffic flow to other areas. Anomalies can be detected by Command and Control Center, using the predictive algorithms to avoid the collapse in conjunction with the SHM Algorithms.	SHM BIM based alerting SAS platform can raise an alarm as soon a collapse is detected in the network. Command and Control Center can detect an anomaly, in conjunction with SHM Algorithms.	Continuisly.	Alerts can be raised from predictive tools (Command and Control Center, SHM Algorithms) in order to perform an action prior to the collapse, or to be detected once these are trigered (SHM BIM based alerting SAS platform).	Needed actuation as soon as it is detected, any kind of anomaly or once it has been trigered.	Governance module: To identify critical transport system sections where to focus the continuous monitoring. Traffic module: Evaluation of affection of different scenarios, assessment of alternative routes. SHM BIM based alerting SAS platform: Detection of a disruption from satellital information or other source. Hybrid Data Assessment: Prediction of the performance of a diverged part of a transport network. Command and Control Center: To predict and detect any anomaly to prevent the collapse. SHM Algorithms: Perform a continuous monitoring of any signal of potential collapse.
OP.05	TRAVEL DELAYS	Delays due to congestion caused by speed reductions, lane closure, driver capabilities, slippery surfaces, etc.	By measuring the time employed of individual users to complete a route predefined.	Using traffic module simulations the travel delays can be simulated under different environments.	Once it is required	Traffic agents need to provide alternative routes to the traffic to the restricted vehicles. Slope flexible systems can prevent a landslide blocking the road. Traffic module can simulate the afection of this restriction to the transport network. SHM BIM based alerting SAS platform for detection of a disruption from satellital information of land movements.	During the event, management of the traffic to diverged routes. Prior an event, simulation and preparedness of the network is this event is trigered.	Traffic module: Evaluation of affection of different scenarios Slope flexible systems can prevent a landslide and block the road. SHM BIM based alerting SAS platform: Detection of a disruption from satellital information of land movements.
OP.06	INFRASTRUCTURE LIFESPAN DECREASE	Lifespan decrease due to infrastructure's damages	Routine inspections detect patologies at the infrastructure. Users may experience uncomodities.	SHM Algorithms can detect damages or deteriorations at the infrastructures.	Continuous monitoring is advised in critical infrastructures.	Command and Control Center detects the anomaly from the data collected employing SHM algorithms	Continuous monitoring is advised in critical infrastructures.	SHM Algorithms can detect structural behavour changes related to damages Command and Control Center detect the anomaly arisen from the data collected and raise an alert.
SF.02	ACCIDENTS (Objects)	Collisions caused by trees on the roads, rock falls, etc.	CCTV, traffic agents report, afections to the traffic flow.	Permanent surveying of the roads. Command and control center can detect an anomaly in the traffic flow in order to raise an alert.	Continuisly.	An accident will lead to a reduction on the service of the road. Traffic aggents have to divert the traffic. Traffic module tool can simulate diferent accident scenarios, in order to predesign the alternative routes for different accident points on the road. Other strategy is clearing the margins of the roads from trees or any other elements, and New slope protection systems can prevent of a rock fall happening.	Prior to an accident, have a catalogue of alternative routes using Traffic module.	Traffic module: Evaluation of affection of different scenarios. Command and control center can detect any anomaly on the traffic flow to raise an alert. New slope protection systems to prevent a rockfall on the road. Flooding Methodology can identify the most sensitive areas to flooding, that can cause an accident.
SF.05	PASSAGE OBSTRUCTION	Presence of obstacles that hinder the passage (water, snow, debris, fallen trees, rock falls, etc...)	Traffic flow afection detected.	Command and control center can detect an anomaly on the traffic flow.	Continuisly.	SHM BIM based plattform can raise alarms in case of excesive land movement that can arise to a passage obstruction. Slope protection systems can protect the slopes of rock/land obstacling the passage. Traffic module can define alternative routes.	Continuously, special attention during a flooding or prior of it is exepcted.	Command and control center to detect any anomaly. SHM BIM based plattform to detect an exceeding land movement. Slope protection systems to improve the slope stability. Traffic module to provide with alternative routes.
SF.07	VEHICLE INMOBILIZATION	Immobilitation of vehicles by being trapped by debris, water... SNOW/ICE - Heavy snowfall can immobilize a vehicle entirely, which may be deadly depending on how long it takes rescue crews to arrive. The clogging of a vehicle's tailpipe by snow may lead to carbon monoxide buildup inside the cabin.	During/after a landslide, report from involved agents.	Triggering of a landslide.	During/after a landslide.	Traffic module to stablish alternative routes in case of inmobilised vehicle blocks a passage. Shakemaps methodology to identify the critical areas that can be subjected to earth movements.	During the event, management of the traffic to diverged routes. Prior an event, simulation and preparedness of the network is this event is trigered.	Traffic module to provide with alternative routes. Shakemaps methodology to identify the most sensitive areas.
SS.01	DIRECT LOSS OF LIVES	Loss of life as a consequence of infrastructure collapse or failure	Infrastructure collapsed	SHM Algorithms can detect damages or deteriorations at the infrastructures. Command and control center can detect the anomalies in the data given	For critical infrastructures, a continuous monitoring is advised.	Hybrid Data Assessment For Diagnosis & Prognosis can predict the operative of the infrastructure if damaged or collapsed. Preventive detection of patologies is mandatory.	For critical infrastructures, a continuous monitoring is advised.	SHM Algorithms can detect structural behavour changes related to damages. Command and Control Center detect the anomaly arisen from the data collected and raise an alert. Hybrid Data Assessment can predict the operative of the infrastructure if damaged or collapsed.
SS.02	INDIRECT LOFF OF LIVES	Indirect loss of life due to an inability to respond and/or to provide medical aid (impeded acces to hospital, evacuation areas)	Traffic flow afection detected, reducing efficiency of sanitary personal to the area.	Decision Support Module can provide an efficient support to manage the situation.	Prior to the accident.	Decision Support Module can provide an efficient support to manage the situation.	Prior to the accident.	Decision Support Module to stablish a minimum level of service to reduce this impact.
SS.03	DIFFICULTY FOR RESPONSE OPERATIONS	Difficulty for response operations due to the state of the road	Traffic flow afection detected, reducing efficiency of sanitary personal to the area.	Decision Support Module can provide an efficient support to manage the situation.	Prior to the accident.	Decision Support Module can provide an efficient support to manage the situation. Porous asphalt can provide a better resilience during an extreme event.	Prior to the accident.	Decision Support Module to stablish a minimum level of service to reduce this impact. Porous asphalt can provide a better resilience during an extreme event.
SO.02	LOSS OF REPUTATION	Loss of confidence of the public in the ability of the roadway/railway operator to deal with flooding/hazard.	Increase of the time required to perform a route.	Estimated/measured time to get from one point to the next.	During analysis.	Reason of losing transport service quality can be traffic restrictions. Traffic module can provide alternative routes to the public transport.	If lack of quality in operations is detected.	Traffic module to provide with alternative routes.
EC.01	MAINTENANCE COSTS	Increase in maintenance - replacement - rehabilitation cost	Increase of the economical maintenance costs of the infrastructure.	Governance module support the managers with finantial tools.	During operation of the infastructure.	Algorithms for the selection and definition of efficient and optimal actions / Intervention & Mitigation can optimise the actions to be performed, reducing the costs associated. Additional solutions can be introduced, analysing the return of the investment period.	When a raising in the costs is detected.	Governance module to provide with finantial tools. Algorithms for the selection of optimal actions to reduce the costs.
SE.01	ISOLATION OF AREAS	Isolation of areas due to closure of roads and railway lines.	Traffic agents reports	Governance module can track this event if happens.	When hazard is triggered.	GIS Risk Analysis plattform support with the identification of the most sensitive areas that can be isolated. Provide alternative routes to access to these areas with Traffic module.	Prior to the isolation of the area.	Governance module analyse the area isolated and the impact on the level of service. GIS Risk analysis plattform gives the most possible areas to be isolated. Traffic module to provide alternative routes.
SE.02	REDUCED ACCESS TO DESTINATIONS	Reduced access to destinations served by the road/rail line: preventing or delaying people from reaching work / education / medical facilities / terminals	By measuring the traffic flow of the transport system.	Counter vehicles devices / satellite monitoring / CCTV	Once it is trigered.	Traffic agents need to provide alternative routes to the traffic to the restricted vehicles. Suistainable drainage systems deployed on a section can prevent the traffic restrictions during a flooding event. Traffic module can simulate the afection of this restriction to the transport network.	During the event, management of the traffic to diverged routes. Prior an event, simulation and preparedness of the network is this event is trigered.	Governance module: To identify critical transport system sections, and define critical dates of peak demand Traffic module: Evaluation of affection of different scenarios Suistainable Drainage Systems: Can provide a better resilience of the restricted area, reducing the duration of the restricted capacity.
SE.03	DISRUPTION OF ECONOMIC ACTIVITY	Reduced commerce in affected areas.	Economical reports on the studied areas, traffic restrictions.	Economical comertial performance of the area. Traffic counter devices.	Once a finantial disruption is detected.	Governance module can stablish the minimum level of service required to satisfy users.	Prior to the reduction of economic activity.	Governance module to identify critical transport system and areas.
EN.02	HAZARDOUS PRODUCTS RELEASE	Release of hazardous products as a consequence of accidents / derailments	Visual releases on the place of the accident.	Pollution measures after cleaning the area.	Depending on the size of the polutioned area.	Cleaning the area after the accident. Compensative measures and biological solutions. Suistanable drainage solutions can help filtering the pollutants.	After an accident.	Suistanable drainage systems to help filtering the polution released.

Figure 70 . Impacts operation

TOOL NAME	Deliverable Id.	Tool Id.	Tool description	Event Detected	Infrastructure type	Life Cycle Phase applied (planning, design,	Resilience Cycle applied (prevention, preparedness, response, recovery)	Inputs required	Outputs obtained
SHM BIM based alerting SAS platform	**D2.9**	**T2.5**	The tool is an API that generates RAG alerts over a BIM and allows 3D visualization. The alerts are raised in correspondence with the datasets of motion ovserved near on on the BIM using landslide failure prediction model, in-situ sensors data and InSAR data.	Landslides	Roads	operations	prevention	Landslide failure prediction model, in-situ sensors data and InSAR data. Rainfall data.	RAG alerts list and RAG-coloured BIM adapted to be visualized by Cesium JS. Prediction of the timing and nature of potential failures along infrastructure corridors
Decision Support Module DSM	**D3.8**	**T3.4.2**	The tool provides an efficient instrument allowing to infrastructure managers and owners to manage assets and financial resources to guarantee the optimal level of service.	All	All	All	All	Transport Network description Asset description Hazard data (e.g hazard curves) Traffic volumes, Travel times and Travel Speeds from the Traffic Module	Risk assessment Direct and Indirect Losses Resilience Assessment Level of Service
GIS risk analysis platform generating prioritised ranked site/asset risk map	**D2.4**	**T2.1**	The tool provides a risk occurrence assessment for the most significant natural disasters (floods, landslides, and earthquakes).	Flood, landslide, or earthquake	All	Design, Operation	All	Historical data of natural disaster related to the asset hazards	Identification of areas with high vulnerability

Figure 71. FORESEE Tools

ANNEX 1.5 TOOLKIT INTERFACE

The toolkit as developed by RINA, integrating the different tools developed by the partner.

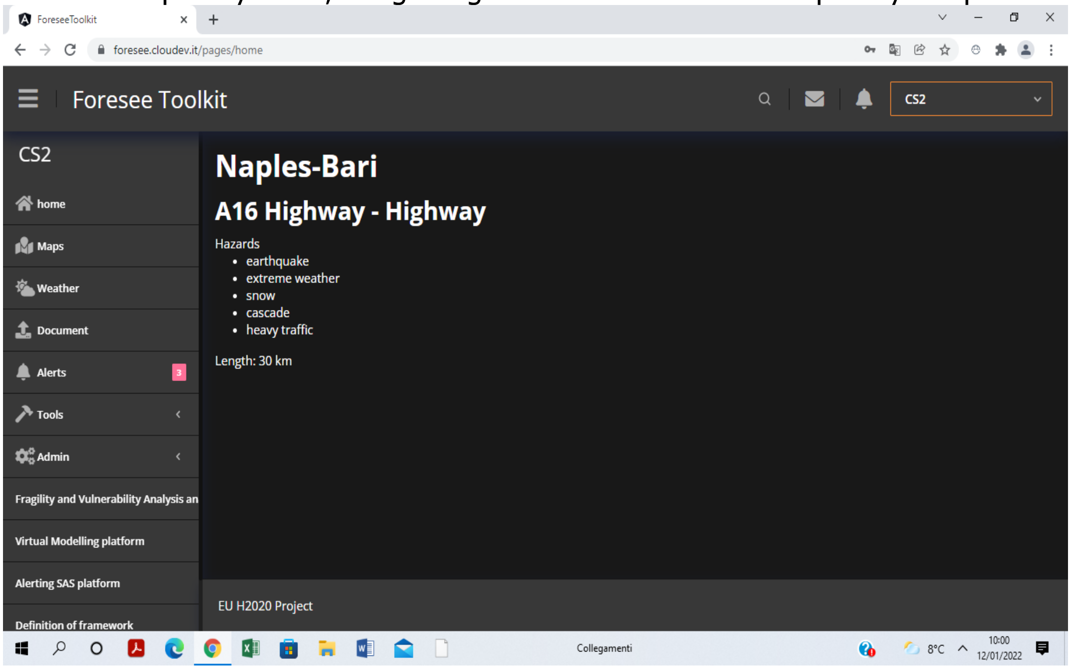


Figure72. Initial interface

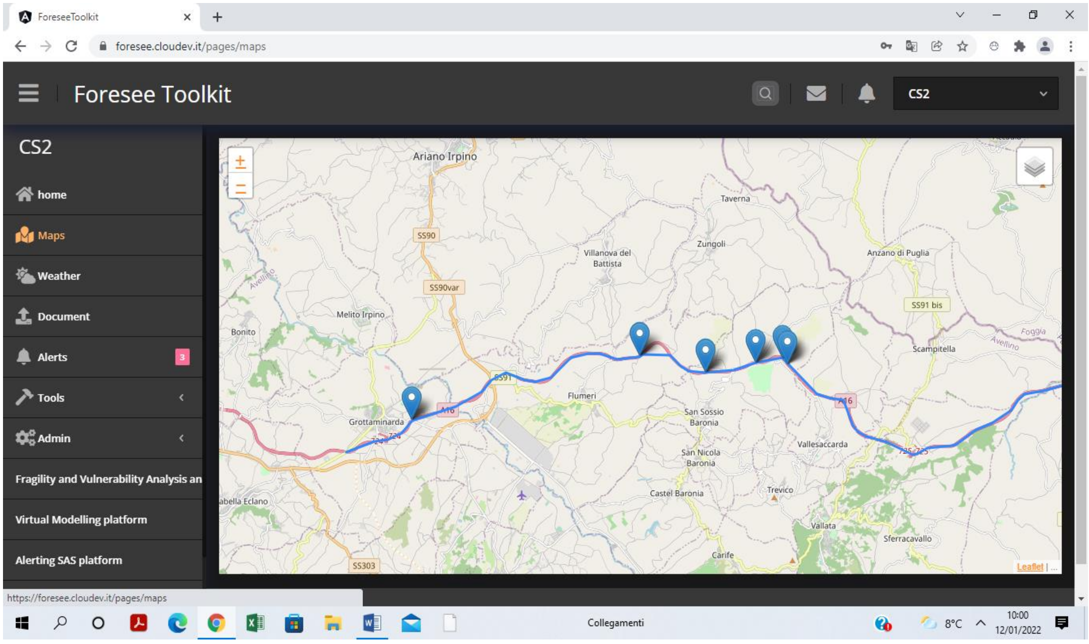


Figure 73. Map of the area of interest for CS#2

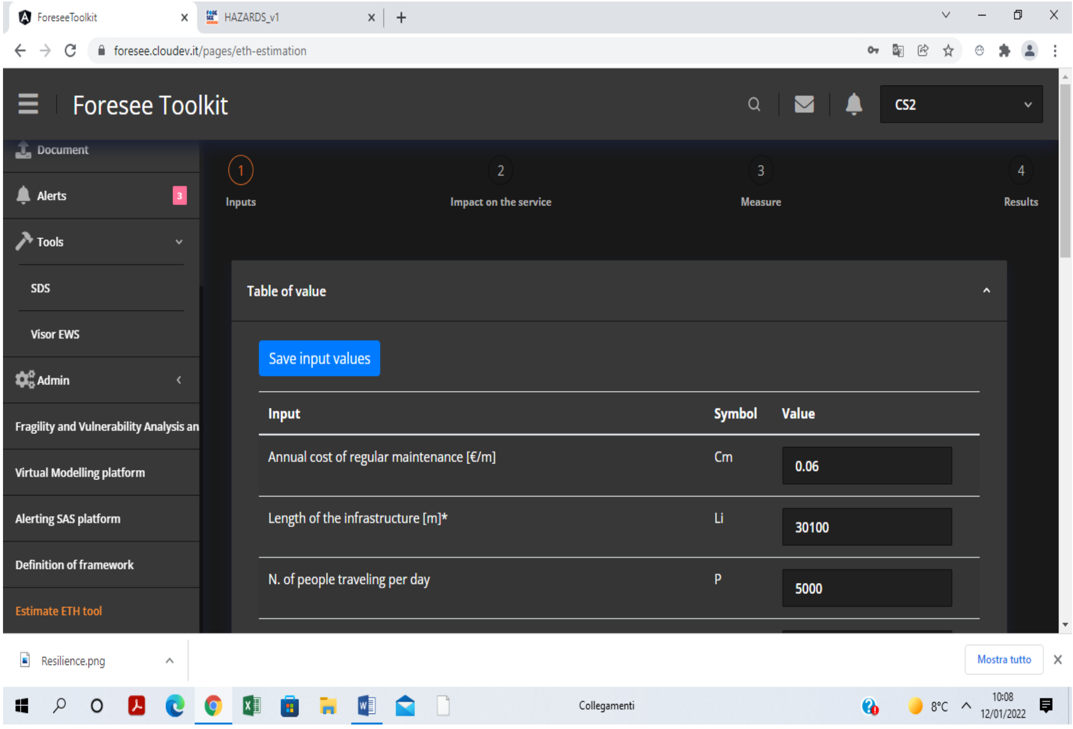


Figure 74. Module "Estimate of ETH Tool" with its four steps: inputs, impact on service, measure, results". Computation of the level of service

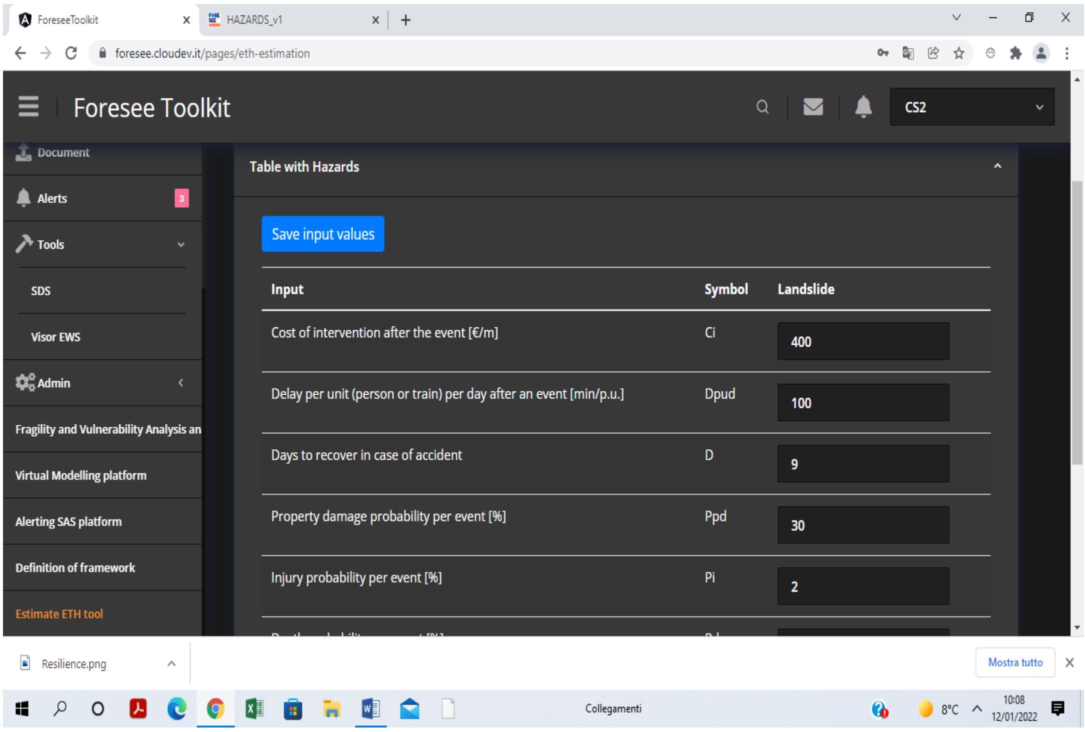
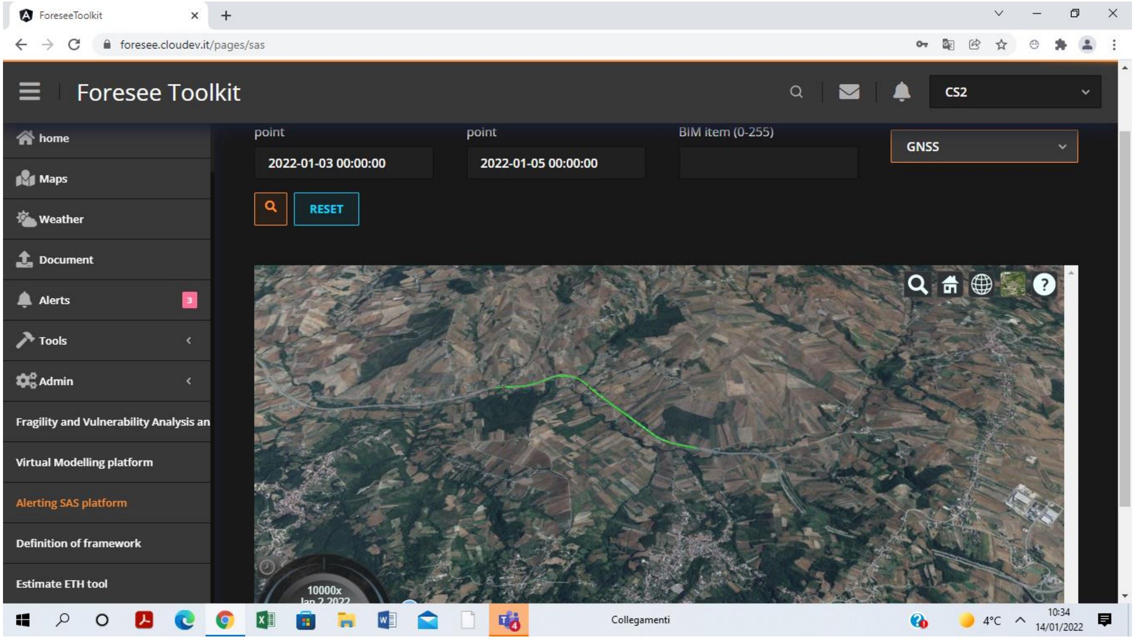


Figure 75. Module "Estimate of ETH Tool" with its four steps: inputs, impact on service, measure, results". Computation of the level of service after the event

Figure 76. Module "Estimate of ETH Tool" with its four steps: inputs, impact on service, measure, results". Measure of resilience



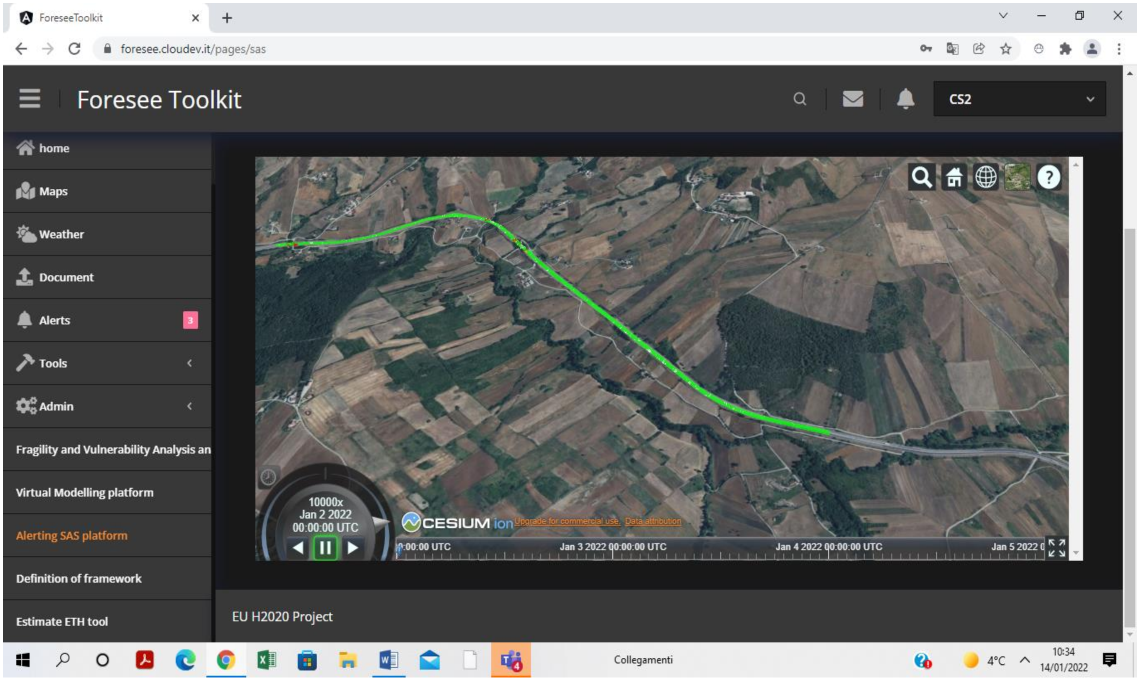


Figure 77. Module "Alerting SAS Platform" showing the area and the BIM of the infrastructure (km 97-99)

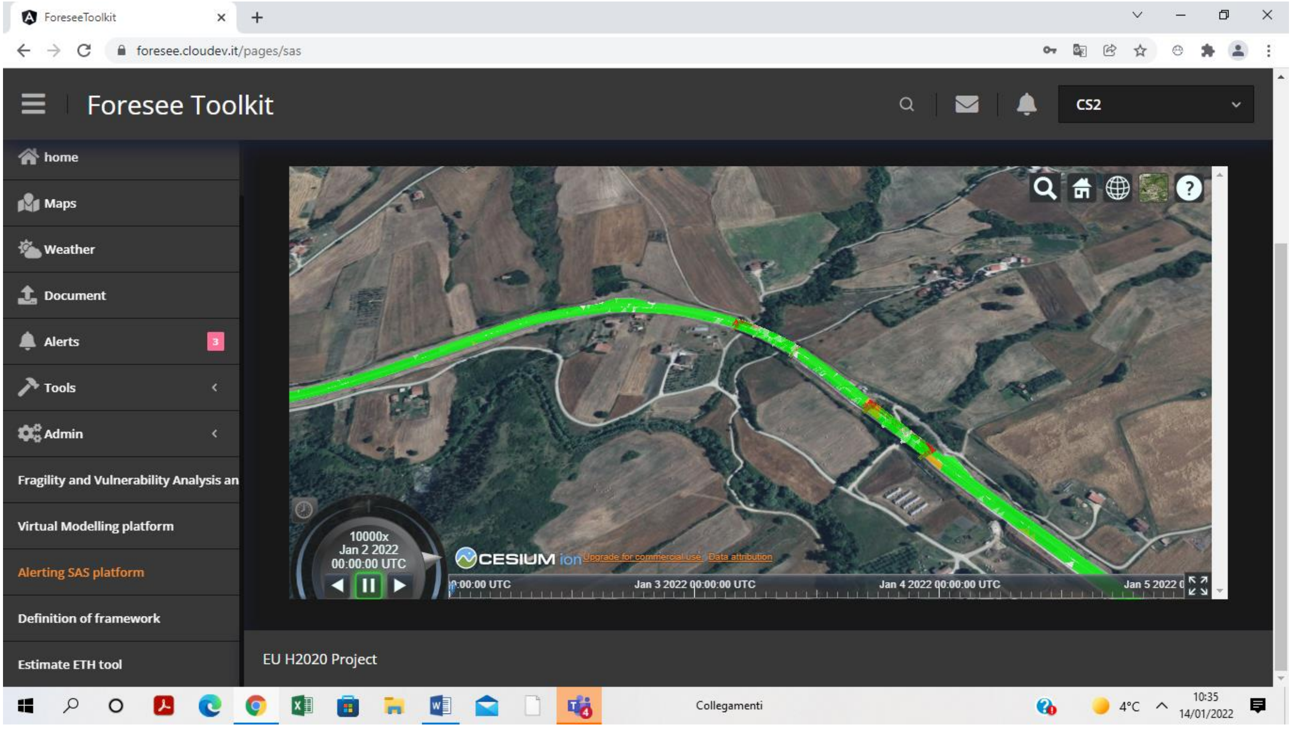


Figure 78. Module "Alerting SAS Platform" showing the area and the BIM of the infrastructure (km 97-99) with the two bridges, chosen for the analysis

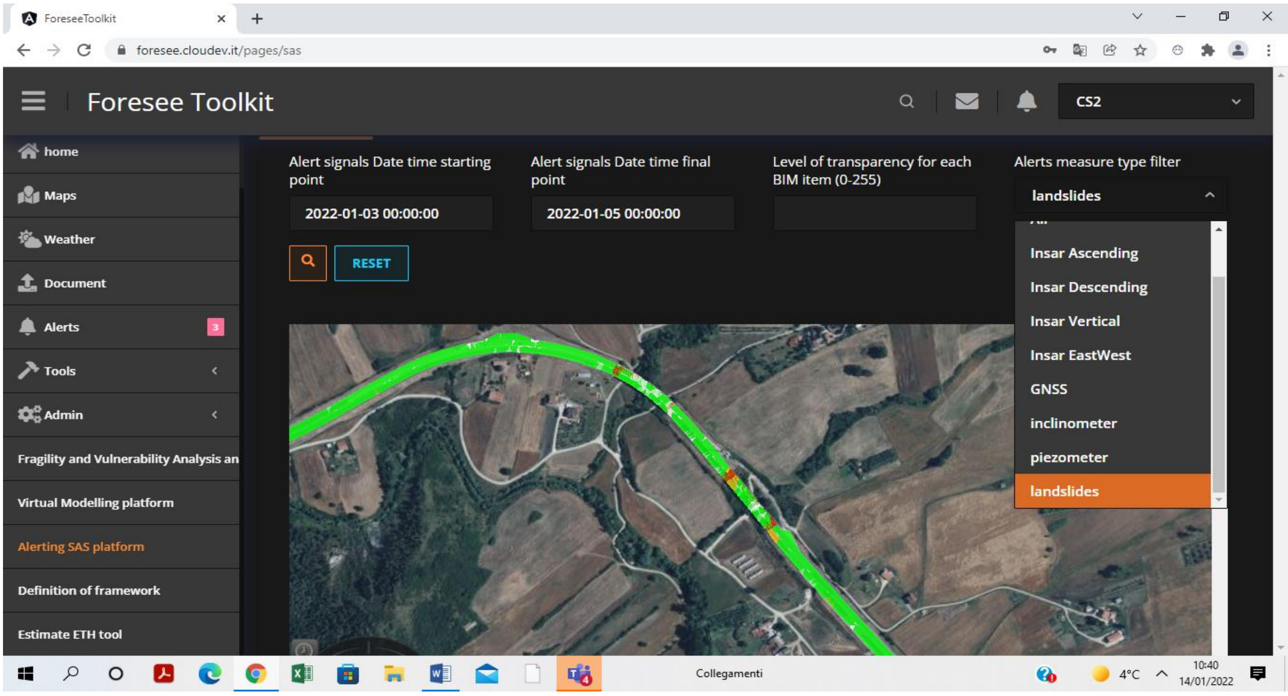


Figure 79. Module "Alerting SAS Platform" showing the different available types of measures and alerts.

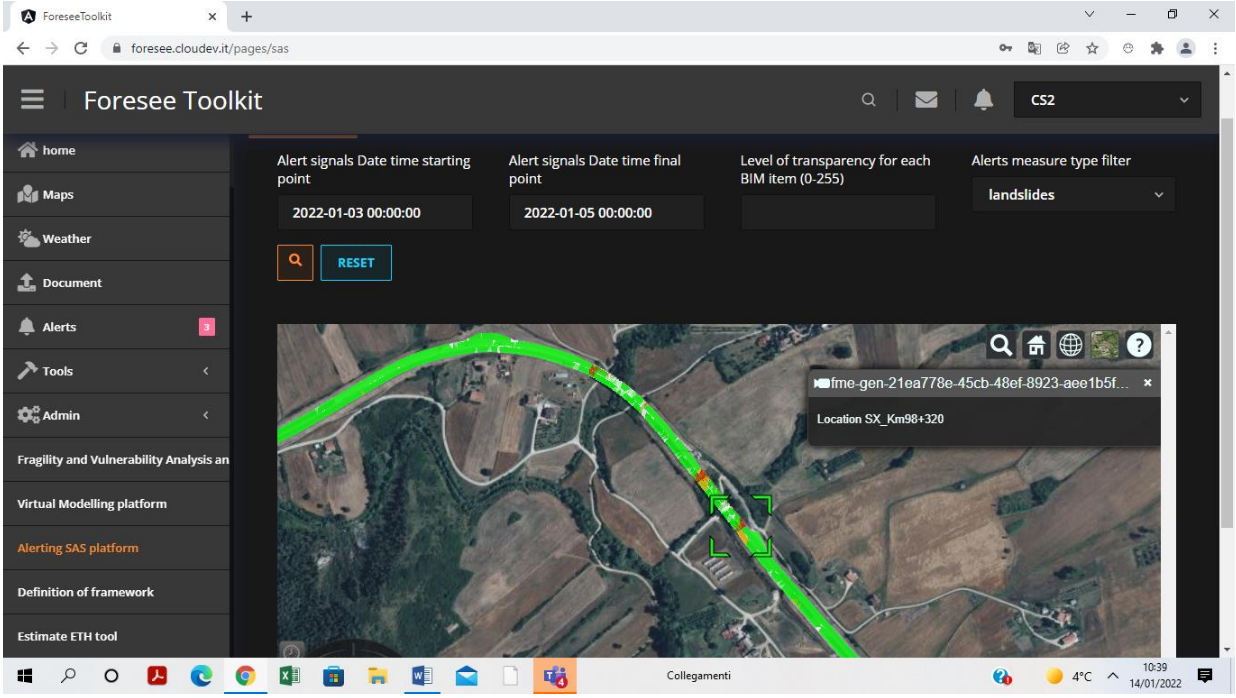


Figure 80. Module "Alerting SAS Platform" showing the different available types of measures and alerts with no alert in the period for GNSS data.

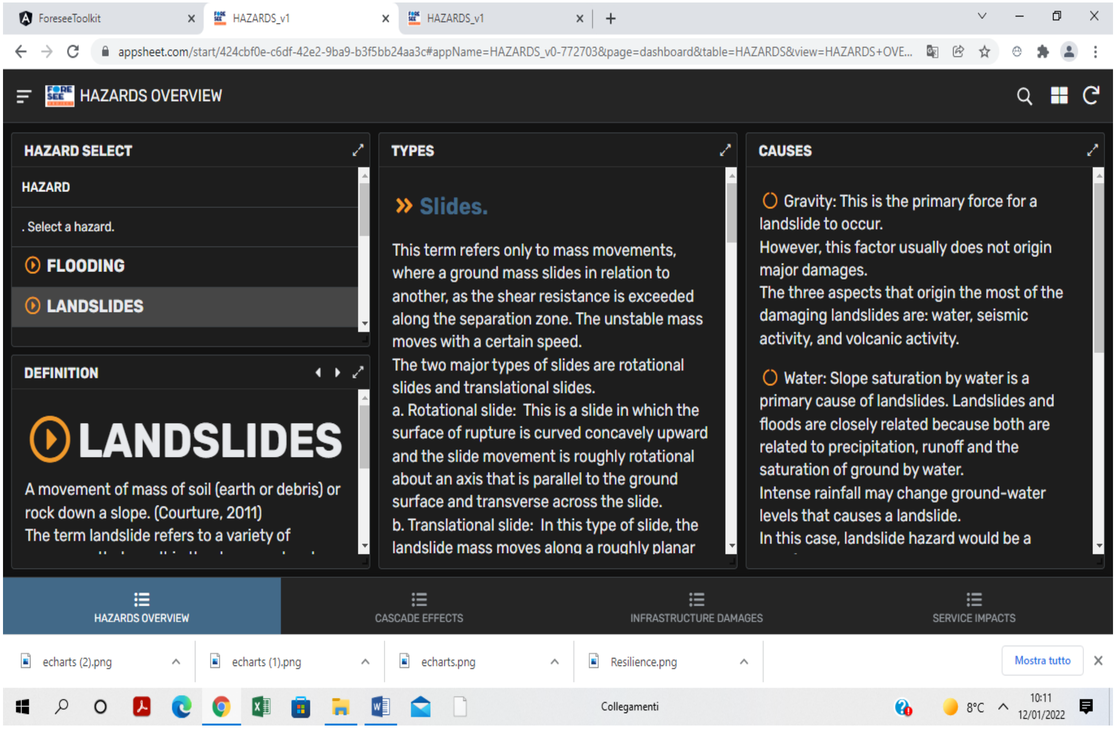


Figure 81. Module "Definition of Framework" for landslides-hazard overview.

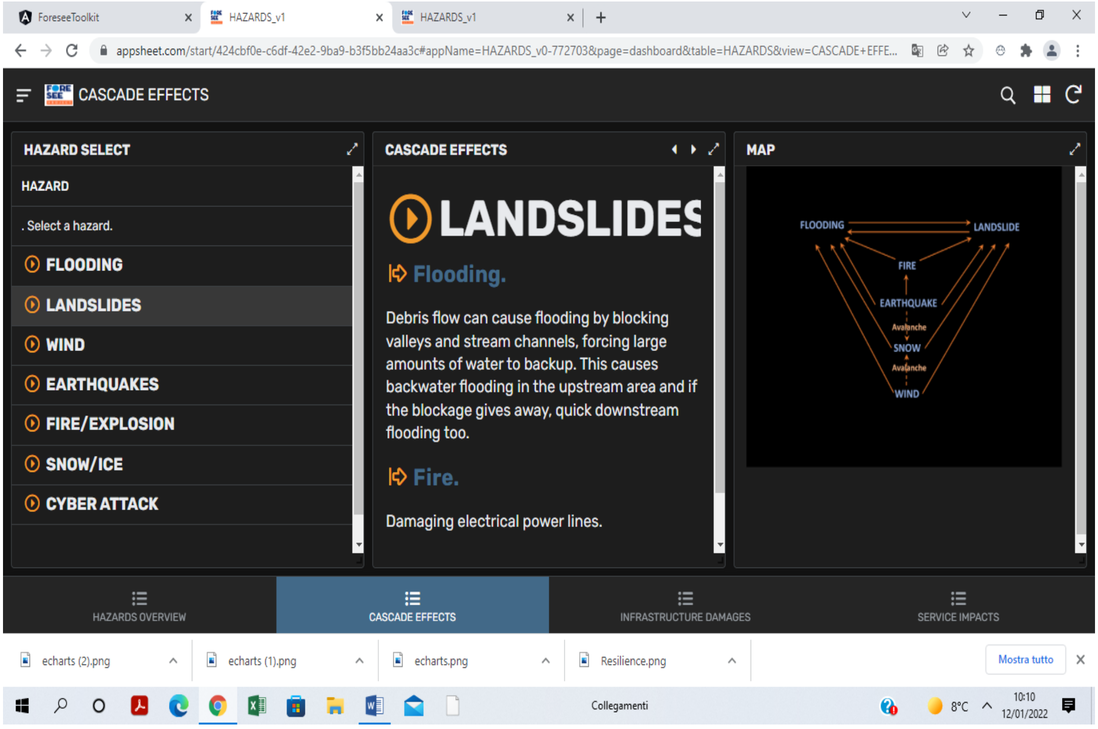
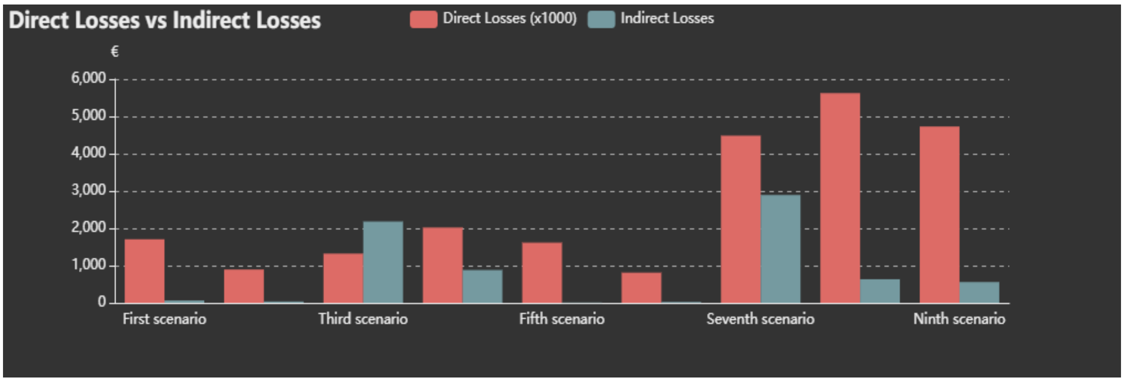


Figure 82. Module "Definition of Framework" for landslides -cascade effect



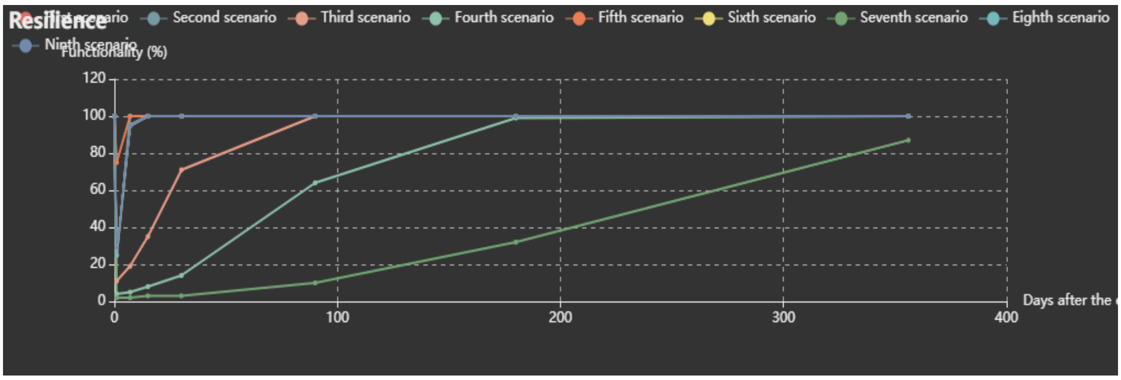


Figure 83. Module "Fragility and vulnerability analysis". Results for CS#2

ANNEX 1.6 SMART AND INTEGRAL SLOPE STABILISATION SYSTEM FUNCTIONS (factsheet)

Design of a slope stabilization-protection system with integrated primary (resistant) and secondary (closing gaps) membrane with the aim of reducing the in-situ installation time. Laboratory testing of an innovative way to monitor the slopes using Fibre bragg grating (fiber optic) to be extrapolated to real slopes. 3D numerical simulation of flexible membranes using a mixed FEM-SPH model.

FORESEE linked document	D 3.6. Smart and integral slope stabilization-protection systems Confidential document.
FORESEE contact info	University of Cantabria. Grupo de Investigación de Tecnología de la Construcción (GITECO). E.T.S.I.C.C.P., Avda. de los Castros 44, 39005 Santander Contact person: Castro, Daniel; daniel.castro@unican.es, Indacoechea, Irune; idacoecheai@unican.es

Scientific publications produced (open source):

- Jimenez Fernandez, J.C., Castanon-Jano, L., Gaute Alonso, A., Blanco-Fernandez, E., Gonzalez Fernandez, J.C., Centeno Gonzalez, V., Castro-Fresno, D., Garcia-Sanchez, D. 3D numerical simulation of slope-flexible system interaction using a mixed FEM-SPH model (2022) Ain Shams Engineering Journal, 13 (2), art. no. 101592, .
- Castanon-Jano, L., Castro-Fresno, D., Blanco-Fernandez, E., Carpio-Garcia, J. Selection of membranes and linking method in slope stabilization systems for the reduction on the installation time using multi-criteria decision analysis (2021) Ain Shams Engineering Journal, 12 (4), pp. 3471-3484.

HOW IT IS CONNECTED WITH THE RESILIENCE.

Flexible membranes are able to keep the traffic routes or the areas to protect (houses, towns…) safe despite the occurrence of a landslide.

RESULTS OBTAINED; POTENTIAL IMPROVEMENTS

A Multicriteria Decision Making Analysis was carried out to select the main membrane, the secondary membrane and the connection type. The results are the following:

- Range up to 45 kN / m^2: the best option is the combination of 300 mm grid side square cable net, with coconut fiber mesh and connected by cable ties with a gun
- Range from 45 to 75 kN /m^2: the best option is the combination of G65/3 wire mesh, with coconut fiber mesh and connected by cable ties with a gun
- Range from 75 to 125 kN / m^2: the best option is the combination of G65/4 wire mesh, with coconut fiber mesh and connected by cable ties with a gun

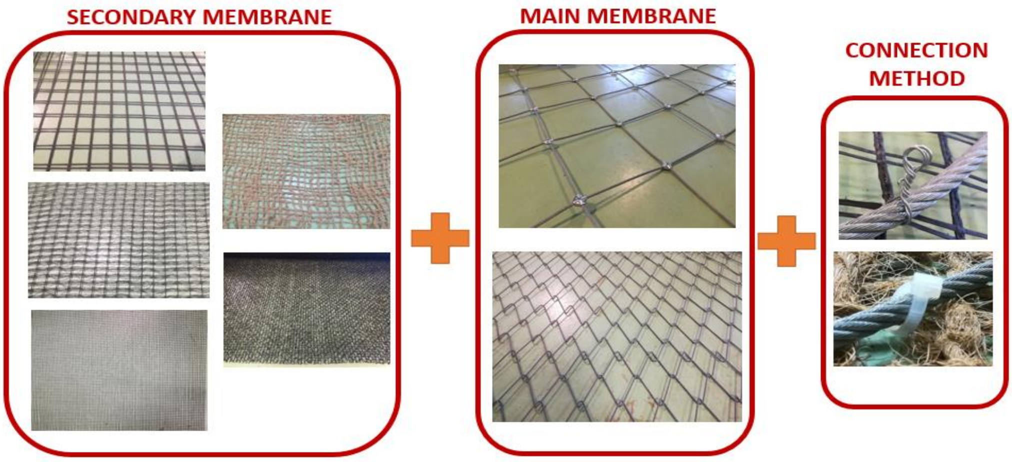


Figure 84. Different alternatives evaluated for secondary membrane, main membrane and connection method between them

Numerical simulations were also developed in Ansys Autodyn, and accurately reproduce the behaviour of the complete system during the soil detachment with different soil conditions. Soil was simulated using Smooth Particle Hydrodynamics formulation (SPH), whilst the flexible components, such as cables, membrane and bolts, were reproduced by means of Finite Element Modeling (FEM). Analysing different scenarios and studying the stresses at the critical points, we are able to predict whether the system will be capable of withstanding the forces transmitted by the or not.

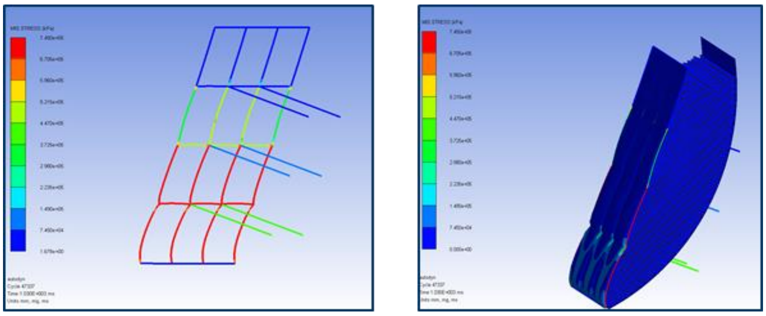


Figure 85. 3D numerical simulation of a landslide on a flexible membrane: a) Von Mises Stress on the cables and bolts, b) Von Misess stress on the whole model, including the membrane and the representation of the soil

Several Fiber bragg gratings (FBG) were glued to metal or plastic plates and located along one of the cables of the diagonal of the membrane. This system was tested on laboratory tests to find out their deflection under a uniform load and the results compared with those of a wire sensor corroborating their accuracy.

BENEFITS FOR THE INFRASTRUCTURE OWNER/OPERATOR

Reduction of the in-situ installation time with lower roads and railway cuts. By finding a way to connect the main (cable net or wire mesh) and secondary membranes (geomat, geogrid, biomat, etc.) at the inside of the warehouse, the installation is reduced to the setting of only one membrane (made of the two main and secondary membranes) instead of dealing with the two ones separately and independently, which doubles the installation time.

Figure 86. a) Distributed load test where the fiber Bragg grating monitoring was tested, b) plate with glued fiber bragg along the diagonal cable of the membrane

The Fibre bragg grating signal has no noise, and multiplexing is possible without mixing signals.

Finally, the numerical models are the most advanced and detailed to date. Few models were found until date and most of them are in 2D and do not include all the components of the flexible systems and hence, its complete response cannot be analysed. The new models developed here can be used as a design tool that has the aim of dimensioning the elements to be installed in the system.

Question	**Impact**
Was this type of analysis made before FORESEE? How it was made?	Yes. Flexible membranes are common solutions used to protect a certain area from rockfalls or a lansdides. The installation of the membranes is executed from the more internal to the more external, one at the time. Their monitoring was done in a very few cases and they consist of load sensors that measure the increase of load to detect an event.
How does FORESEE improve the results/analysis previously made?	Reduction of the in-situ installation time with lower roads and railway cuts. 3D numerical simulations accurately reproduce the behaviour of the complete system during the soil detachment with different soil conditions. This make possible to use the simulations a design tool. Fibre Bragg is used to monitor the strains of the flexible system, that avoids signal noise, allows multiplexing and the measure of the distributed deformation, not only punctual.
How does this FORESEE result improve your infrastructure's management	Flexible membranes are able to keep the traffic routes or the areas to protect (houses, towns…) safe despite the occurrence of a landslide.
If it was not made, How does this FORESEE result improve your infrastructure's management ?	NA
What cost/resource efficiencies you expect these tools/results to have on your day-to-day business? (e.g. 10%-20% decrease in working hours over the first year; reduction of maintenance costs (20%-25%), Return on Investment (ROI) – 10-15%, increase in productivity 25-30%)	The design of these kits using 3D numerical modelling would lead to a tailor-made solution that would reduce the maintenance costs, although it is difficult to make an estimation of the percentage. The monitoring of the slope would be used as an indicator of a future or imminent landslide that could reduce the damages on the roads and even in the kit, also reducing the maintenance costs. The installation kit with integrated membranes would imply a reduction on its installation time.

Table 36-Questions and impacts

ANNEX 1.7 NEW FAMILY OF PA MIXTURES

New porous asphalt mixtures with improved infiltration capacities able to manage extreme rainfall events, reducing flooding problems, risks and users´ risk perception in wet weather conditions.

FORESEE linked document	D 3.5.-New family of PA pavements for extreme events conditions Confidential document. Only for members of the consortium (including the Commission Services).
FORESEE contact info	University of Cantabria. Grupo de Investigación de Tecnología de la Construcción (GITECO). E.T.S.I.C.C.P., Avda. de los Castros 44, 39005 Santander Contact person: Castro, Daniel, daniel.castro@unican.es, Indacoechea, Irune; indacoecheai@unican.es

Scientific publications produced (open source):

- Slebi-Acevedo, C.J.; Lastra-González, P.; Calzada-Pérez, M.A.; Castro-Fresno, D. (2020). Effect of synthetic fibers and hydrated lime in porous asphalt mixture using multi-criteria decision-making techniques. Materials, 13 (3), 675. Doi: 10.3390/ma13030675
- Slebi-Acevedo, C.J.; Pascual-Muñoz, P.; Lastra-González, P.; Castro-Fresno, D. (2019). Multi-response optimization of porous asphalt mixtures reinforced with aramid and polyolefin fibers employing the CRITIC-TOPSIS based on Taguchi methodology. Materials, 12 (22), 3789. Doi: 10.3390/ma12223789
- Slebi-Acevedo, C.J.; Castro-Fresno, D.; Pascual-Muñoz, P.; Lastra-González, P. (2021): A combination of DOE – multi-criteria decision-making analysis applied to additive assessment in porous asphalt mixture, International Journal of Pavement Engineeri. International Journal of Pavement Engineering. Doi: 10.1080/10298436.2020.1859508

HOW IT IS CONNECTED WITH THE RESILIENCE.

According to the definitions of resilience and service given by the guideline to measure levels of service and resilience in infrastructures (deliverable D1.1), the use of the new porous asphalt mixtures would improve resilience of the infrastructure as they are able to increase the ability of the road to continue to provide service if a hazard event occurs, understanding service as the ability to transport from A to B goods without being damaged and persons without being hurt or losing **their lives.**

Specifically, the new mixtures will improve the following resilience indicators:

- Design resistance to hazard. The road will react better during and immediately after an extreme rainfall event since it is able to remove surface water faster. This will positively affect:
  - Safety. By preventing tire spray and hydroplaning, as well as improving visibility during the hazard event.
  - Time of travel: the better visibility and the lower amount of water accumulated in the surface will reduce the speed decrease of vehicles during and after the event.
- Condition state of infrastructure. The new porous asphalt mixture clogging resistance is higher than conventional porous asphalt mixtures. This provides the road surface with a better condition state of the infrastructure during and after an extreme rainfall event, in terms of their capacity to drain water, for longer.

RESULTS OBTAINED; POTENTIAL IMPROVEMENTS.

The solutions consist of fibre-reinforces porous asphalt mixtures with a higher air void content and higher clogging resistance but without compromising their mechanical performance. These mixtures include fibres to strengthen the mortar and maintain the asphalt mixture mechanical performance despite the increase of air voids. Actually, the mixtures have been designed for the highest traffic category.

Figure 87. Materials of experimental mixtures (from left to right): polymer-modified bitumen, natural aggregates, hydrated lime and aramid fibres

The higher air void content allows a higher volume of water to be drained. This means that during an extreme rainfall event, tire spray and hydroplaning are minimized, increasing driver safety. Likewise, visibility is improved during the extreme event, thus also increasing safety.

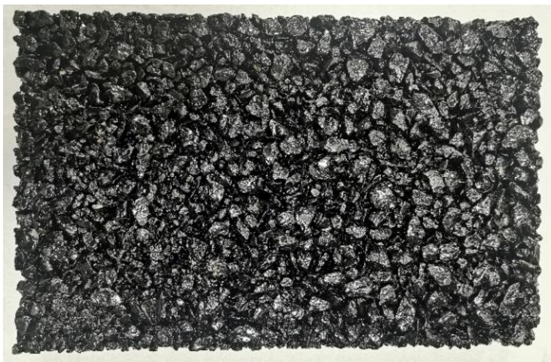


Figure 88. PA16 Foresee slab

An economic assessment covering the entire life cycle of a pavement incorporating these new PA mixtures has been carried out. Based on the results obtained, comparing the total costs of the other mixes, we can conclude that the price of the experimental mixes is competitive, especially considering that the social costs of these mixes are lower than those of conventional mixes. In order to analyse this aspect, the influence on the resilience indexes of the experimental mixtures has also been analysed.

Several simulations were done to evaluate the PA layer resilience. The main conclusion of the resilience analysis, based on the resilient indicator time of travel define on the deliverable D1.1, is that new asphalt mixtures are more resilient in terms of time of travel due to the capacity of water absorption in comparison with the ordinary asphalt mixtures like the conventional PA-16 or PA-8.

BENEFITS FOR THE INFRASTRUCTURE OWNER/OPERATOR

Useful for infrastructure owners to increase the resilience of the road pavement. The new mixtures can be applied in a new road construction or during major maintenance actions such as the surface layer milling and overlay.

In addition, due to their lower clogging susceptibility, the need of surface maintenance to prevent clogging is reduced, what result in lower costs for road operators comparing to conventional PA mixtures.

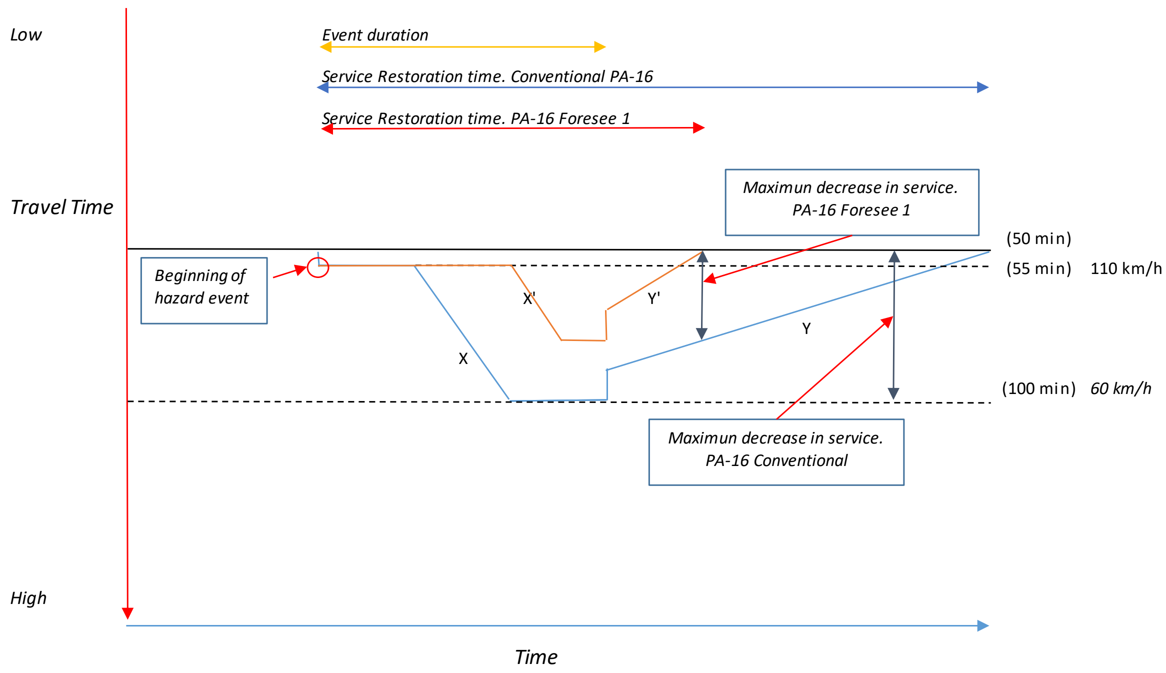


Figure 89 Resilience illustration Case 3

Figure 90. Clogging resistance test

Question	Impact
Was this type of analysis made before FORESEE? How it was made?	Yes. Porous asphalt mixtures are commonly used in areas with large rainy seasons and frequent heavy rainfall events.
How does FORESEE improve the results/analysis previously made?	New enhanced PA mixtures have been developed in FORESEE. These mixtures have higher air void content allowing a higher volume of water to be drained. This improves the drainage of water during the rainfall event improving safety and time of travel.
How does this FORESEE result improve your infrastructure's management	New PA mixtures increase resilience of the infrastructure, reduces travel time comparing to conventional PA mixtures and increase safety.
If it was not made, How does this FORESEE result improve your infrastructure's management ?	NA
What cost/resource efficiencies you expect these tools/results to have on your day-to-day business? (e.g. 10%-20% decrease in working hours over the first year; reduction of maintenance costs (20%-25%), Return on Investment (ROI) – 10-15%, increase in productivity 25-30%)	Although promising, it is difficult to quantify the efficiency in terms of return of investment or increase in productivity. However, the impact on travel time has been estimated being possible to significantly reduce it during moderate and heavy rainfall events, meaning saving costs for end-users. The benefit related to the increase in safety by preventing tire spray and hydroplaning, as well as improving visibility during the hazard event need also be considered.

Table 37.-Questions and impacts

ANNEX 2 ROUTE ASSET PLAN UPDATING

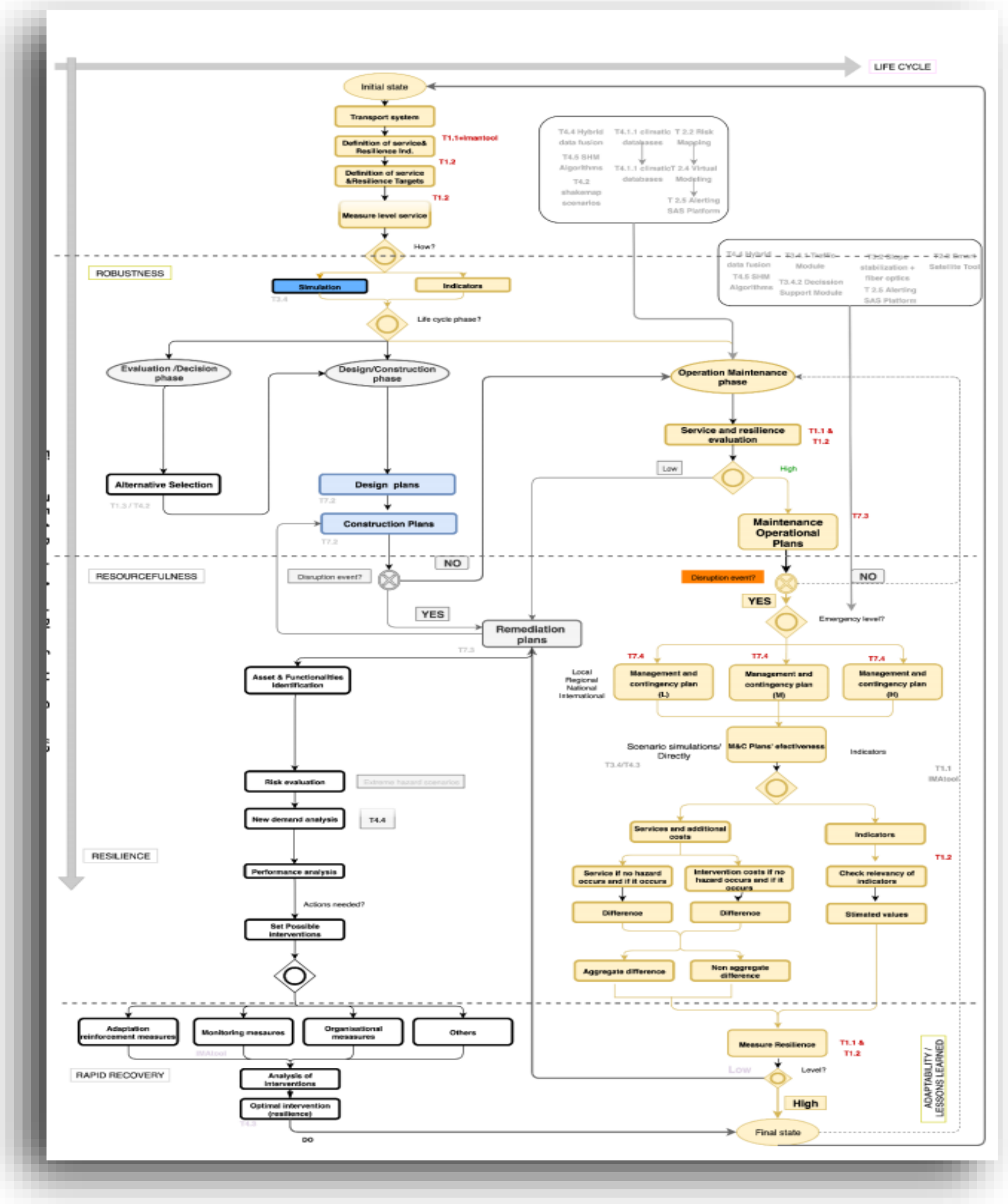


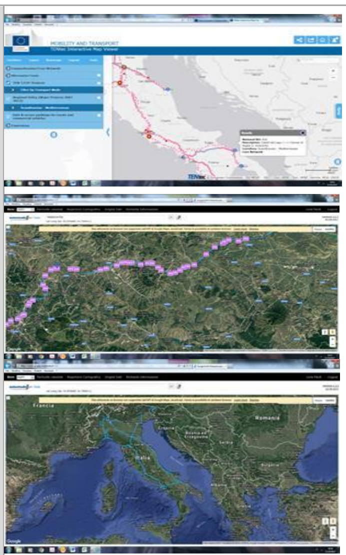
Figure 91. ROUTE ASSET PLAN FOR CS#2. FORESEE APPLICATION

The updating used in the route asset plan for CS#2, corresponds to:

- in the Phase Design and Construction is selected the resilience typology of infrastructure along specific risks, wind and snowfall, to include on operation & Maintenance Plan.

in the Phase Operation & Maintenance Plan based on Resilience Design.

ANNEX 3 PILOT DESCRIPTION AS IN DOW

Case Study Data Sheet		*ITALY-A16-OWNER. ASPI* The A16 has been built in late 60s and it runs from Naples to Bari along the TEN-T Corridor n.5 Scandinavian –Mediterranean. The area, between km. 70 and km. 100, will be investigated where a total of 20 bridges (for a total length of approx. 3 km) are present. The bridges, generally with a simply supported structural scheme with beams and cross beams in prestressed post-tensioned concrete, are representative of a wide population of structures across Italy in similar conditions of environmental attack and hydrogeological risk. Most of the geological formations emerging in the motorway in question are characterized by thick layers dominated by the clayey component, with rare inclusions of a lithidic nature. The highly clayey nature of these soils strongly influences the stability of the slopes. A zoom will be made on a smaller area of 10-15 km of highway where 1-2 bridges and or slopes will be selected for a specific application of the project results, the final choice depending on the project schedule.
Significant aspects	*Criticalities and problems of the pilot*	Bridges suffer from a diffused deterioration problem. Due to the construction techniques of the time and of the adverse climate conditions (a large use of de-icing salts is made during the winter) they present the same patterns of deterioration over the years. It is expected to carry out maintenance interventions in the next years. Along the infrastructure, we can distinguish morphologies related to surface instability ("slow surface deformations"), but also deep instability phenomena, referring to the slope scale. There are many sites in area, considered for validation, that, over the years, where ASPI has undergone instrumental geotechnical monitoring activities, essentially inclinometric and piezometric.
	Extreme events	The highway is also subject to extreme weather conditions (i.e. snow) as it crosses a mountainous region, prone to landslides. Moreover, the area presents a high degree of seismicity. To date, there are about 30 sites that are subject to instrumental monitoring activities, whose results have provided the necessary elements for defining consolidation interventions.
	Replication	The bridges may be considered as a "champion" of similar bridges either along the same highway and along other highways of the network. The identified consolidation interventions and solutions have to be customized for the other ASPI network sections as the results on the A16 are strongly linked to the geology and geomorphology of the sites.
Technical information		All information from the construction phase (technical drawings, design, final test) are available. Data on traffic are available as well.
Monitoring Data		Visual inspections (on a three-month basis) and instrumental monitoring data are available. It is expected to integrate the current monitoring systems with structural health monitoring and geotechnical monitoring for the objectives of the validation.
Maintenance Data		Maintenance interventions programming depends on the condition level assessed during surveillance and monitoring activities both for bridges and slopes.
Usage conditions		The highway is subject to a heavy traffic of goods and passengers all over the year.
Test		The Project outcomes will be tested and validated: o as input to the choice and design of the best technical preventative maintenance solutions. o as control of the territory and of the highway (evaluation of risk). o for the safety of the users (alerts and management of events). The outcomes will be applied both to the entire stretch and to 1-2 bridges and slopes in order to plan future maintenance interventions and set procedures for management of events.

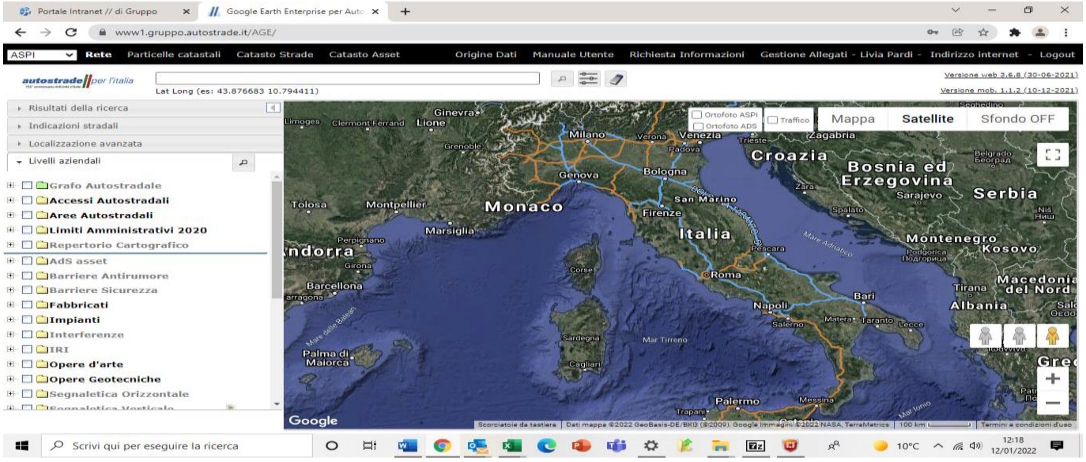


Figure 92. Company's network

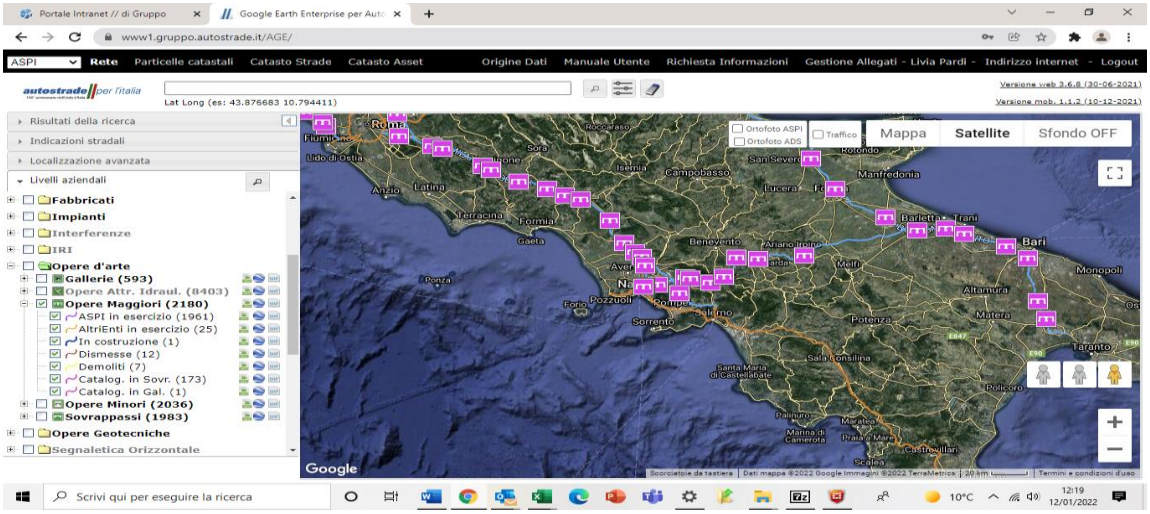


Figure 93. A16 from Naples to Bari

Location of the bridges as from AGE_Autostrade Google Earth

Figure 94. Area of interest around km 97-99

ANNEX 4 TEN-T EUROPEAN NETWORK

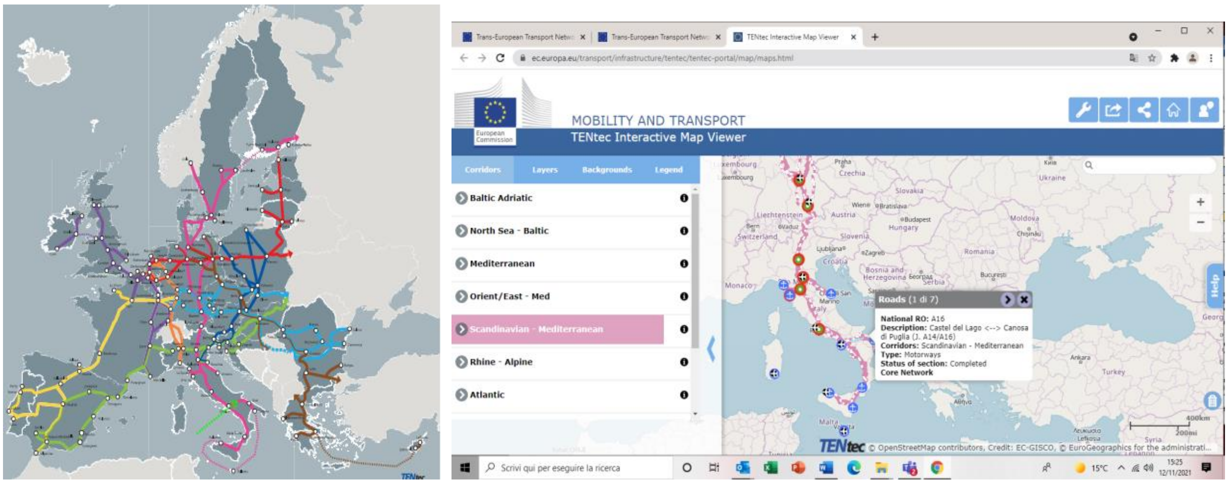


Figure 95. ***TEN-T network (https://ec.europa.eu/transport/infrastructure/tentec/tentec-portal/map/maps.html)***

Autostrade per l'Italia (ASPI) company asset covers:

- ~2.855 km of motorways
- ~ 4.300 bridges/tunnels/etc.
    - 1.943 bridges and viaducts
    - 1.799 overpasses
    - 574 tunnels (~ 350 km)

The A16 has been built in late 60's and it runs along the TEN-T Corridor n.5 Scandinavian – Mediterranean. With its 172 km., it connects Naples, on the Tyrrhenian coast, with Candela, on the Adriatic coast, playing a strategic role for the connectivity of the country.

It is considered a critical infrastructure.

The EC understand as critical infrastructure an asset, system or part thereof located in Member States which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact in a Member State as a result of the failure to maintain those functions.

ANNEX 5 REVIEW OF DELIVERABLES

	T 3.3	Sustainable Drainage System	CEM	
	T 4.3	Development of algorithms for the selection and definition of efficient and optimal actions	ETH/CEM	
	D 3.5	New Family of PA-pavements	UC	√
	D 3.6	Smart & Integral slope stabilization system	UC	
	D 4.4	SHM Algorithms	TEC	

Table 38. CS#2, Foresee Tools

Porous mixtures, which we identify as draining bituminous conglomerates with high percentages of voids, made solely with modified bitumen, have been in use in Italy since the 90's of the last century. Limiting itself to the ASPI network, about 80% is made with porous asphalt.

Exceptions are mountain sections and / or sections with high slopes in consideration of the sections where there are criticalities in the management of winter operations.

The know-how of ASPI on these mixtures (common today to all Italian managing bodies) as far as it concerns design, construction and performance in extreme climatic conditions, as well as the susceptibility to aggressive agents, can be considered consolidated and in line with the recommendations resulting from what is described in the document.

The report includes the results of an experiment focused on the development of a new type of porous mixture capable of providing a higher void content than the traditional ones (i.e., 18%-20% minimum) upon an adequate level of structural capacity (durability).

The mix design comprises the use of fibres and additives whose effects are tested for: voids content (total and interconnected), particle loss, moisture sensitivity, binder drain down, permeability, freeze and thaw, and resistance to fuel speels. Aside from fibres and additives, also the effects of binder type, binder content and aggregate gradation were considered in the study. Results are analysed through Design of Experiments (DOE) principles and multi-Criteria selection of materials and parameters.

Overall, the experiment is wide and well planned in all the details; furthermore, the analysis of the results is critical and robust. Some detailed comments are given as follows:
In Chapter 2 Materials and Methods, the paragraph on bitumen could be integrated with the indication of the main types of polymer used for the production of modified bitumen and a paragraph could be added relating to the aggregates use

ANNEX 6 DESCRIPTION OF THE GNSS MONITORING SYSTEM

The bridge monitoring system applied is GeoGuard (www.geoguard.eu), an innovative end-to-end service for the continuous monitoring of critical infrastructure and natural hazards.

The sensing infrastructure is based on mass-market hardware technology consisting of cost-effective GNSS (Global Navigation Satellite System, including Galileo) antennas and receivers. GeoGuard provides 3D displacement measurements of points on the infrastructure, or on the area subjected to natural hazards (e.g. a landslide), with accuracies of few millimeters in near real-time (sub-daily solution of 1 or 2 hours), or of the order of one millimeter or less for daily solutions (in a situation of unobstructed sky visibility from the GNSS antenna).

Measurement accuracy is computed by mathematical methods and state-of-the-art software specifically developed for the purpose, that allows to reach a high level of accuracy using low-cost GNSS technology and to implement customized solutions for each specific application.

These measurements allow us to better monitor the infrastructure health status, to make the right decisions in time to prevent structural failures, to optimize maintenance operations and to evaluate the impacts of natural events like landslides, earthquakes, and failures that can affect infrastructure stability.

Customized alert thresholds calibrated on the specific case study can be defined to notify alarm situations by e-mail or sms. Moreover, GeoGuard has been designed to guarantee maximum versatility: it is capable to integrate and manage other sensing instruments (like barometers, thermometers, accelerometers, etc.) that are useful to have a more complete overview of the stability conditions of the infrastructure or natural risk to be monitored.

GeoGuard system is composed of the two following components:

- the monitoring units (GMU), composing the survey infrastructure. It is based on a newly designed low-cost GNSS receiver and can integrate additional services gathering environmental measurements like temperature, barometric pressure, humidity, etc., or other displacement measurements as accelerometers, inclinometers, etc. It is mainly equipped with a single or dual frequency GNSS receiver and a bi-directional communication system; the unit connects one to two GNSS antennas installed on the monitored points. The antenna can be installed at a maximum distance of 50 meters from the receiver;
- a cloud-based service: the computing data center where the software platform runs. There are four software modules:
  - sensing infrastructure interface, that collects the GNSS and other sensors raw data;
  - remote GMU management, that provides all the information needed to manage the service;
  - data processing, tailored to best exploit low-cost GNSS receivers and devoted to performing statistical and quality analyses of input observations and output results;
  - end-user service interface that exposes the information to customers by a web browser, a dedicated app, or direct data transfer.

GeoGuard is intended to be a turnkey service since considers all steps requested to deliver the solution.
The GeoGuard service model can include the following modules:

- preliminary inspection of the site to be monitored, to design the most appropriate solution;
- sensing infrastructure delivery and deployment, according to the site characteristics;
- connectivity set-up between the sensing infrastructure and the data processing center (GeoGuard Cloud);
- GeoGuard Cloud, the central system that collects and organizes the data, checks the data flow integrity, performs the positioning data processing, and analyses the results;
- help desk service, to support the customer in the day-by-day operations;
- professional services: to build customized solutions according to technical requirements.

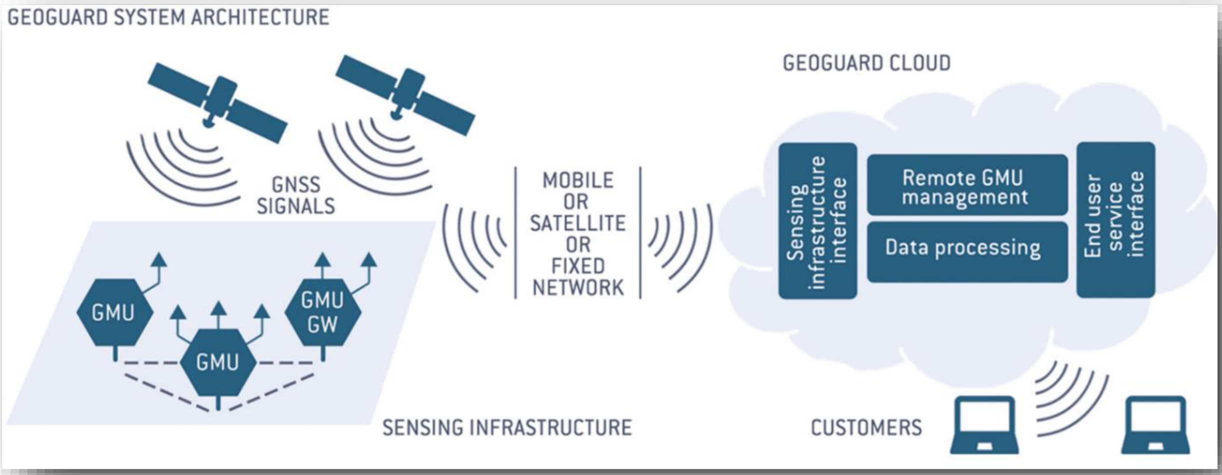


Figure 96. System architecture

SENSING INFRASTRUCTURE

The sensing infrastructure is composed of an array of GMU permanently installed at the object to be monitored that gathers and transmits data to the GeoGuard Cloud. The GNSS antennas are connected to the GMU and are installed on the points subject of the monitoring, which require as much unobstructed sky visibility as possible to track the highest number of GNSS satellites in an environment as much as possible free of GNSS signal disturbances. It should be noticed that, in order to reach the highest accuracy in the determination of the position of the points, GeoGuard applies the so-called 'differential positioning', where the position of one point is computed relatively to the known position of a reference one.

PROCESSING STRATEGY

Depending on the choice of single or dual-frequency receivers, two different processing schemes can be used to compute the positions of the points of interest.

RELATIVE POSITIONING

Typically, an additional antenna (Local Master) is installed near the object to be monitored in a location that is not subject to the same phenomenon that is under investigation. In this way, the position of the points to be monitored is computed with respect to the local master point (Local reference frame); the accuracy depends on the baseline length: to achieve an accuracy of one millimeter per day, the baseline should not be longer than 2-3 km for single frequency receivers. It is possible also to deploy a sparser GNSS network, but the use of dual-frequency receivers is in this case mandatory to compute the positions of interest with such accuracy. The local master point stability can be in turn monitored by using the GNSS data of other GNSS permanent stations (CORS: continuously operating reference station, Global Master in the following) belonging to open networks that freely publish their data (Global Reference Frame); the accuracy depends on the distance between the local master antenna and the reference CORS.

Furthermore, positioning results can be expressed in the ENU reference system or another one useful for the final user.

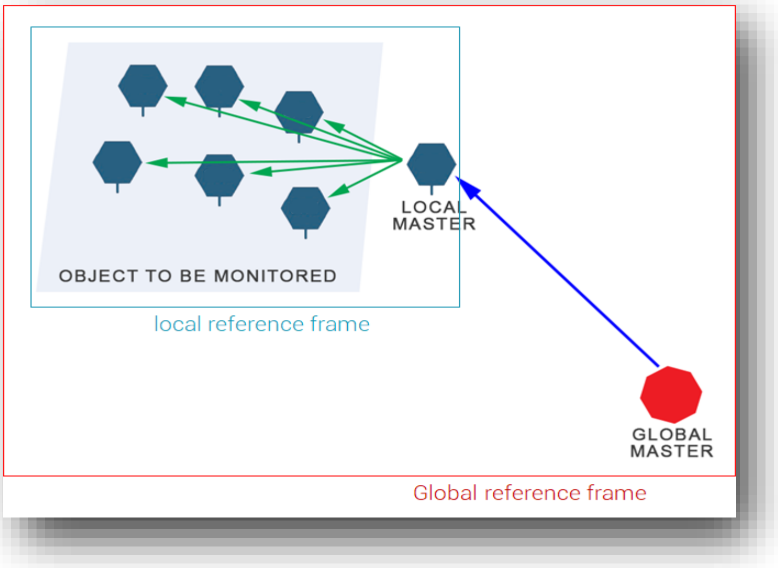


Figure 97.-Processing strategy.

If for any reason it is not possible to define and install a local master point, a relative positioning is still possible by using the Global Master receiver as Local Master. In this case, the use of at least one dual-frequency receiver on the object to be monitored is strongly recommended. If for any reason a Global Master is not available, the positioning can be performed by means of the so-called Precise Point Positioning.

Precise point positioning

With this type of processing each GNSS receiver is independently considered when computing the point position, without relying on a local master point and on the relative positioning.

This processing scheme requires the use of dual-frequency GNSS receivers: it can be useful if the final user is interested in only one point or if there are no stable points in the surroundings; moreover, it is useful if the final user, given a fixed number of GMU, would like to monitor several critical areas far from each other, avoiding to leave vast portions of territory uncovered. Within this computational framework, the precision in the determination of coordinates is worse than the relative positioning one, but still acceptable for most of the monitoring applications. Moreover, thanks to the precise point positioning processing, GMUs can be used for the reliable and continuous monitoring of atmospheric water vapor with high horizontal resolution. Since water vapor is one of the key ingredients involved in cloud and rain formation processes, continuous information on it is essential to improve the prediction of heavy rain and thunderstorms.

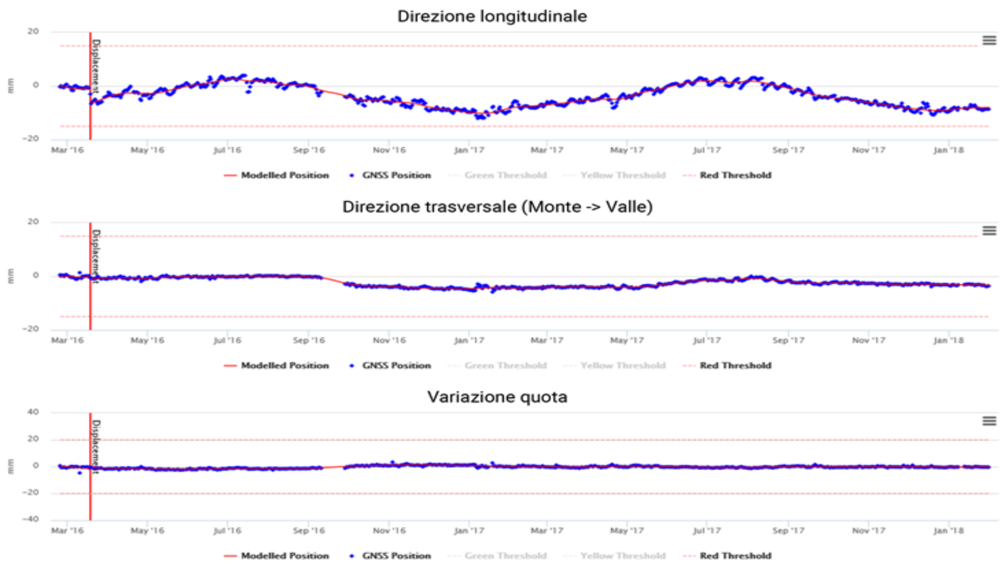


Figure 98. Example of time series of coordinates of a monitored point expressed in a custom reference frame

GEOGUARD MONITORING UNIT (GMU)

A GMU is a remote terminal unit specifically designed to operate in challenging environments. It can accept different power sources, such as AC, DC, and photovoltaic, and can be equipped with a backup battery. Moreover, a GMU establishes a bi-directional communication with the GeoGuard Cloud, allowing a direct link to remotely manage the receiver.

A GMU is composed of:

- microprocessor module: cortex-A7. The operative system consists of a Linux embedded environment, useful also for edge-computing computations;
- communication module: MQTT communication module; different technologies, such as Ethernet, GSM/UMTS (2G/3G); M2M with radio link at 868 MHz; if needed LoRaWAN communication module to communicate with other sensors;

- positioning module: up to four GNSS receivers (GPS+GLONASS+GALILEO) with a maximum acquisition rate of 1 Hz, a 3-axes MEMS accelerometer useful to verify the stability of the GMU box, an internal temperature sensor to check the heat condition of the system;
- survey module: a series of digital and analogic I/O ports and an industry-standard communication bus to connect external devices (PT100, RS485). A GMU can work also as a hub to gather data from external sensors;
- power modules: AC, DC power source. It is also possible to include a backup battery to keep the receiver on even if there is a lack of external power source (up to a few days), additionally allowing the continuous monitoring of the power supply itself.

A schematic example of a GMU is shown in the next figure:

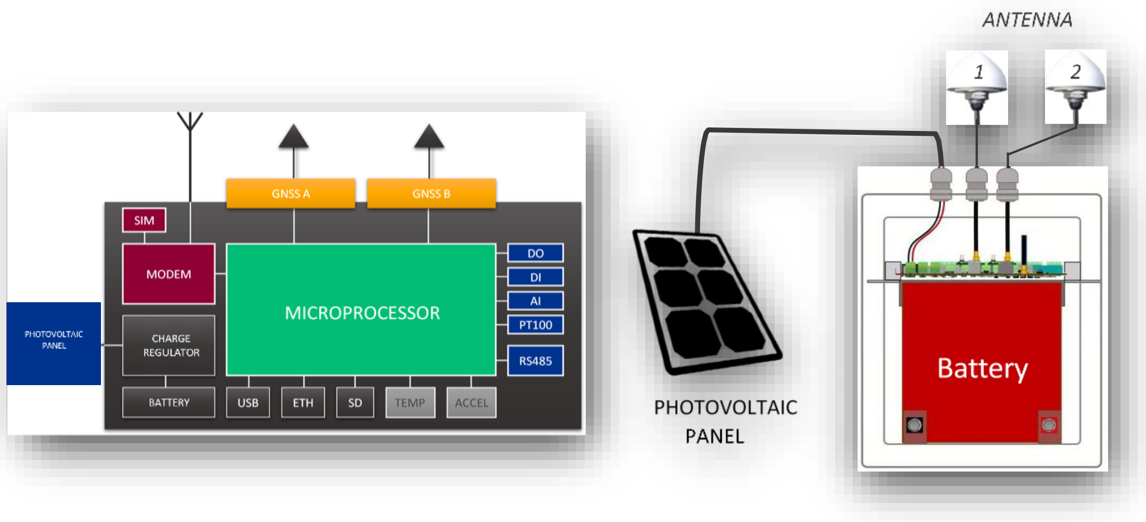


Figure 99. Schematic representation of the GMU

CONNECTIVITY
GMU have great flexibility as regards the transmission of data to the GeoGuard Cloud, being enabled for transmission via Ethernet, GSM / UMTS, or satellite connection. Moreover, a GMU can manage intelligent local mesh networks for connection via GMU with a radio link. Each GMU can also play the role of concentrator and repeater with the sole function of collecting and transmitting the data collected by the other units when they are unable to access a global communication network (absence of GSM / UMTS signal).

GEOGUARD CLOUD
The GeoGuard Cloud is the core component of the GeoGuard service: it receives and processes the data from the GMU and delivers the results to the user. It is composed of the following functionalities:

- Sensing infrastructure interface: interface with the sensing infrastructure that receives raw data and telemetry and allows the remote management of the GMU;
- Remote GMU management permits the remote GMU control in order to change the configuration, update the systems, perform diagnostic examinations, etc.
- Data processing: the data processing is designed to obtain the best results from the GNSS receivers through specifically designed proprietary algorithms. GeoGuard uses two software applications to guarantee the reliability of the solution: the well-known international standard Bernese Software 5.2 and Breva (proprietary software). At the end of every processing session (daily and/or sub-daily) data and results are deeply analyzed in order to identify discontinuities greater than user-defined thresholds, trends, problems, data quality deterioration that are highlighted by early warnings messages;
- End-user service interface: to publish data and results in different modes depending on the user needs:
    - a web application (https://www.cloud.geoguard.eu) that allows users to visualize the results in a reserved area on the web, download PDF reports, datasheets, …
    - a series of REST APIs, that allow accessing the numeric results for easy integration with the information systems of the users,
    - early warning notification via SMS or email, in case of anomalies.

Figure 100 shows examples of the products generated by the GeoGuard Cloud: interactive maps, trend estimates, graphs reporting the time series of coordinates, customizable threshold alerts, automatic reports generation, data exporting tools, etc.

Figure 100. Examples of products generated by GeoGuard Cloud.

ALARMS AND ALERTS

At the end of each computation session (with a frequency of 24h, 02h, or 01h), an automatic data analysis system identifies any movements in the position of the monitored points. In particular, it is raised:

- a WARNING, if the last calculated position differs from the previous position (calculated as the average of the last 10 previous positions) in a statistically significant way, for a value beyond the threshold defined in the GeoGuard portal;
- an ALERT, if the last two calculated positions deviate in a consistent and statistically significant way from the previous position (calculated as the average of the last 10 previous positions), for a value beyond the threshold defined in the GeoGuard portal.

SELECTED PUBLICATIONS

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- Šegina E., Peternel T., Urbančič T., Realini E., Zupan M., Jež J., Caldera S., Gatti A., Tagliaferro G. , Consoli A., Reyes González J., Jemec Auflič M., Monitoring Surface Displacement of a Deep-Seated Landslide by a Low-Cost and near Real-Time GNSS System. Remote Sensing, 2020

Awards

- European Satellite Navigation Competition 2015
  Issuer: Anwendungszentrum GmbH Oberpfaffenhofen & GNSS Research & Applications Centre of Excellence; The Netherlands Space Office (NSO)
- Double Winner: University Special Prize and The Netherlands Regional Prize.
  Project title: GNSS Monitoring of Precipitable Water Vapour over East Africa Using Low-Cost Receivers
  Authors: Nick van de Giesen, Eugenio Realini
- March 2015 – GReD was awarded the H2020 SME Instrument Phase I funding, to develop a complete business plan that will bring GeoGuard to industrial maturity.
- June 2015 – GReD, with the GeoGuard service, was among the 20 SMEs selected by the H2020 JUPITER project to participate to the EGNSS Village at the ITS Bordeaux 2015.
- September 2015 – GReD and GeoGuard received the Keys to Japan award by the EU-Japan Centre for Industrial Cooperation to develop a business plan to introduce GeoGuard in the Japanese market.
- February 2016 – GReD was selected by the H2020 e-Knot project to receive consultancy from an academic institution on the topic of designing a Galileo E1/E5a dual-frequency software receiver. The consultancy will be beneficial to both GReD and Saphyrion in the framework of their EDWIGE project.
- Funded R&D projects
- 2020 – 2022
- SINOPTICA (Satellite-borne and IN-situ Observations to Predict The Initiation of Convection for ATM) – H2020 project – Consortium partner
- 2018 - 2019

- STEAM (SaTellite Earth observation for Atmospheric Modelling) – ESA project – Sub-contractor
- 2018 - 2020
- LAMPO (Lombardy-based Advanced Meteorological Predictions and Observations) – Fondazione Cariplo project – Sub-contractor
- 2018 - 2021
- TWIGA (Transforming Water, Weather, and Climate Information through In-situ Observations for Geo-services in Africa) – H2020 project – Consortium partner
- 2017 - 2020
- GIMS (Geodetic Integrated Monitoring System) – H2020 project– Project Coordinator
- 2016 – 2018
- EDWIGE (Early Detection of Water-vapor Instabilities by GNSS Estimation) – EUROSTARS EUREKA project – Consortium partner
- 2016 - 2019
- BRIGAID (Bridging The Gap For Innovations In Disaster Resilience) – H2020 project – Consortium partner
- 2017 – 2019
- POR FESR 2014-2020 Asse 1 – September 2016, settore Sicurezza e Monitoraggio del Territorio: Prevenzione e gestione di disastri naturali ed emergenze

GeoGuard: declarations and certifications

POLITECNICO
MILANO 1863

POLO TERRITORIALE DI COMO

Como, October 29th 2015

The undersigning Giovanna Venuti and Ludovico Biagi, members of the Geomatics and Earth Observation laboratory (GEOlab) of the Politecnico di Milano, Polo Territoriale di Como, declare to be aware of theoretical, numerical and technological methods and results, applied by GReD to the local geodetic monitoring by low-cost GNSS receivers, known as GeoGuard method. We believe that the method proposed is at the edge of international achievements on the topic and in particular, that the daily accuracy and repeatability, as provided by GReD, are reliable; these have typically a standard deviation between 1 and 3 mm, depending on enviromental conditions.

In faith

Prof. Giovanna Venuti
(scientific responsible for GEOlab)

Prof. Ludovico Biagi

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DIPARTIMENTO DI INGEGNERIA
CIVILE EDILE E AMBIENTALE

SAPIENZA
UNIVERSITÀ DI ROMA

Roma, November 25, 2015

Dr. Eng. Stefano Caldera (CEO)
GReD - Geomatics Research & Development srl
c/o ComoNExT
via Cavour 2
22074 Lomazzo (CO)

DECLARATION

I undersigning Mattia Giovanni Crespi hereby declare to duly know the theoretical, numerical and technological results and methods applied by GReD to the local geodetic monitoring through low-cost GNSS receivers, known as GeoGuard method.
I do believe that the proposed method is at the edge of international achievements on this topic; in particular, I feel quite reliable the results related to the daily accuracy and repeatability as provided by GReD; these results show a standard deviation within 1 and 3 mm, depending on the enviromental conditions.

Yours faithfully,

Mattia Giovanni Crespi

Prof. Mattia Giovanni Crespi
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TECHNICAL SPECIFICATIONS

Annex 2 -GEOGUARD MONITORING UNIT (GMU)

GNSS - GeoGuard Monitoring Unit (GMU)	
Box	Gewiss IP66 GW46001F (250 x 300 x 160 mm)
Power supply	**220VAC:** - Power supply via AC / DC 220VAC / 24VDC - 20W with buffer battery (24Ah) - 24VDC / 1.5A - 20W power supply with buffer battery (24Ah) - 12VDC / 1A power supply **PV:** - Powered by 30W-50W-80W photovoltaic panel based on the configuration and interfaces used with 24Ah battery - Integrated 6A MPPT charge controller
CONSUMPTION (GMU Base)	**MEDIUM:** 1,5-2W **MAXIMUM:** 5W
GNSS tracking modules and antenna	**Double Frequency:** **u-blox ZED-F9T** Acquired signals: L1C/A, L2C, L1OF, L2OF, E1B/C, E5b, B1I, B2I; GPS/QZSS, GLONASS, GALILEO, BeiDou constellations **Tallysman Antenna TW3882:** - Architecture: Ciruclar, Dual Feeed, Dual stacked patch - Dimensions: 66.5mm diameter - Weight: 185g - Case: Radome: EXL9330, Base: Zamak White Metal - Fixing: Through hole (M18 x 1 thread) - LNA Gain: 35dB min. - Noise: 2.5 dB typ. - Axial Ratio at Zenith over full bandwidth: <1dB typ. ≤1.5dB max **Single Frequency:** **u-blox NEO-M8T** Acquired signals: GPS L1C/A, SBAS L1C/A, QZSS L1C/A, QZSS L1 SAIF, GLONASS L1OF, BeiDou B1, Galileo E1B/C) **Tallysman Antenna TW3740:** - Architecture: Dual, quadrature feeds - Dimensions: 66.5mm diameter / - Weight: 150g - Case: Radome: EXL9330, Base: Zamak White Metal - Fixing: Through hole (M18 x 1 thread) - LNA Gain: 40dB min. - Noise: 1 dB typ. - Axial Ratio at Zenith over full bandwidth: <2dB typ. ≤3dB max - Acquisition rate: >= 1 sec - GNSS RAW data format: ubx, RINEX
Transmission module	**SARA- U201** 3G UMTS/HSDPA/HSUPA Modem 800/850/900/1900/2100 mhZ 19,5,8,2,1 Bands

Module Processor	**Microprocessor Cortex-A7 core up to 528 MHz** - DDR3L SDRAM 4Gb, 256Mx16, 933MHz - QSPI NOR 256 Mb - Micro Secure Digital - Modem 3G (PCB 4G READY) con uSIM - N.1 Ethernet - RJ45 - N.1 Porta USB + N.1 USB Console - N.1 Serial Line RS485 - N.4 Analog Input - N.1 PT100 Input (2-3-4 fili) - N.2 Digital Output - N.2 Digital Input

END USER SERVICE INTERFACE

End user service interface	
REST API	
Data and results	- RINEX observation file; - positions computed in several modes and reference systems; - time series modelling; - GMU telemetry; - GMU metadata; - data of external sensors.
Ways of access	several levels for user access, several user roles (administrator, read only, alarms viewer, etc.)
WEB Application	
Architectures	- cloud platform; - based on microservices; - highly scalable; - trusted and verified access; - SSL cryptography.
Web address	https://cloud.geoguard.eu
Features	Queries: - Monitored sites - network status - GMU management - alarms - global map
Position data viewer options	- date range - modes (relative, absolute) - solution frequency - reference system - reference point (local master)
Position data viewer information	- role, type, power supply type, alert thresholds, - movements summary - detailed graphs of the time series - models overlay
GMU management	- information about the monitored points; - localization; - alarms; - telemetry:

	- energetic balance; - battery voltage; - battery level; - solar radiation; - external temperature; - data transfer rate; - uptime time - memory usage; - CPU usage; - modem traffic; - number of satellites; - GNSS samples collected.
Export	- reports in PDF format; - data and results in .csv format; - data and queries on results via API REST

GNSS DATA PROCESSING

GNSS data processing	
Input GNSS data format	Ublox UBX, Rinex 2, Rinex 2.11, Rinex 3.0
GNSS data sampling rate	>= 0.1 sec
Frequency of the processing solution	1h, 2h, 6h, 24h
Processing mode	Post-Processing in relative mode, PPP
Management software	Breva geodetic processing engine
Pre-processing software	Breva geodetic processing engine
Processing software	-Bernese GPS Software 5.2 -Breva geodetic processing engine
Data/ancillary products used	- GNSS orbits and clocks (broadcast, ultra-rapid, rapid, final) - Ocean Loading correction - data from external CORS - IGS/EPN Sinex Solution - regional ionospheric maps - ATX phase center offset / variation
Ambiguity resolution strategies	ROUND, SIGMA, QIF, LAMBDA
Derived product	Coordinates (SINEX format), ZTD/ZWD/PWV (SINEX format)
Precision (rms) single base (~1km)* (* values with optimal sky visibility)	24h solution: Horizontal ±0.5mm, Vertical ±1mm 02h solution: Horizontal ±1mm, Vertical ±2mm 01h solution: Horizontal ±1.5mm, Vertical ±3mm
Reference systems	Global (ECEF, geographic, UTM), Local (ENU, user defined)
Interpolation models of time series	Mean, Linear, Cubic spline, Frequency analysis