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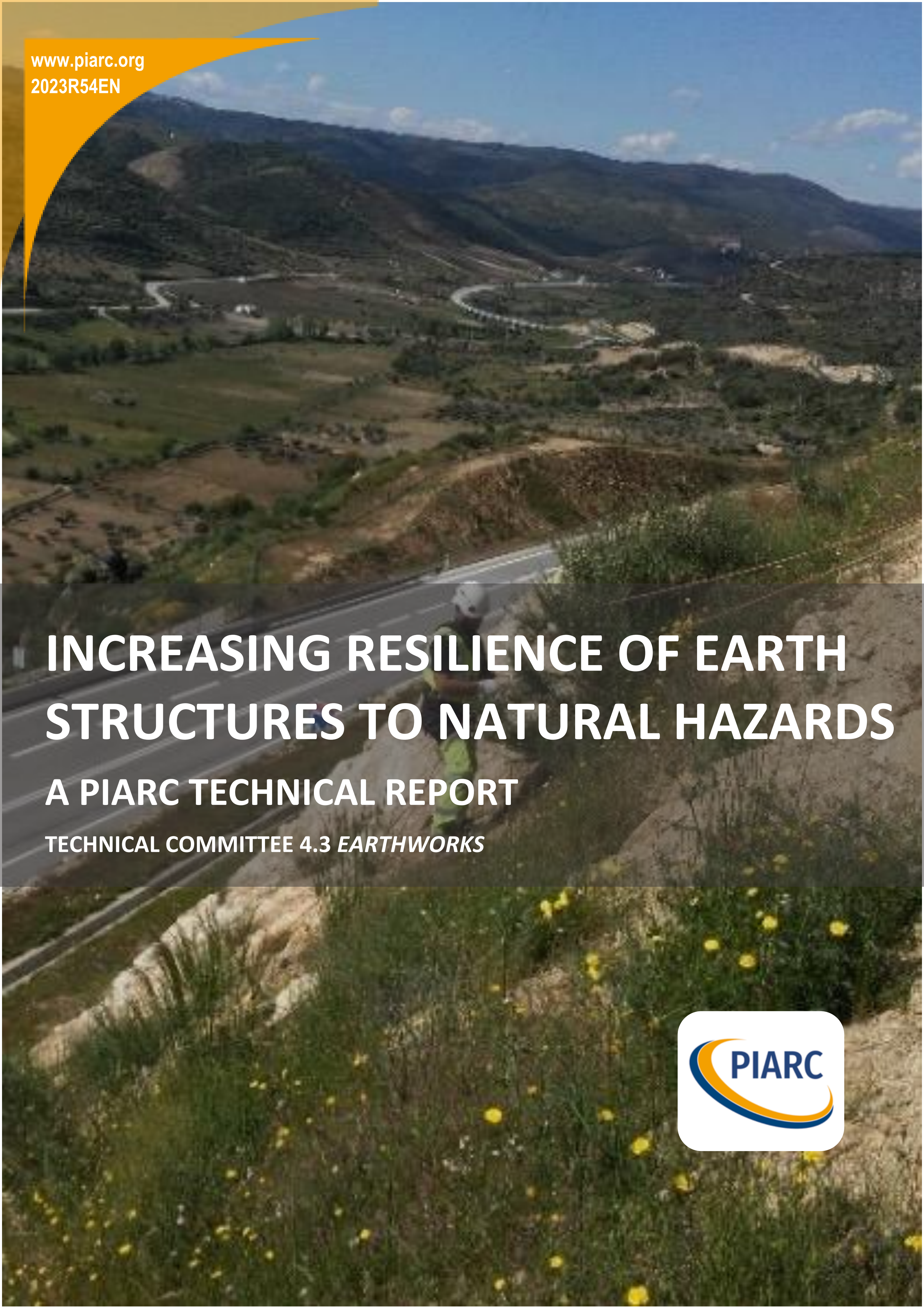

INCREASING RESILIENCE OF EARTH STRUCTURES TO NATURAL HAZARDS

A PIARC TECHNICAL REPORT

TECHNICAL COMMITTEE 4.3 *EARTHWORKS*

STATEMENTS

The World Road Association (PIARC) is a nonprofit organization established in 1909 to improve international co-operation and to foster progress in the field of roads and road transport.

The study that is the subject of this report was defined in the PIARC Strategic Plan 2020–2023 and approved by the Council of the World Road Association, whose members are representatives of the member national governments. The members of the Technical Committee responsible for this report were nominated by the member national governments for their special competences.

Any opinions, findings, conclusions, and recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of their parent organizations or agencies.

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AUTHORS/ ACKNOWLEDGEMENTS

This report was prepared by Working Group (WG) no. 1 of the World Road Association’s (PIARC) Technical Committee (TC) 4.3 on “Earthworks” during 2020-2023 cycle. In that period, TC 4.3 was chaired by Patrick Boisson (France). Yasmina Boussafir (France), Paul Nowak (United Kingdom) and Natalia Pérez (Mexico) were the French, English and Spanish Secretaries, respectively. The scope of WG1 was focused on the topic “Increasing Resilience of Earth Structures to Natural Hazards” outlined in the 2020-2023 Work Program for TC 4.3.

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EXECUTIVE SUMMARY

2023R54EN

INCREASING RESILIENCE OF EARTH STRUCTURES TO NATURAL HAZARDS

A PIARC TECHICAL REPORT

This report provides a complete background on the topic of "Increasing Resilience of Earth Structures to Natural Hazards" assigned to WG1 of PIARC TC 4.3 as part of the 2020-2023 Work Program. This topic has been developed as part of the 2020-2023 Work Cycle and is complemented by two additional documents for this topic: a Case Studies Report and a Literature Review Report.

The production of this report was carried out in multiple phases. The first phase involved a cursory review and selection of relevant documents from the literature that address, directly or indirectly, the concept of resilience. The selected documents address the concept of resilience in various ways, from the most general meaning of the concept to its specific application in road infrastructure.

In a second phase, relevant case studies related to resilience in earth structures, collected among members of PIARC TC 4.3, have been analyzed using a common framework, to identify which are the most common hazards that are currently affecting earth structures, what is the most common damage they suffer due to these impacts and which are the most commom measures that are applied to repair or to adapt these assets.

As a result of this WG1 final review, it was concluded that resilience is a concept that can be applied to earth structures taking into account the whole life cycle of the assets, starting from the inception (design phase) up to construction and management. Specific directions and recommendations have been identified and their application was discussed together with relevant examples taken from cases.

In order to serve its function as background and reference for the resilience concept as applied to earth structures, recommendations and conclusions have been provided in Chapters 10 and 11 of the document.

CONTENTS

1. INTRODUCTION

This report deals with the concept of resilience for earth structures. This work continues the task started in the previous deliverables for WG1 of PIARC TC 4.3 (2021LR04EN – "*Increasing Resilience of Earth Structures to Natural Hazards – A PIARC Literature Review*" ref. [1] and 2022R21EN – "*A PIARC Collection of Case Studies Report*" ref. [2]).

The aim of the report is to obtain a better knowledge of how resilience can be improved, considering specifically earth structures and focusing on natural hazards, through the analysis of:

- The type of earth structures that are currently most affected by natural hazards.
- The most common natural hazards that are currently affecting earth structures.
- The most common damages resulting from these disruptive events.
- The type of measures to implement following such events.

The document is organised into different chapters, as follows:

- A clarification of the concepts of **"earthworks"** and **"earth structures"**, which are the main focus of PIARC TC 4.3, so that the reader can have an accurate understanding of the exact meaning of these concepts, in the sense in which they are used in this report.
- A brief reminder of the definition of "resilience of earth structures". Although a standard definition of this concept has not yet been reached within our TC, the main common characteristics of this concept which have been identified are explained.
- A brief explanation of the **methodology** used ifor its preparation, presenting the survey distributed as a request for the case studies.

2. EARTHWORKS AND EARTH STRUCTURES

As a starting point, it is important to identify earth structures that are the focus of the present study.

An earth structure, as it is defined, for instance, in the European Standard EN-16907, is a *"civil engineering structure, made of soils, rocks, by-products or recycled materials, resulting from earthworks (cut, fill, infill)»*.

Earth structures are, therefore, finished products which are the result of a completed earthworks process (i.e. a cutting or an embankment). In Figure 1 different examples of earth structures that can be present on a modern motorway are illustrated.

Figure 1. Examples of different earth-structures in a modern motorway

Earthworks, as they are defined in the European Standard EN-16907, are the result of a "civil engineering process that modifies the geometry of ground surface, by creating stable and durable earth-structures".

In this sense, earthworks include excavation, loading, transport, transforming/improving placement, stabilisation and compaction of natural materials (soils, rocks – fig. 2), by-products or recycled materials in order to obtain stable and durable cuttings, embankments or engineered fills (i.e. earth structures), with prescribed properties, for road construction and maintenance. Earthworks require planning, design, construction and maintenance. They depend on the properties on the materials, the required properties of the structure and the environment.

To summarise, earthworks are the whole procedure and techniques that are necessary to design, build and maintain earth structures.

Figure 2. Excavation (top), compaction

2.1. DESIGN

For earth structures, "design" refers to the selection of the properties of the fill materials and the specification of requirements for the earthworks construction process to ensure that the completed earth structure complies with the geotechnical design. In Europe, the design of earth structures, with regard to stability and deformations, is regulated by EN 1997 (Eurocode 7) and other relevant national standards.

Geotechnical and structural designs generate the requirements for the properties and functionality of the final structure (e.g. geometry, stiffness, load-bearing capacity, permeabilility).

The description, identification, classification and characterisation of soils, rocks and other fill materials are an essential part of the design of earthworks. They yield the necessary information to determine the nature of each material, the optimum method of removing that material from excavations or cuttings, the final state it may reach after compaction and the most effective means to achieve this final state.

Geotechnical site investigations for an earth structure project shall provide adequate and sufficient information for the design and construction process of the new structure. Guidance is given by EN 1997-2 with respect to depth and frequency of investigation. This information should cover the design of the completed structure and of the temporary slopes and structures created during the construction works. The geotechnical model will cover the zone of influence of the structure, for both mechanical and hydrological/hydrogeological analyses (fig. 3).

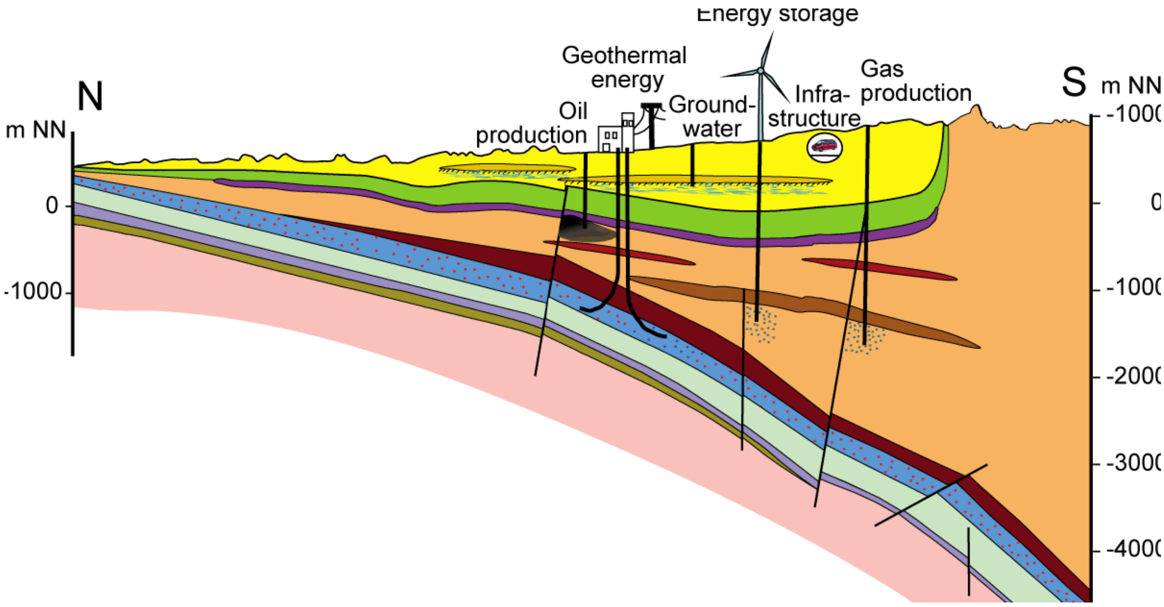


Figure 3. Example of a geotechnical model tailored to specific design requirements

Design consists of "defining the process" for transforming in situ natural soil (earth or rock) and/or by-products or recycled materials into a stable, durable embankment with the required properties, or into a stable cut. This decision-making process involves the characterization of the natural soil, the selection of the appropriate equipment and the regulations for planning the extraction, transport, compaction and control of the materials. The outputs of this design process include risk assessment reports, implementation plans, work schedules, workflow schemes and so on. These requirements can be met by experience-based recommendations or by performance-based design. All the standards on earthworks assume that the earth structure (i.e. the embankment or the cutting) to be built has been properly designed.

2.2. CONSTRUCTION

Construction of earth structures should be carried out by general contractors that have expertise in civil engineering and may be specialised in this particular type of infrastructure. The work should be managed from design to completion by experts working in collaboration, when necessary, with specialists in equipment.

Sufficient quality-assurance testing on materials should be carried out during works in order to guarantee their quality and characteristics fully comply with the project documents.

In some countries, a final technical testing may be required in order to check that the whole process has been carried out in compliance with design requirements. This final technical testing is to be carried out by technicians acting as a third part, other than designer and contractor, in order to guarantee its impartiality.

2.3. MAINTENANCE

Maintenance includes all routine recurring works required to keep a structure in such condition that it may be continuously and safely used, at its original designed capacity and efficiency for its intended purpose.

3. DAMAGE TO EARTH STRUCTURES

Due to their nature, earth structures are particularly sensitive to external actions. Referring to case studies collected (see 2022R21EN – "*A PIARC Collection of Case Studies Report*", ref. [2]), most of earth structures damage is related to hydro-meteorological events: extreme rainfall events, flash floods, increasing sea level/storms and increasing internal water content in the earth structures and the substrate. This is also consistent with the data extracted in Literature Review (2021LR04EN – "*Increasing Resilience of Earth Structures to Natural Hazards – A PIARC Literature Review*", ref. [1]).

In any case, many hazards can affect earth structures and create damage, such as water action, wind erosion, gravity (inducing soil instabilities and landslides), earthquakes. Temperature variations can have effects on particular soils, as described in [2] for a case from Benin.

3.1. WATER ACTION

The action of water is to be seriously considered, as running water has a destructive effect on earth structures (fig. 4). The identification of the meteorological, hydraulic, or hydrogeological hazards and their consideration in the design of earth structures is, therefore, of the utmost importance.

Figure 4. Effects of water action on earth structures

3.2. Wind Erosion

Soil erosion caused by wind is produced by the tangential action generated by the movement of air against the soil (fig. 5). This action is much more dependent on soil characteristics and soil surface conditions than it is in the case with water.

The presence of ground "roughness" (obstacles of various sizes such as houses, trees, bushes, etc.), significantly reduces this action and therefore erosion. As a result, soils with low cohesion and low coverage (desert soils, alluvial plains, coastlines) are the most susceptible to this type of erosion.

Wind erosion (and consequent deposition) phenomena up to 1 mm/year have been recorded in soils of this type.

Dust storms are generated by strong winds and may cause additional damages apart of soil erosion and/or deposition (fig. 6).

Figure 5. Effects of wind action on earth structures (Morocco)

Figure 6. Dust storm (USA)

3.3. Gravity

Gravity is the primary driving force for a landslide to occur. Landslides are typically triggered by a specific event, such as heavy rainfall, earthquakes, anthropic slope modifications (cuts, embankments), raising of water table. Landslides occur under a wide range of forms and magnitudes: even small-magnitude landslides are able to completely destroy earth structures (fig. 7, 8, 9).

Landslides occur when the slope (or a portion of it) undergoes a process that renders its condition from stable to unstable. This is essentially due to a decrease in the shear strength of the slope material, an increase in the shear stress endured by the material, or a combination of the two. A change in the stability of a slope can be caused by a number of factors, acting together or alone.

In 1978, geologist David Varnes (ref. [3]) developed a classification system for mass movements and subsidence processes, which is still in use to this day as illustrated in the following table 1.

Figure 7. Embankment completely destroyed by a landslide (Southern Italy)

Figure 8. Huge landslide (Canada)

Figure 9. Highway cut by a landslide

Type of movement	Rock	Soil
Fall	*Rock/ice* fall	*Boulder/debris/silt* fall
Topple	Rock block topple	*Gravel/sand/silt* topple
	Rock flexural topple	
Slide	Rock rotational slide	*Clay/silt* rotational slide
	Rock planar slide	*Clay/silt* planar slide
	Rock wedge slide	*Gravel/sand/debris* slide
	Rock compound slide	*Clay/silt* compound slide
	Rock irregular slide	
Spread	Rock slope spread	*Sand/silt* liquefaction spread
		Sensitive clay spread
Flow	*Rock/ice* avalanche	*Sand/silt/debris* dry flow
		Sand/silt/debris flowslide
		Sensitive clay flowslide
		Debris flow
		Mud flow
		Debris flood
		Debris avalanche
		Earthflow
		Peat flow
Slope deformation	Mountain slope deformation	Soil slope deformation
	Rock slope deformation	Soil creep
		Solifluction

Table 1. Landslides classification from Varnes (1978)

3.4. EARTHQUAKES

An earthquake is a shaking of the Earth's surface resulting from a sudden release of energy in the Earth's lithosphere that generates seismic waves. The magnitude of earthquakes may vary, from those so low in intensity that they cannot be sensed, to those strong enough to severely damage infrastructure and devastate entire territories.

Earth infrastructure is often severely impacted by earthquakes (fig. 10), as shaking can induce forces that surpass the resistance of the materials of which the earth structure is made.

Figure 10. Effects of earthquake on a road (Japan)

3.5. OTHERS

Among other hazards we can quote groundwater level variations, seepage scouring effects, marine action, volcanic eruptions, effects of fire, deforestation, ice and snow, temperature (fig. 11, 12 and 13).

A summary of various natural hazards which can affect earth structures is presented in table 2.

Figure 11. Lungarno riverfront road collapsed behind a retaining wall due to huge sewer leakage. The famous 'Ponte Vecchio' in the distance (Florence, Italy)

Figure 12. Effect of ice on an embankment (Canada)

Figure 13. Effects on buildings of soil settlement/rising due to temperature variations (Houeyogbe, Benin)

Landslide, creep, solifluxion	   Uganda, Tunisia, Italy
Runoff, gullying, mud flow, lava flow, erosion	  South Korea, Chile
Sinkhole, settlement, large ground deformation	   Spain, Tunisia, France
Rock falls	  Portugal, France (La Reunion)
Flash floods, flooding	   Spain, Italy (centre and right)

Drought	 France

Table 2. Synopsis of damages to earth structures due to different mechanisms

4. RESILIENCE IN EARTHWORKS

Although there is no consensus on a specific definition for resilience, common ideas and themes for this concept exist and are presented by selected documents (2021LR04EN – "*Increasing Resilience Of Earth Structures to Natural Hazards – A PIARC Literature Review*" ref. [1]).

Terminology employed in describing the concept of resilience varies widely according to specific applications. (Fig. 14).

Resilience concepts	Characteristics	Focus on	Context
Engineering resilience	Return time, efficiency	Recovery, constancy	Vicinity of a stable equilibrium
Ecological/ecosystem resilience Social resilience	Buffer capacity, withstand shock, maintain function	Persistence, robustness	Multiple equilibria, stability landscapes
Social–ecological resilience	Interplay disturbance and reorganization, sustaining and developing	Adaptive capacity transformability, learning, innovation	Integrated system feedback, cross-scale dynamic interactions

Figure 14. Evolution of resilience concepts (Folke, 2006, from Djalante, 2013, ref. [4])

4.1. General definitions

General definitions for this concept are exposed:

General definition of resilience: the capability of a hazard-prone system, community or society to withstand, absorb, adapt to and recover from the impacts of a hazard in a timely and effective manner, including through the preservation and restoration of its essential core structures and functions, as defined by the United Nations International Strategy for Disaster Reduction (UNISDR - Djalante et al., 2012, ref. [5]).

- **Resilience in a system**:
  - The ability of a system to plan for, recover from and adapt to adverse events over time, as defined by USA National Academy of Science (Ientile et al., 2020, ref. [6]). In most cases, the concept is recognized to be multifaceted.
  - The ability of a system to reduce the chances of a shock, to absorb a shock capable of causing abrupt reduction of performance, and to recover quickly after the occurrence of a shock. (Marcelo et al., 2018, ref. [7]).
- **Resilience in a complex system**:
  - The ability of the system to react to perturbations, internal failures, and environmental events by absorbing the disturbance and/or reorganizing to maintain its functions.
  - A measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist.
  - The ability to absorb environmental shocks and still maintain function.
  - The ability of the system to face and adapt to change.

- A multifaceted capability of complex systems that encompasses avoiding, absorbing, adapting to, and recovering from disruption.

In the literature, resilience can be subclassified as ecological resilience, organizational resilience, engineering resilience, system resilience, and psychological resilience (Frascaccia et al., 2018, ref. [8]).

- **Engineering resilience:** Ability of a system to sense, recognize, adapt, and absorb variations, changes, disturbances, disruptions, and surprises. The ability to bounce back when hit with unexpected events. The joint ability of a system to resist (prevent and withstand) any possible hazards, absorb the initial damage, and recover to normal operation. (Frascaccia et al., 2018, ref. [8]).
- **Resilience in a transport system:**
  - The ability of assets, networks, and systems to anticipate, absorb, adapt to and/or rapidly recover from a disruptive event (Highways England, 2020a, ref. [9]).
  - The ability of assets to withstand shock in such a way that minimizes functionality losses (i.e., robustness or resistance) and asset capacity to recover functionality across multiple dimensions following a disaster event (i.e., recoverability – Onishi, 2018, ref. [10]).
- **Resilience of critical infrastructure:** a transformative, cyclical process that builds capacity in technical, social, and organisational resources for critical system function, so as to mitigate the impacts of disruptive events and long-term progressive changes, thus guaranteeing the continued provision of its basic functions. Critical infrastructure resilience is based upon new forms of risk management, adaptability, and the assessment of potential trade-offs between parts of a system. A resilient infrastructure can cope with scenarios linked to disastrous events with the aim of minimizing service interruptions and quickly recovering. (Ientile, 2020, ref. [6]).
- **Resilience of infrastructure:** Ability to absorb, withstand, and rapidly recover from hazard strikes impacting the local, regional, or national level. The Infrastructure Resilience Domain (IRD) focuses on built civil infrastructure and lifeline systems and how they interact with other infrastructure systems to support the greater local, regional, and national resilience (Kiyoshi, 2018, ref. [11]).
- **Resilience of transport infrastructure with respect to a defined service:** The ability to continue to provide service if a hazard event occurs. (Burkhalter et al., 2021, ref. [12]).

After analysing these definitions, the question of “**resilience of what**” (Marcelo et al., 2018, ref. [7], Frascaccia et al., 2018, ref. [8]) clearly arises. The term resilience can be defined at various levels, based on its application: a general definition, in a system as a general concept, in a specific system (e.g. a transport system), in a part of a system (e.g. a transport infrastructure) or in specific, defined assets (e.g. earth structures). Our own opinion is that, to provide a comprehensive definition of resilience, it is crucial to have a predefined scope or, in other words, the level or the scale at which resilience is to be considered.

4.2. Specific definitions

Regardless of the field and the scale of application, resilience is a property of a system. It is strictly connected to processes more than to physical assets.

It is important to emphasize that resilience is not a synonym with resistance. Resistance is indeed the ability of an infrastructure or a physical asset to withstand actions; these actions must be properly determined and correctly quantified. Nevertheless, it is possible that:

- actions may be underestimated (unintentionally or for economic reasons),
- actions may vary over the whole lifecycle of assets and exceed design values (e.g., for climate change, loads of vehicles, etc).

Depending on the infrastructure's geographical location, design, materials and environmental characteristics, a risk analysis is the basis on which resilience is founded.

The risk analysis enables the stakeholders to make decisions regarding:

- The investment to increase the resistance of assets (prevention),
- The introduction of minor modifications to attenuate effects of hazards (prevention),
- The non-intervention at all, but rather preparing to act after the occurrence of events and resulting damages (preparedness), in order to promptly restore the functionality of assets (response and recovery).

After a decision has been taken, assets may be monitored to collect data about their behaviour during their life, even without disruptive events. These data can be used to produce new risk analyses and, therefore, new decisions.

All these procedures are related to resilience.

The concept of resilience and related topics can therefore be aptly defined by using a cyclical framework that includes the following stages: **prevent**, **prepare**, **respond** and **recover** (the "Resilience Wheel" – fig. 15).

Figure 15. The "Resilience Wheel" (Lange et al., 2016, ref. [13])

4.3. INDICATORS OF RESILIENCE

Authors (ref. [1]) present a detailed list of quantitative indicators of resilience. The proposed indicators directly consider resilience through the concept of drop in performance (or loss in functionality). Drop in performance conceptually relates inversely to resilience. In other words, the lower the drop, the more 'resilient' the system.

Referring to figure 16, an event at time t_1 affects an infrastructure causing a sudden drop in performance (i.e. the infrastructure is put out of service). Repair work is ready to start at the time t_2 and it will finish at t_3.

The duration t_3-t_1 can be taken as another indicator of resilience: the shorter this time lapse, the more resilient the system. It is worth to note that the duration t_3-t_1 depends on at least two variables: the delay before intervention (duration t_2-t_1) and the duration of repair work itself (duration t_3-t_2).

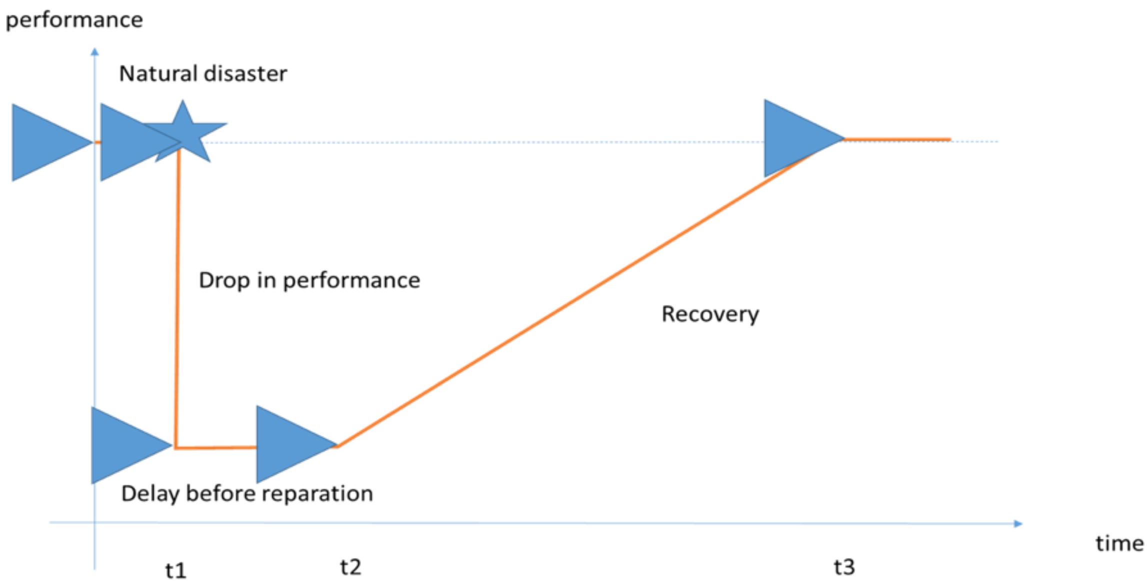


Figure 16. Delay before repair

As shown in figure 17, indeed, for a less-resilient infrastructure (in orange) the time for recovery is greater than the corresponding time for a more resilient infrastructure (in green). Resilience can therefore be introduced working on <u>adaptation</u> (reducing drop in performance), on <u>promptness</u> of reaction after a disaster (duration t_2-t_1), and on <u>preparation/organisation</u> of repair work (duration t_3-t_2).

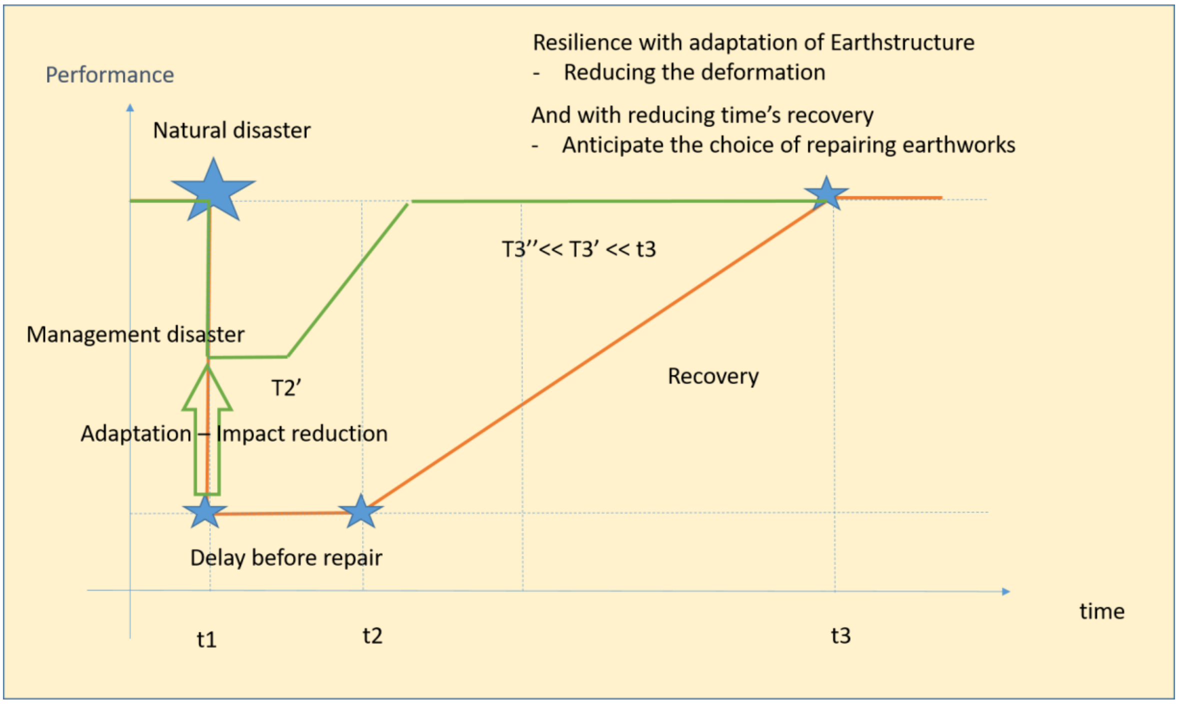


Figure 17. Comparison between systems with different behaviour after the impact of a natural hazard (poor-resilient and high-resilient)

4.4. QUANTIFICATION OF RESILIENCE - A PROPOSAL

In order to establish a general method for quantitative and qualitative resilience evaluation, at project level of highway earthworks and earth structures, we may assume that on any highways project a balance must be achieved between the main pillars of resilience: technical, socio–economic, environmental and strategic aspects, as well as concepts on adaptation to climate change. Consequently, in any analysis of project resilience, at least the following five resilience criteria must be considered and selected:

- Technical criteria: (T),
- Social–economic criteria: (SE),
- Environmental criteria (E),
- Adaptation to climate change (ACC), alone or in combination with environmental (E) criteria (E & ACC),
- Safety & Strategic aspects (SS).

The following description is taken from document [14].

The identification and measurement of each of these five aspects, must be performed in each stage of the life of an earth structure, starting with the design and selection of materials and continuing with the execution, maintenance, and rehabilitation.

For each case study of an earth structure project, it is necessary to identify the main factors that are associated with it, to collect the required data or their evaluation and to apply the mathematical and statistical tools, needed to estimate the impacts they may produce separately and then assess their cumulative impacts qualitatively and, if possible, quantitatively. An in-depth analysis is therefore needed to assess the resilience of such projects. Such detailed analysis, based on experience, literature research and specific aspects of the project, must be undertaken for each of the subsystems of the investigated resilience system.

Before starting the resilience assessment phase of an earth structure, project objectives and priorities must be addressed accordingly, and the following aspects must primarily be clarified:

1. Adopt and describe the strategies necessary to achieve the requirements of these components. According to these approach, in resilience studies conducted for a new project it is recommended to investigate at least two alternatives are adopted, a classical/standard one in parallel with the proposed one, so that, it will finally be possible to compare and decide which alternative may better satisfy the designed/desired resilience requirements.
2. Thus, in case of a new solution/ project, to justify its implementation, in comparison with the classical/standard ones, it will be necessary to include in the evaluation study, at least one classical project, considered as a reference.
3. In this respect, for each alternative project, the five components of resilience, T, SE, E, SSA, SCC & ACC, should be considered as being independent systems, each of them being structured by a finite number of subsystems.
4. For each subsystem, according its specific aspect/ quality, a corresponding quantitative or qualitative weighing factor may be assigned, expressed in term of the probability with which that specific quality will possible to be achieved/assured by the investigated technology.
5. Describe in detail the problem encountered, the context in which it appeared and the new innovative solution/ project intending to resolve the existing problem, in comparison with the classical ones.
6. Function of the specific / complexity of the project, select and describe in detail, the specific resilience systems, and subsystems, which should be investigated and evaluated in terms of probabilities established for the evaluation of resilience in both, the reference project and the new proposed one.
7. For each aspect/subsystem (i = 1…n) selected for resilience investigation, choose the appropriate qualitative and/or a quantitative method for evaluation of the subsystem achievement probabilities. Such a detailed analysis, based on experience, literature and specific aspects of this project, must be undertaken for each of the subsystems of both investigated resilience systems, X1 and X2, as shown in Annex 1.
8. For each investigated project, based on these subsystems probability values, calculate for each alternative project the resulting Resilient Index of the system (i), I_{rri}, expressed in terms of the Shannon classical entropy formula (1).

$$H(X) = -\sum_{i=1}^{n} P(x_i)\log_b P(x_i) \qquad (1)$$

where the variables have the following meaning:
H(X) is the entropy value of the complex H system, composed from (n) subsystems, when i = 1,2,3,…n
(x_i) is the identifier of the subsystem (i).
P(x_i) is the estimated probability, with which the technical or other requirements of the subsystem (i), may achieve the designed/ desired quality, expressed in quantitative or qualificative values; The sum of the P(x_i) = 1
(b) is the base of the logarithm, (b=2, for Shannon entropy calculation).

9. Considering the following two earthworks projects systems: X1- the new proposed project and X2- the reference ("classical") project. The new proposed project X1 is composed of the subsystems: x11 , x12 , … x1n), each subsystem being characterized by its corresponding probability : P(x11), P(x12), … P(x1n). Similarly, the reference project X2 is composed of the

subsystems: x21 , x22 , … xn) , each subsystem being characterized by its corresponding probability: P(x21), P(x22), … P(x2n).

10. Evaluate/calculate the Resilient Index (RI_{new}), according to the Shannon formula for the evaluation of the entropy of the investigated system, expressed in digit units of information (bits), for the new proposed project with relation (2):

$$RI_{new} = H(\mathbf{X1}) \qquad (2)$$

11. Evaluate/calculate the Resilient Index (RI_{ref}), according to the Shannon formula for the evaluation of the entropy of the investigated system, expressed in digit units of information (bits), for the reference project, with the relation (3):

$$RI_{ref} = H(\mathbf{X3}) \qquad (3)$$

12. Finally, compare the values of both resilience indexes: RI_{new}, RI_{ref} , and decide which project will be selected, based on its feasibility and resilience efficiency.
13. Formulate the final conclusions and appreciation about the resilience of the new project, justify the need for its implementation and specify its main aspects which must be observed and supervised during stages of earthworks construction and those of performance monitoring after the delivery of the road for traffic.

4.5. ENQUIRIES ABOUT RESILIENCE

To gather information regarding the concept of 'resilience' applied to the design, construction, and repair of earth structures subject to natural hazards (including those due to climate change) in different countries and to collect data on cases, techniques and practices employed, an enquiry was distributed among members of our TC.

The framework of the enquiry was as follows:

Question 1: *In your opinion, what does the concept of 'resilience' mean when applied to geotechnical assets?*

Question 2: *In your opinion, what are the main features or parameters to describe a resilient geotechnical system?*

Question 3: *In your opinion, what are the possible benefits inferred from the application of a 'resilient' design approach to the geotechnical assets?*

Question 4: *Are there standards/best practices in your country that explicitly implement design approaches or technical maintenance strategies to guarantee the resilience of a geotechnical asset?*

Results are summarized in the following table 3 and collated in Annex 1.

	Country	Answers			
		Question 1	Question 2	Question 3	Question 4
1	Benin	Y	Y	Y	-
2	China	Y	Y	Y	Y
3	France	Y	Y	Y	Y
4	Italy	Y	Y	Y	Y
5	South Korea	Y	Y	Y	Y

	Country	Answers			
		Question 1	Question 2	Question 3	Question 4
6	Spain	Y	Y	Y	Y
7	United Kingdom	Y	Y	Y	Y
	Y =answer collected				

Table 3. Answers for enquiry about resilience

4.6. Resilience of Earth Structures

Further to the enquiry among members, a specific definition of resilience of earth structures can be given as the ability of a structure subject of environmental actions to resist, absorb and recover from the effects of unexpected actions within an acceptable timeframe and with reasonable economic effort, implementing at the same time measures derived from "lessons learned", for an enhanced behaviour in the future: all of these actions must be performed in a cyclic manner (see "galaxy of resilience" in fig. 18).

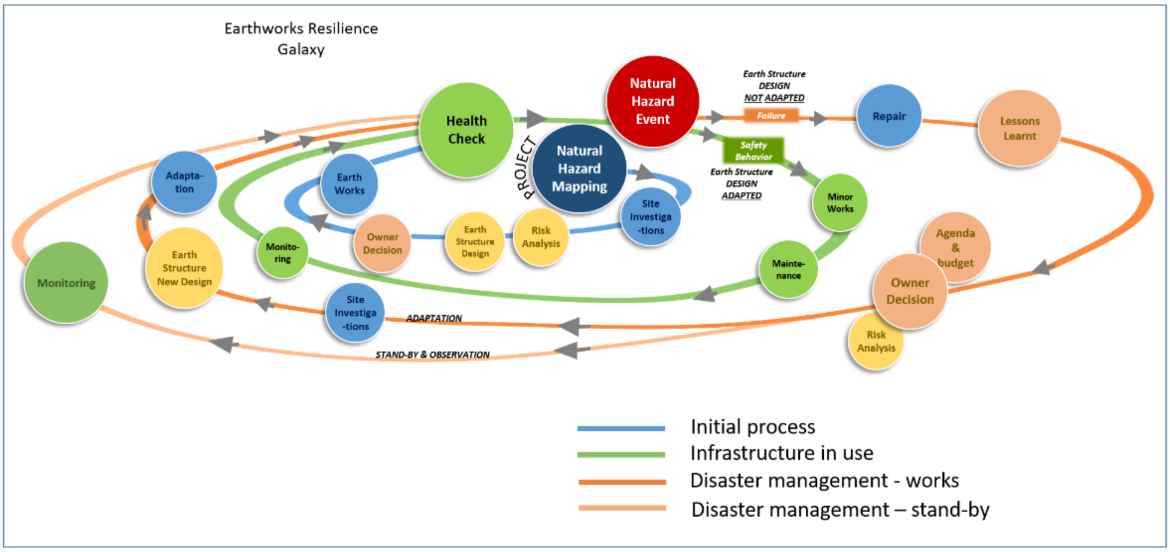


Figure 18. The "galaxy of resilience"

5. SPECIFICATIONS FOR RESILIENCE

As seen in previous chapter 4, resilience procedures framework includes four stages:

- prevention,
- preparedness,
- response actions,
- recovery actions.

As a starting point, it is worth to put in evidence the following breakdown:

- Prevention
  - risk management,
  - monitoring.

- Preparedness
  - maintenance,
  - preventive actions.

- Response & recovery actions
  - adaptation,
  - lessons learned.

All these stages will be illustrated in detail in chapters 6, 7, 8 and 9.

6. RISK MANAGEMENT

6.1. General Considerations

Risk Management consists of the identification, evaluation, and prioritization of risks defined in International Standard as: “the effect of uncertainty on objectives”, ref.[15]) followed by co-ordinated and economical application of resources to minimize, monitor, and control the probability or impact of unfavourable events or to maximize the realization of opportunities.

Risks can come from various sources including accidents, , natural disaster, deliberate attack from an adversary, or events of uncertain or unpredictable root-cause.

As a general approach, risk management is based on the following steps:

1. Identify the threats,
2. Assess the vulnerability of critical assets to specific threats,
3. Determine the risk (i.e. the expected likelihood and consequences of specific threats),
4. Identify ways to reduce those risks,
5. Prioritize risk reduction measures.

6.2. Identify the threats

6.2.1. Identification of natural hazards

As many natural hazards exists it is mandatory to identify which of them are actually to be taken into account for each case. According to the geological history of the site, the climate, the morphology etc., indeed, some hazards can be completely excluded and, on the other hand, some can occur with significant frequency.

Hazards can be gathered in families if their failure mechanisms are similar; each family needs the same type of geological information and ground investigations.

For example:

1- Landslide, creep, solifluxion,
2- Runoff, gullying, mud flow, erosion,
3- Sinkhole, settlement, large ground deformation,
4- Rock falls,
5- External erosion due to flash floods, flooding, rising of sea level,
6- Drought,
7- Lava flow, other volcanic phenomena.

Other hazards, such as earthquake potential, can be mapped but they need additional knowledge and geotechnical analyses than just a geological assessment.

6.2.2. Importance of geotechnical model

Geotechnical investigation, hazard mapping and topographic survey enable the geotechnical model of the site to be defined. Based on this information, geotechnical engineers can correctly identify relevant threats and choose the appropriate design of earth structures, in order to cope with these expected hazards. Many types of structure can be designed to “treat the source, not the symptom”. For example, if a mud flow is expected, water management upstream the infrastructure is of utmost importance; if any slope instability is expected due to excess pore pressure, drainage is mandatory to prevent potential landslide occurrence.

6.2.3. Triggers

Triggers are accentuated by the meteorological events. Moreover, meteorological actions may be amplified by climate change effects.

Previous PIARC studies have defined the following global parameters regarding the climate impact on earthworks:

- Temperature (very high to very low, icing/de-icing),
- Rainfall and snowfall,
- Wind,
- Water runoff and flood.

6.3. Assess the Vulnerability

6.3.1. Vulnerability

Regarding the defined output of this report, the design parameters shown in the following figure 19 are to be investigated:

Rainfall	intensity [mm/h]	The rate at which rainfall occurs expressed in depth units per unit time. It is the ratio of the total amount of rain to the length of the period in which the rain falls
	return period [1 in "n" years]	Estimation of how long it will be between rainfall events of a given magnitude
	duration [minutes or hour]	Duration of rainfall
	Maximum [mm/h]	The rain of a certain amount and duration that can be expected with a known return period
Temperature	temperature impact [°Cd]	The thermal energy transferred into the road structure during an uninterrupted period of hot days or frost days
	air temperature [°C]	The highest temperature measured about 1 meter above ground
Wind	velocity [m/s]	Wind velocity
Runoff	max Quantity [m^3/s]	Portion of the maximum rainfall that appears in roadside ditches or culverts
	max Volume [m3]	The maximum volume of water which has to be stored temporarily during a rainfall period

Figure 19. Design parameters to be investigated

Each of them has impact on specific parts of earth structures, as shown in Figure 20.

			Cluster 1 Slope	2 Roadside ditch	3 Shoulder	4 Bituminous surfacing	5 Base	6 Subbase	7 Capping layer	8 Fill Embankment
Rainfall	intensity [mm/h]	The rate at which rainfall occurs expressed in depth units per unit time. It is the ratio of the total amount of rain to the length of the period in which the rain falls	X		X		X		X3)	X3)
Rainfall	return period [1 in "n" years]	Estimation of how long it will be between rainfall events of a given magnitude	X	X	X				X3)	X3)
Rainfall	duration [minutes or hour]	Duration of rainfall	X		X				X3)	X3)
Rainfall	Maximum [mm/h]	The rain of a certain amount and duration that can be expected with a known return period		X						
Temperature	temperature impact [°Cd]	The thermal energy transferred into the road structure during an uninterrupted period of hot days or frost days	X		X	X	X	X2)	X3)	X3)
Temperature	air temperature [°C]	The highest temperature measured about 1 meter above ground								
Wind	velocity [m/s]	Wind velocity Sand and dust storms	X1)				X1)			X
Runoff	max Quantity [m^3/s]	Portion of the maximum rainfall that appears in roadside ditches or culverts		X					X3)	X3)
Runoff	max Volume [m3]	The maximum volume of water which has to be stored temporarily during a rainfall period							X3)	X3)

Figure 20. Summary of climate impact on each part of the route (cluster) –
(1) In combination with temperature impact; (2) Only in areas with permafrost; (3) The Cluster 7 (capping layer) and Cluster 8 (Fill/Embankment) are affected by climate impact. But it is not easy to separate the impacts on slopes and hydraulic structures (ditches and culverts) from those caused to embankments and the capping layer.

6.4. DETERMINATION OF RISK

6.4.1. Evaluation of the hazards

Geological engineers are familiar with risk assessment, which is the result of evaluating both the magnitude of a natural event and its probability. The information can be cross checked in a matrix of hazards as follows. Generally, three to five levels are required. The figure 21 is based on three/four (columns/rows) levels:

Likelihood of the expected event → Magnitude / intensity of the expected event ↓	Not expected	Moderately expected	Highly expected
minor	Minor event, very low likelihood	Minor event, moderate likelihood	Minor event, high likelihood
moderate	Moderate event, very low likelihood		
high			
Very high / catastrophic			Very high magnitude, very high likelihood

Figure 21. Graphic representation of hazard evaluation process

The hazard that “seldom happens and that is just mapped for information” is clearly something which is not important for the structure and the users. This hazard can be mapped in green.

The hazards which “have a catastrophic intensity and may happen in a very short time” have a great impact on the infrastructure and the users. These hazards are mapped in red.

Between the “green condition” and the “red condition” all intermediate interpretations are possible (yellow and orange in fig. 21). Evaluation of hazards, therefore, requires expert advice for accurate definition and a perfect understanding of their consequences.

6.4.2. Hazard maps

The cost of hazard mapping depends on the extension of the area to be mapped and the complexity of the site (geographical and geological). This cost is usually small compared to the total cost of the road and may represents some 1-2%.

Comprehensive hazard mapping must be considered as a prior investment for safe asset management.

An example of hazard mapping is shown in figure 22 where seismic hazard for Italy (express in terms of horizontal peak ground acceleration) is presented.

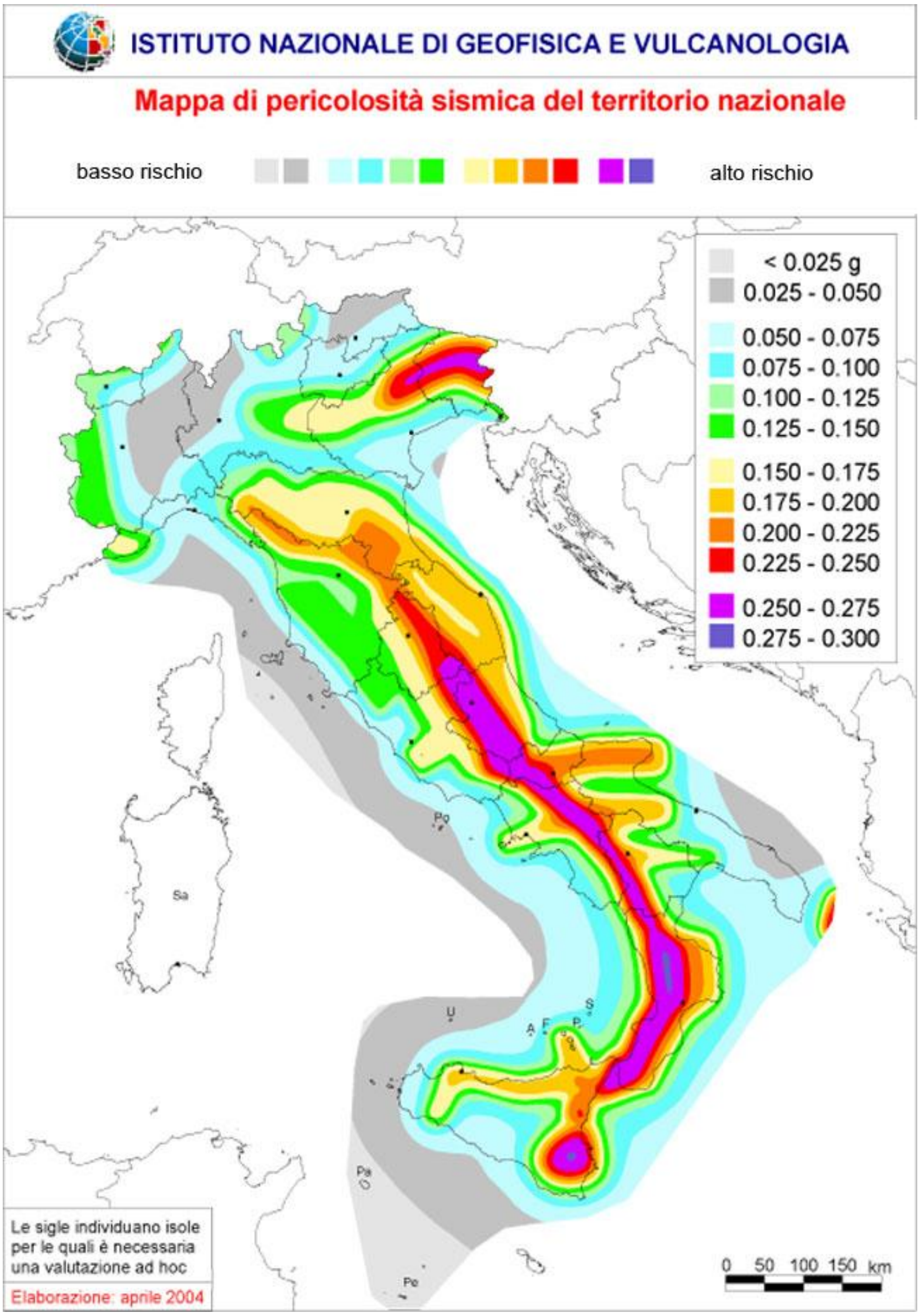


Figure 22. Map of seismic hazard in Italy

6.4.3. Design

As previously said, a resilient approach is based on the identification of natural hazards and their mapping along the infrastructure corridor and in the geographical area of influence.

Hazards have to be estimated in volume around the infrastructure that is identified at least by a distance from the axis that is threefold the height of each earth structure (e.g., for a 10-metre-high cut, the zone of investigation would be 30 m from each side of the crest of slope). A specific hazard map, focused on the road alignment, can be therefore produced (fig. 23).

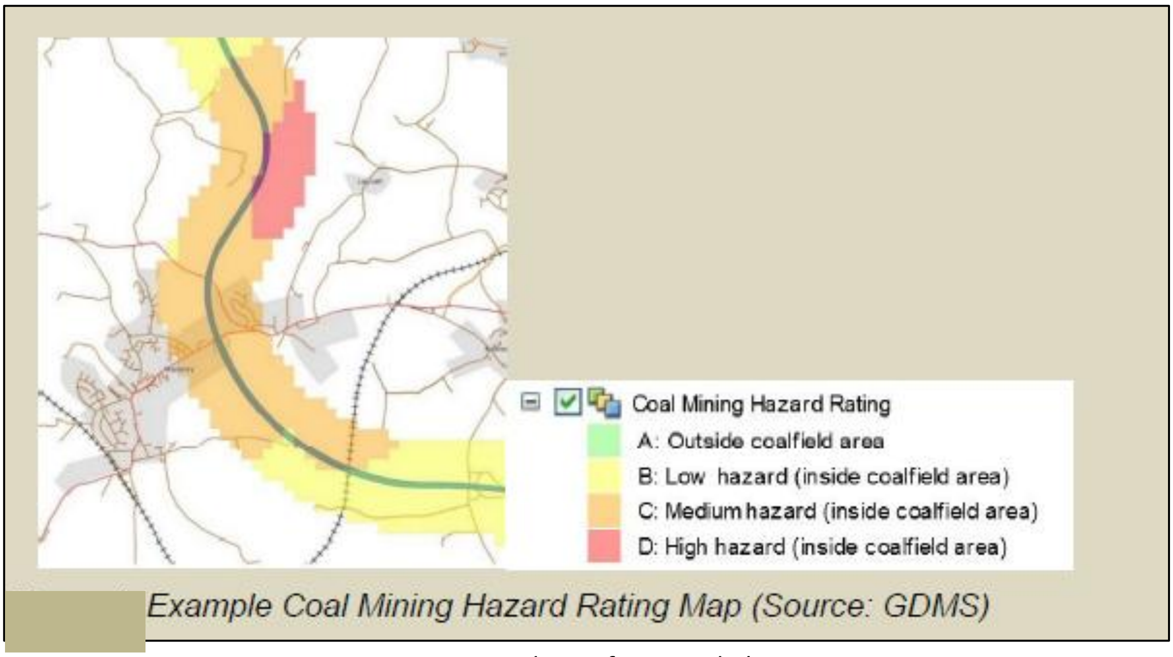


Figure 23. Hazard map for a road alignment

6.4.4. Evaluation of the risk

Once the hazard is identified, the vulnerability of the infrastructure is evaluated separately considering the consequences in terms of user injuries, loss of economic value, repair costs, possibility of a temporary lane deviation, ease of repair. Hazard intensity and probability are combined with vulnerability of the specific infrastructure with the assistance, if this is the case, of a geological engineer. These data are then compared with the level of performance targeted by the owner (number of days of of interruption, loss of economic value, etc.) to obtain a comprehensive definition of the risk.

According to the level of performance, the risk R is therefore the result of comparing information between the hazards probability of occurrence P and the vulnerability V:

$$R = P \times V$$

Risk evaluation can be presented in a very similar way to that of hazards, by using colour codes ranging from green (low risk) to red (high/very high risk) passing though intermediate conditions (fig. 24).

Evaluation of risk, just as the same for hazards, requires expert advice for accurate definition.

Consequences of a hazard → Probability of the hazard ↓	Not expected	Moderately expected	Highly expected
negligible	This hazard will seldom happen and is mapped just for information		
moderate			
high			
Very high			This hazard will have strong effects and need immediate decision

Figure 24. Graphic representation of risk evaluation process

6.5. Risk Reduction Measures

A perfectly resilient infrastructure ideally corresponds to a case where all the risks have been identified. That means a perfect knowledge of:

- all type of natural hazards and triggers that can affect earth structures,
- a corresponding evaluation of risks and and whether or not to accept damages, given an appropriate level of performance,
- all type of repair work, maintenance, monitoring that are needed during the lifespan of all earth structures.

Among risk reduction measures we can take into account:

- design quality,
- prevention and maintenance,
- preparedness of organizations in terms of prompt response after events,
- use of appropriate techniques for construction and materials,
- implementation of temporary solutions.

All these measures are to be considered specifically relevant for earth structures. Moreover, these measures are suggested by the results of our enquiry on resilience (see chapter 4).

7. MONITORING

7.1. HEALTH CHECK

Earth structures, during their life cycle, are exposed to events that cause degradation and damages.

These events (fig. 25) may be classified as:

1. non-human actions - natural hazards.
2. human actions.

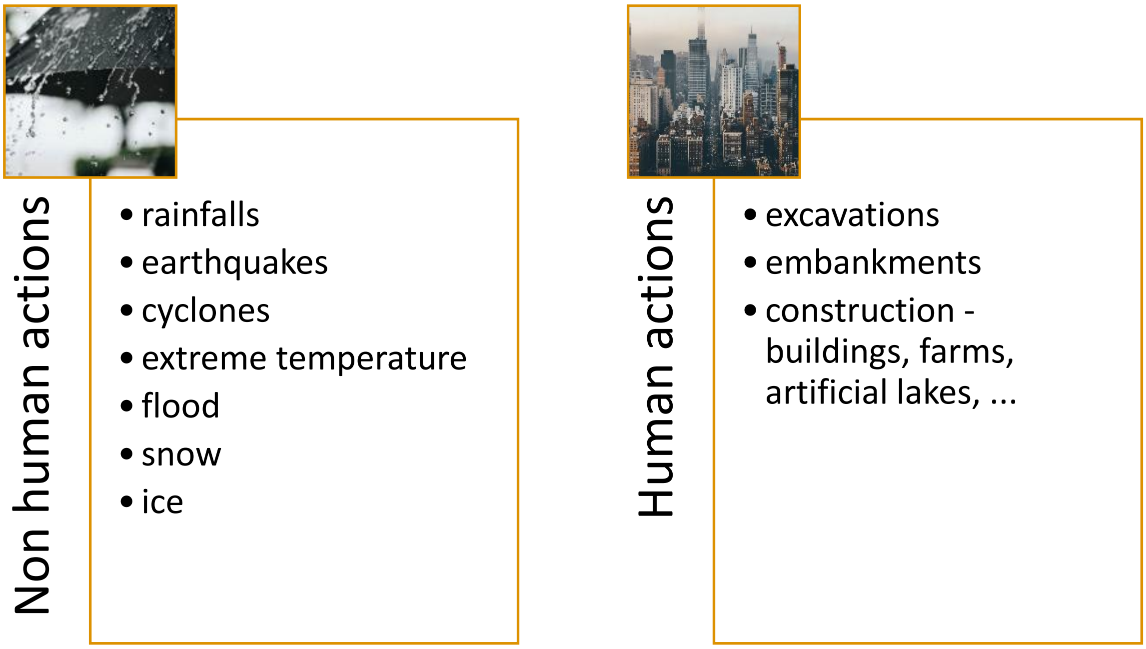


Figure 25. Classification of external actions on earth structures.

A health check of geotechnical structures is, therefore, essential during their life cycle to improve the resilience of the infrastructure to natural hazards, as it provides information on the state of preservation, maintenance, and stability of the asset. A health check also permits the highlighting any hidden defect, not otherwise evident.

It is worth noting that events can occur in sequence and, if no recovery action is taken after the first event, further ones even of greater magnitude may compromise partial or global stability of any earth structure. This is because hidden defects may occur; thus, a structure may be at an imminent risk of "rupture" and then collapse without the Asset Manager being aware of this fact.

7.2. VISUAL INSPECTION

The simplest form of health check is the visual inspection of earth structures that is carried out by specifically trained personnel in order to collect qualitative data on the condition of assets.

The plan for health checking of a earth structure should be defined during the design phase for the construction and operation period. This plan should identify the frequency of inspection that are needed for health check and alert levels to be applied for the relevant case.

Type of inspections are:

- Routine Inspection – a total or partial visual inspection of components of the structures, in order to verify their general state of maintenance only.
- Complete Inspection – a total inspection of all structures and their parts, in order to accurately check their state of conservation and maintenance.
- Partial Complete Inspection – a partial inspection of selected parts of structures only, (considering their relevance), in order to accurately check their state of conservation and maintenance.
- Exceptional inspection – an inspection carried out after an event or accident is reported.

Type of Inspection	Object	CS (assignment)	MS (assignment)	Frequency
Routine	All or selected infrastructural components.	No	Yes	Annual
Complete	All infrastructural components	Yes	Yes	5 in 5 years
Partial Full	Selected infrastructural components	Yes	Yes	As needed
Exceptional	All infrastructural components.	Yes	Yes	After an event or damage

CS – Conservation State MS – Maintenance State
Table 4. Field inspection for earth structures health check

A typical layout for a visual inspection is (fig. 26):

- ✓ Preparation:
  - data collection and history (accidents, meteorological data, rehabilitation history).
  - scheduling of the inspection.
- ✓ Field inspection – at site, inspectors collect information on: cadastral data, defects (with photos), additional recommendations and notes.
- ✓ Final report – information processing, analysis of data collected and recommendations about maintenance.

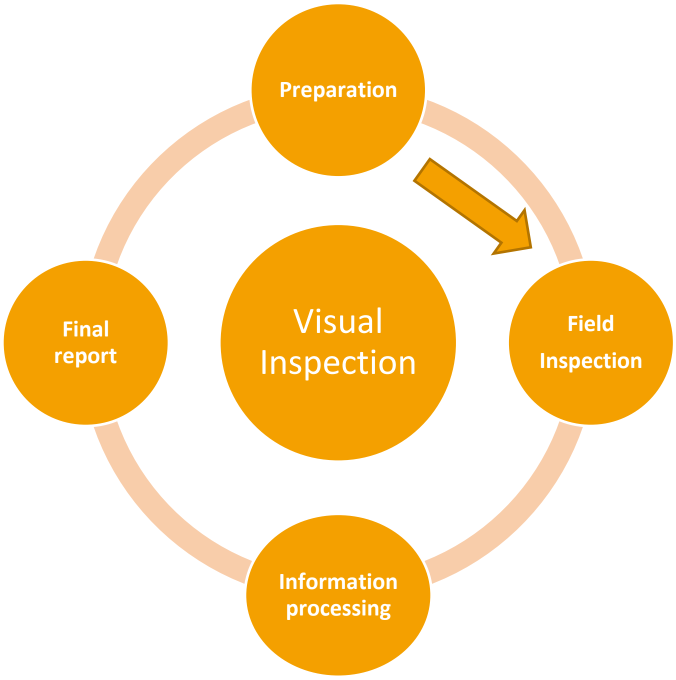


Figure 26. Visual inspection layout

Based on the final report, a list of maintenance and/or conservation actions is drawn up. Examples of field inspection activities are shown in Figures 27 and 28.

Figure 27. Checking condition of drainage lines

Figure 28. Checking condition of slopes

7.2.1. Special inspection after events

After events of significant magnitude a specific inspection should be planned. This inspection must be more accurate than "ordinary", with more details and specific aspects. In some events the inspection must be carried out in several steps:

- Immediately after the event;
- After a subsequent rainfall event or seismic replica.

In Figure 29 main events to be considered in planning a special inspection are shown.

Figure 29. Events that require special inspections

The aim of these inspections is to detect damages derived from the specific event and to plan appropriate actions to guarantee the functionality of the asset.

In any case, the direct and immediate damage/impact of the event on the asset itself must be recorded, as well as other aspects.

The main aspects to be verified are:

Heavy rainfall and flooding

- functionality of drainage system,
- obstruction of transverse drainage,
- scouring of foundations,
- erosion.

This inspection should be carried out immediately after the event.

Strong wind

- integrity of the asset (wind erosion),
- integrity of the drainage system,
- obstruction of transverse drainage,
- instability of rock slopes.

Strong winds may act simultaneously with heavy rainfall.

Wildfire

- direct fire damage,
- obstruction and/or damage of the drainage system,
- erosion.

This inspection should be carried out immediately after the event and again after further rain events.

Transport of ashes through a drainage system can last a long time after the fire. It could include a change in the runoff coefficient. Moreover, ash deposition may cause corrosion to structural elements. These phenomena must be very carefully evaluated by means of special plans.

Change in land use

- change in the runoff coefficient and natural drainage lines,
- erosion,
- scouring,
- integrity and capacity of the drainage system.

Inspection should be carried out as soon as possible and after rainy periods even if intense rainfall is not recorded.

A particular case of change in land use is the development of new urban areas near (mainly upslope) a road. Specific studies might then be performed.

Seismic events

- integrity of earth structures.
- integrity of the drainage system.
- instability of slopes.

This inspection should be carried out immediately after the event and again after any replicas. Examples are shown in fig. 30 and 31.

Damage of an embankment due to heavy runoff

Fire

Rockfall

Figure 30. Various examples of events affecting earth structures. Top, flooding after heavy rainfall. Middle, fire and rockfall. Bottom, change in land use: as a result of the construction of new mountain tracks and firebreaks upslope, new runoff paths (not previewed in the initial design of the road) have been produced after rainy periods.

Figure 31. Change in land use: new urban infrastructure and buildings will modify runoff coefficients and the interaction of the road with its surroundings.

7.3. Automated Monitoring

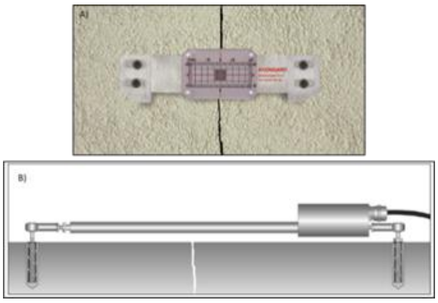
Automated monitoring provides a robust and rapid prevention methodology which produces very important results for health checking of assets throughout their life cycle. In this way, both automated monitoring and visual inspections are measures to prevent damage and loss of human lives.

It should be noted that most earth structures are not instrumented, but only those that are considerably large and/or for which a specific geotechnical risk has been identified.

7.4. Automated Monitoring Equipment

Automated monitoring is carried out by using a wide range of techniques and equipment. The choice among this range is to be done considering the specific physical entity to be monitored.

In Table 5 monitoring techniques and equipment are presented in connection with their specific target (physical entity).

Equipment	Objective	Photo
Topographic target	Horizontal and vertical surface displacement (three directions)	
Load Cell	Load variation in ground anchors	
Inclinometer	Internal horizontal displacement along the depth	
Piezometer	Variation of the piezometric level (groundwater level)	
Seismograph	Vibration measurement and recording	
Crackmeter	Surface fissures and joints in rock structures	

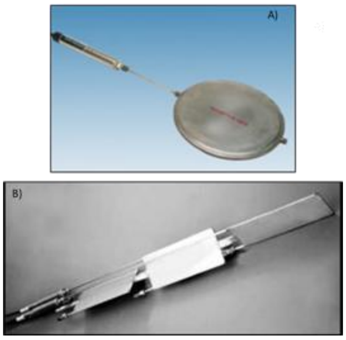
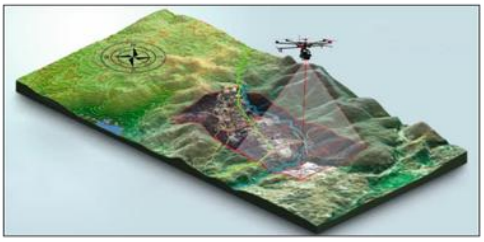
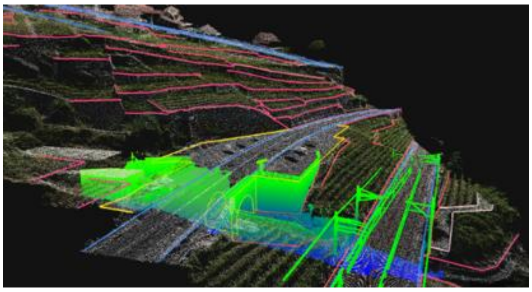
Pressure cell/station	Pressure monitoring	
Laser scanner	Control of behaviour of geotechnical structures	
Terrestrial and satellite interferometry	Control of behaviour of geotechnical structures	
LIDAR	Control of behaviour of geotechnical structures	

Table 5. Monitoring technologies and equipment

7.5. MANAGEMENT OF VISUAL INSPECTION/AUTOMATED MONITORING DATA

The following Table 6 summarizes the main features for each kind of monitoring activity.

MONITORING	COLLECTED DATA	RESULTS	PERIODICITY	Inspector	Cost
Visual Inspection	Defects and damage, cadastral elements	Maintenance and conservation state, report	Stable - Annual Unstable – according to the plan	Geologist / Engineer	Low
Automated monitoring	Values of selected geotechnical	Graphics Report	Stable – annual, Unstable – according to the plan	Technician	Low

Table 6. Main features of monitoring activities

These inspections must be prepared in advance taking into account analyses of all the reports from previous inspection campaigns.

Based on the results of the inspection sheets and reports, an action plan to prevent the appearance and evolution of defects, to select conservation works and curative actions to rehabilitate or reinforce the structure by replacing it and/or safeguarding its stability is to be developed.

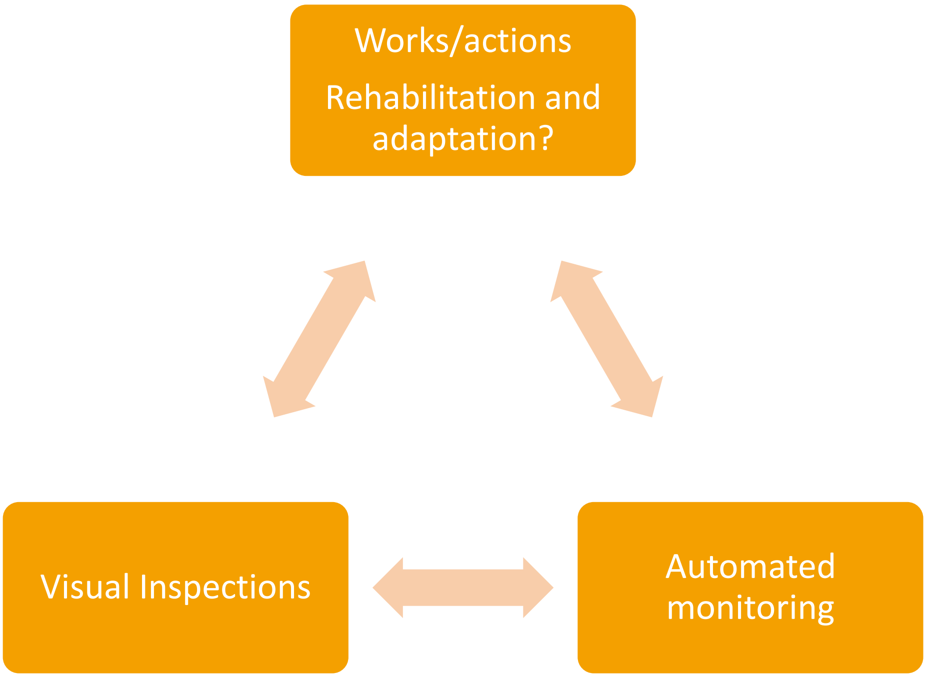


Figure 32. Data flow for an action plan after health check.

The methodology and monitoring parameters are established in the Inspection and Health Check Plan, enabling a rigorous and reliable diagnosis of the structural condition of assets. An alert to the Asset Manager can be automatically sent, leading to a timely decision-making of: i) intervention, ii) increase of the frequencies of reading campaigns, iii) reinforcement of the installed equipment.

Alert and alarm levels must be set by the designer with reference to the specific case and conditions.

For instance, in case of the application of the EuroCode EC7 there are three categories of geotechnical structures, as presented in the following Figure 33, and three alert criteria to be defined.

Alert criteria are therefore based on the specific geotechnical category of the structure and may consider:

- Horizontal displacements,
- Vertical displacements,
- Pre-stress losses,
- Deformation speed.

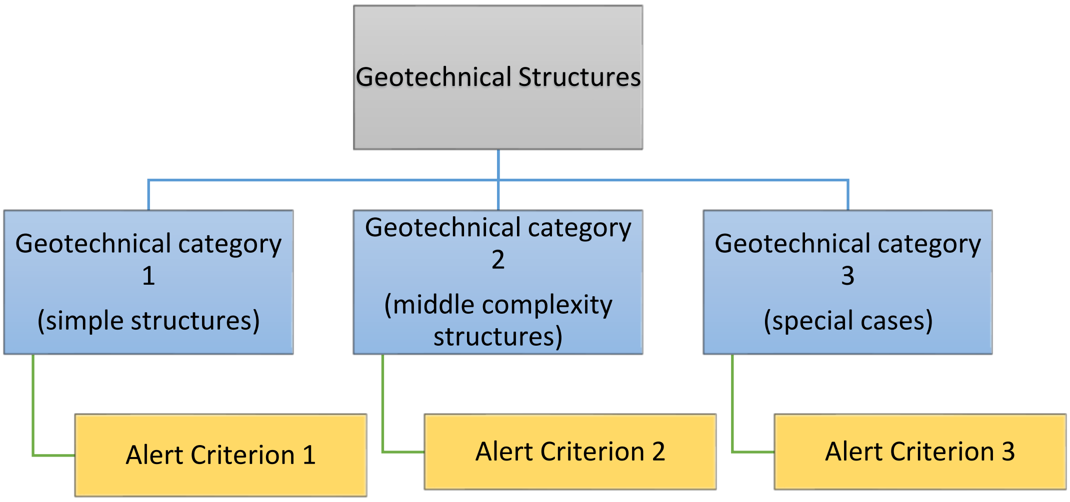


Figure 33. Alert criteria related to geotechnical complexity.

8. MAINTENANCE

8.1. PREVENTION AND MAINTENANCE

Once the natural hazards have been mapped, the owner can schedule maintenance and monitoring of the infrastructure (fig. 34) and prepare a budget for urgent intervention in case an event occurs. The type of repair and type of contract can be evaluated in advance. When the event happens, the owner can act and correctly manage the repair works.

The cost of normal maintenance is always lower than the cost of repairs. For example, for a very important collapse on a highway in France, the cost of repair was about 3 million Euro. The cost for the maintenance of a similar structure would have been around 20,000 Euro.

We emphasize that the quantification of costs is a complex and time-consuming process as indirect costs can be even higher than those directly caused by the damage of the structure.

Figure 34. An example of poor maintenance of a culvert: sedimentation filled nearly half of the culvert volume (France, courtesy Cerema St. Brieuc)

8.1.1. Preparedness

A natural disaster has an impact on the economy and is often reflected negatively in the public perception of the event (in newspapers, television, etc.). Preparedness is a way to face the worst effects of events, including their “mediatic” consequences (fig. 35).

Figure 35. Example of announcements of infrastructure damage in newspapers

Preparedness can be achieved in a variety of ways, acting on several aspects that are mainly of a managerial nature. All methods consider the availability of at least one of the following elements:

- trained teams for urgent intervention,
- a catalogue of technical solutions for intervention, covering all failure cases,
- dedicated contractors for urgent intervention, in the frame of asset management,
- availability of alternative routes if a road closure is required,
- an alert system and rapid communication channels with the users.

8.1.2. Innovation in construction techniques and materials

The solution to be adopted for construction and repair of an earth structure after an event should be carefully studied and dimensioned, by adopting innovative and sustainable solutions whenever possible and by taking into account:

1. Geometry,
2. geographical location,
3. geology and morphology;
4. climate – temperature, humidity, precipitation, seismic risk,
5. history of events and repairs,
6. access to the site,
7. importance of the road,
8. ease of maintenance,
9. observation and monitoring plan,
10. overall costs.

A resilient solution promotes the use of green and ecologically friendly materials and techniques, preserving environment and biodiversity.

The Techniques and Innovations in Earthworks Case Study Report (2022R11EN – ”*Techniques and Innovations in Earthworks – A PIARC Collection of Case Studies*”, ref. [16]) developed by the WG2 of TC4.3, presents a wide range of case studies with sustainable innovative solutions, summarized in the following tables 7-12.

PERFORMANCE

Case Study	Name of the project	Problem	Country
1	Dry Compaction	Soil classification system reusing very wet or very dry soils	Romania
2	Decision tool and software for soil identification and harmonization of various classification systems	Soil classification system	Romania

Table 7. Performance-oriented innovation cases

MATERIALS

Case Study	Name of the project	Problem	Country
3	Rehabilitation of the Espiridião de Sousa street (lightweight aggregate)	Existing wall movement; earth pressure to be reduced	Portugal
4	Story of the design of a motorway (Glass backfill)	Limited room for constructing a widened portion of the roadway; needed cheaper solution than wall while maintaining steeper slope	UK
5	©Pneu sol	Unstable slope requiring steeper slope; opportunity for environmental solution by using old tires	France
6	Embankments made of end-of-life tyres (ELTs) on soft soils	Lightweight embankment over soft soils; can be used to reduce lateral pressure on walls; opportunity for environmental solution by reusing tires	Spain

Table 8. Material-oriented innovation cases

Technologies

Case Study	Name of the project	Aplicability	Country
7	The Restore the Corridor Wilmington Rehabilitation Project	Identification depth of rock in advance of construction	USA
8	Lidar Robot	Cheaper and faster method for collecting topographic data	France
9	Reinforcement system including detection, survey, and warning system (PREDITECT®)	Observation and monitoring of earth structures	France
10	Comprehensive geotechnical monitoring of the landslide processes and the retaining structures in the city of Sochi	Observation and monitoring of earth structures	Russia
11	Development of smart compaction management system for earthwork	Soil compaction	South Korea

Table 9. Technology-oriented innovation cases

Resources – Design Solutions

Case Study	Name of the project	Problem	Country
12	ER238, PK 25+200 – excavation slope rehabilitation	Geology incompatible with geometry of excavation	Portugal
13	A17 Motorway Slope Failure	Erosion and infiltration causing slope failure; find cheaper and easier solution	Portugal
14	A-23 “Autovía Mudejar” from Sagunto to the French border in Somport. Stretch: province limit between Castellón and Teruel – Sarrión	Many small cavities in the ground; need to prevent road collapse	Spain
15	Cavities risk management - Gypsum dissolution phenomena	Many small cavities in the ground; need to prevent road collapse	Tunisia
16	Castilla La Mancha A-40 dual carriageway construction project.	Bottom of excavation intercepted water table	Spain
17	Temporary and permanent culvert construction	Soft soils with large settlement; need to maintain culvert under embankment	USA
18	Geosynthetic Reinforced Soil (GRS) bridge abutments with stage constructed full height rigid facings	Soft soils under embankment	Slovenia

Table 10. Design solutions-oriented innovation cases

Environmental - Social

Case Study	Name of the project	Problem	Country
19	Regional Road no. 578 Rieti-Torano (Central Italy) – Vegetative solution protection nets environmental appearance improvement	Erosion causing falling rocks	Italy
20	Use of bioengineering for slope stabilisation	Erosion	Uganda
21	Reinforced embankmentwith damaged by fire - located at EN 351	Embankment and georeinforced walls damaged by fire	Portugal

Table 11. Environmental-oriented innovation cases

Techniques/Methodologies – Reinforcement

Case Study	Name of the project	Problem	Country
22	A4 - large embankment construction	Stability of very high embankments	Portugal
23	A16 Gabion Wall	Gabion wall sagging and settling and needed to be reinforced without removing	Portugal
24	Ground Treatment Solutions using Jet Grouting	Overall stability of gabion wall and slope	Portugal
25	Cavibag	Many large cavities in limestone rocks; need to prevent road collapse	France
26	Liquid lime-soil mixing treatment inclusion	Large cracks in clayey soils caused by drought	France
27	Column-supported embankment for the Harlem River Drive Bridge replacement	Large layer of very soft soil with major utilities under proposed embankment in major city	USA
28	Project: High Speed 2 (HS2) Phase One, under construction (as of 2021)	Limited room for constructing a widened portion of the roadway; needed cheaper solution than wall while maintaining steeper slope	UK

Case Study	Name of the project	Problem	Country
29	Technology of construction of anti-landslide structures in cramped conditions.	Large layer of very soft soil with major utilities under proposed embankment	Russia
30	Rete Ferroviaria Italiana – RFI – Fortezza-San Candido international railway (Alto Adige-Sudtirol - Northern Italy) – Restoration of a landslide-damaged railway embankment	Emergency restoration of embankment without removing existing earthwork	Italy
31	Reinstatement of the failed Segmental Retaining Wall (SRW)	Wall collapsed - water pressure	South Korea
32	Control of debris flows with steel mesh	Protection against falling rocks and debris flow	Peru
33	Stabilization work to control landslides in urban areas	Slope stabilization	Bolivia
34	Rehabilitation of Tunnel 1 Cacheuta	Protection against falling rocks	Argentina
35	Slope stabilization route T350 Valdivia-Niebla	Slope stabilization	Chile
36	Soil improvement of organic soil in the substructure of a road or railway line with the Cut-Mixing-Injection method	In situ soil treatment	Germany

Table 12. Methodology-oriented innovation cases

8.2. PREVENTIVE ACTIONS

Preventive actions are defined as the set of activities and measures that, taken in advance, permit avoidance or minimising effects of damage and accidents.

Prevention is the most effective way to increase resilience of assets to natural hazards. The advantages of investing in this methodology are very evident, highlighting:

- the reduction of repair costs.
- minimization of the development and evolution of pathologies,
- minimization of the occurrence of damage;
- improvement of asset performance.
- increase in asset safety.

The activities applicable to these assets are divided into two groups:

- minor works - repair, deforestation and cleaning.
- monitoring - which includes inspections and instrumentation reading campaigns.

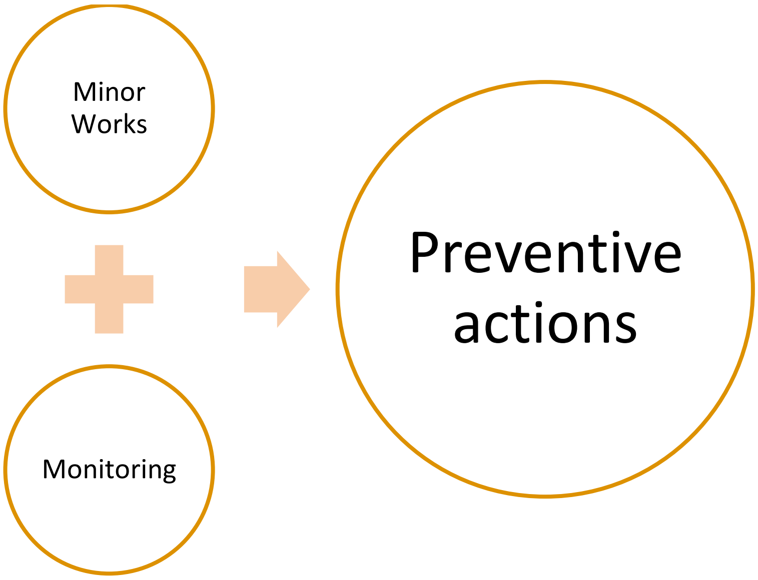


Figure 36. preventive actions as a result of minor works and monitoring application

The frequency of activities is variable and adapted to the state of maintenance and conservation of the asset in order to ensure its stability.

8.3. MAINTENANCE ACTIONS

Maintenance means "taking care" of an asset throughout its life cycle, promoting actions so that the components do not degrade, ensuring a state of conservation appropriate to the fulfilment of stability and integrity and promoting resilience to natural hazard.

The maintenance of an asset implies the adoption of a preventive and proactive methodology, in the alternative of a reactive and curative approach. Maintenance work and actions must therefore be planned in detail on an annual basis, and tailored to the specific needs of the asset.

Maintenance activities are based on three main pillars:

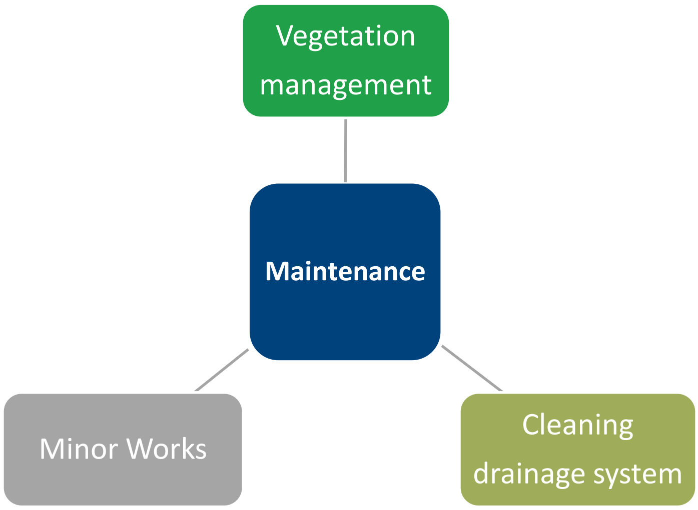


Figure 37. Main pillars of maintenance

These activities may improve the functionality and stability of the asset. They reduce and mitigate the evolution of pathologies. Although generally characterised by low technical complexity and low cost, they must be carried out by specialized teams with appropriate equipment.

Activity	Asset	Periodicity	Project	Cost
Minor Works	Earth structure / drainage system	Whenever necessary	no	low
Vegetation management	Earth structure	Every one or two years	no	low
Cleaning drainage system	Drainage system	Semestral/annual	no	low

Table 13. Suggested frequencies for maintenance activities

The work should be properly planned in order to evaluate the most appropriate access conditions and methodology, ensuring the appropriate selection of mechanical equipment and personal safety equipment, safeguarding the safety of workers and users and minimising their impact on the environment in which asset is located.

8.3.1. Minor works

Punctual and discrete, even if minor repairs are of utmost importance for the functionality and integrity of every single part of the assets.

These activities are generally identified and planned after periodic visual inspection. They originate from "natural wear or tear" and the result of natural or man-made events or incidents. As already mentioned, they are of reduced technical complexity and cost.

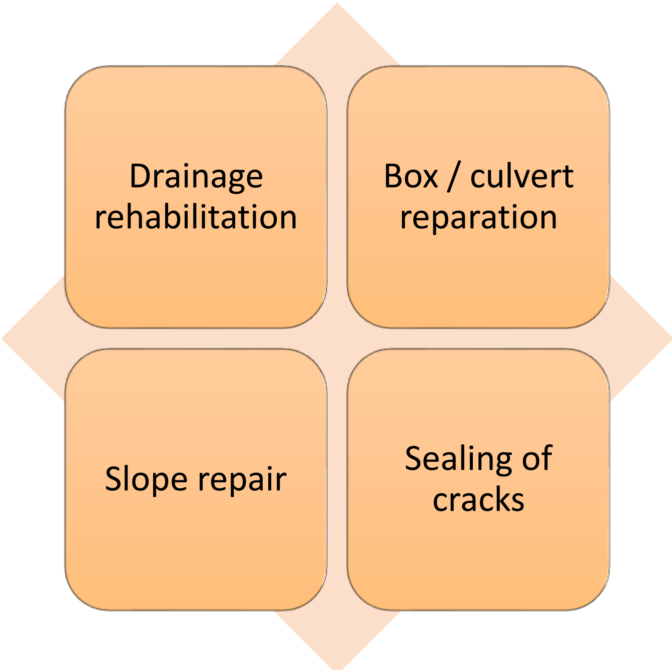


Figure 38. Minor works for earth structures

Some examples are given in following fig. 39.

Repair of foot ditch of talude

Reconstruction of drainage gulley

Slope repair | Sealing of cracks in drainage channel

Figure 39. Some examples of minor works for earth structures

8.3.2. Vegetation management

This activity consists in controlling undergrowth vegetation, trees and shrubs hanging over the road, weeds and reforesting. The three main objectives are:

1. stability - control of trees and shrubs and vegetation cover to prevent surface erosion.
2. risk of fire - preventing causes and limiting spread of fires.
3. safety - visibility of the signalling and demarcation of the carriageway.

Proper planning is essential, as an uncontrolled clearance can weaken the vegetation cover by exposing the structure to climate actions, increasing the risk of erosion and ravination phenomena. These activities should be coordinated by a team with the appropriate technical skills (agricultural engineer, forestry, biologic and landscape architect).

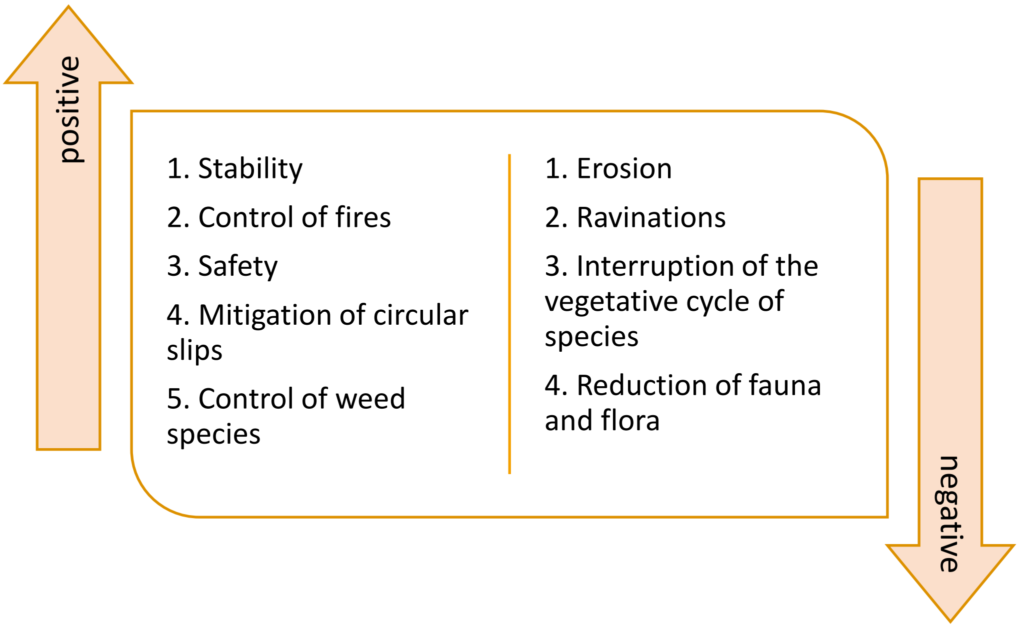


Figure 40. Vegetation control

Some examples are given in following fig. 41.

Cutting trees Vegetation management

Figure 41. Side vegetation control

8.3.3. Cleaning - superficial drainage system

The cleaning of the surface drainage system is essential to ensure its functionality in periods of high rainfall. It is a preventive activity, of low technical complexity and easy to be planned. Preferably it should be undertaken in non rainy periods (e.g. early spring or late summer in Mediterranean countries).

Some examples are given in following fig. 42.

Obstructed drainage Clean drainage

Figure 42. Drainage lines maintenance

9. ADAPTATION TO NEW CONDITIONS

9.1. GENERAL CONSIDERATIONS

Even when a perfect design has been carried out and all hazards have been taken into account, unexpected events can still occur, especially if related to climate changes and their impact on triggers.

A resilient approach is based on the acceptance of the possibility of the occurrence of unexpected events. In such cases, there is evidence that new conditions are to be considered in the design and the asset management (fig. 43).

Many papers in the literature review emphasized the idea that resilience is:

- The acceptance of events and disruptive events by users and owners
- The improvement of design and asset management practices, based on lessons learned and case history of the event
- The implication not only of the infrastructure management staff but also of the maintenance team, users and if necessary researchers Involvement implies a long-term investment in human resources, via team training, media communication with users, cooperative work with researchers and engineers, and development of research programs.

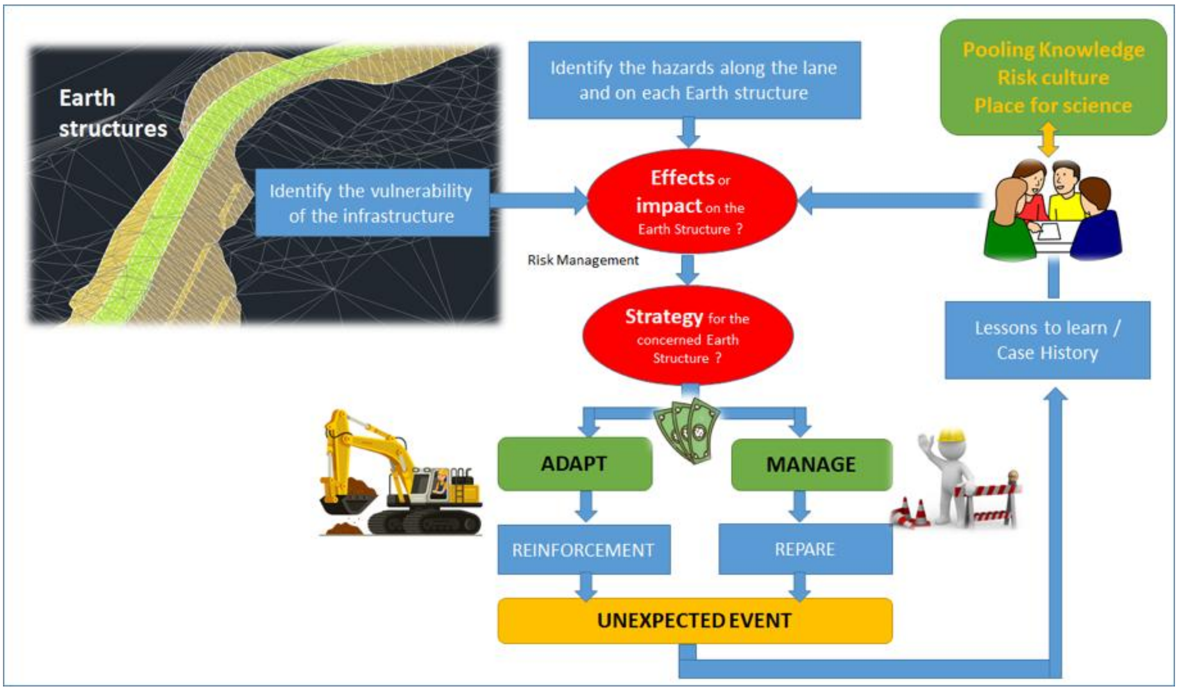


Figure 43. Adaptation actions flow chart

9.2. LESSONS LEARNED

Managers of road assets must learn from past experience. Maintenance teams can, therefore, collect information and gather it to provide a useful knowledge bank.

For a case study of unexpected events, it is very important to collect data concerning the altered conditions of site and natural triggers.

As an example, it is worth to quote the work done by the maintenance team of RN1, in La Réunion Island (for details refer to doc. [2], 2022R21EN – “*A PIARC Collection of Case Studies Report*”). In brief, information continuously collected during rockfalls permits to focus permanent solutionsand countermeasures that greatly reduce the occurrence of new events. In fig. 44 a comparison between frequency of events before (in blue) and after (in red) countermeasures having put in place.

Rockfalls on RN1, Cliff side

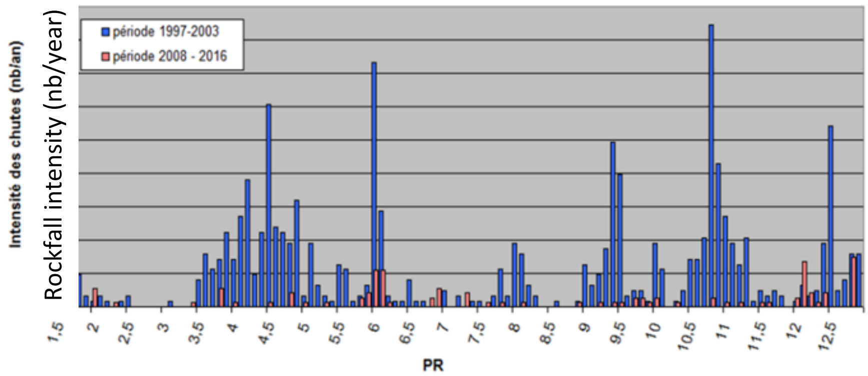


Figure 44. Example of rockfalls intensity measures (number of falls) along the RN1 in La Réunion Island. In blue the registration of rockfalls before work and in red, the same information after the countermeasures. This information collected by the maintenance team is a great help for the geotechnical engineer to design the retaining structure and their location.

9.3. Temporary Solutions subsequent to Failure

After a failure has occurred, immediate actions must be taken to safeguard users on the road and/or railways, as well as surrounding dwellings, factories, dams, energy transmission lines, natural environment.

The main objectives of these temporary measures are:

1. marking the place and limiting access to it, as to prevent consequent accidents involving people, animals and vehicles;
2. erecting containments or temporary structures and putting in place detours (roads or water resources) to prevent effects of further landslides and/or rockfalls with a consequent aggravation of damage to the structures.

There is a large amount of temporary measures and each specific situation should be studied in detail in order to choose the most appropriate solution, with greatest ease of implementation and speed.

Typology of temporary solutions :

1. Marking of the place
    - Installation of sealing nets,
    - Installation of panels for warning,
    - Installation of safety signs and equipment to mark out and label the site.

2) temporary signage

- deviations from the affected roads, directing traffic to other alternative roads, stopping traffic if there are no alternatives;
- road construction to connect the section that has been put out of service;

3) Redirecting water flow;
4) Construction of cofferdams;
5) Contentions:
    - containment landfills;
    - support/containment structures.

Some examples of temporary solutions to be adopted are presented in the following fig. 45.

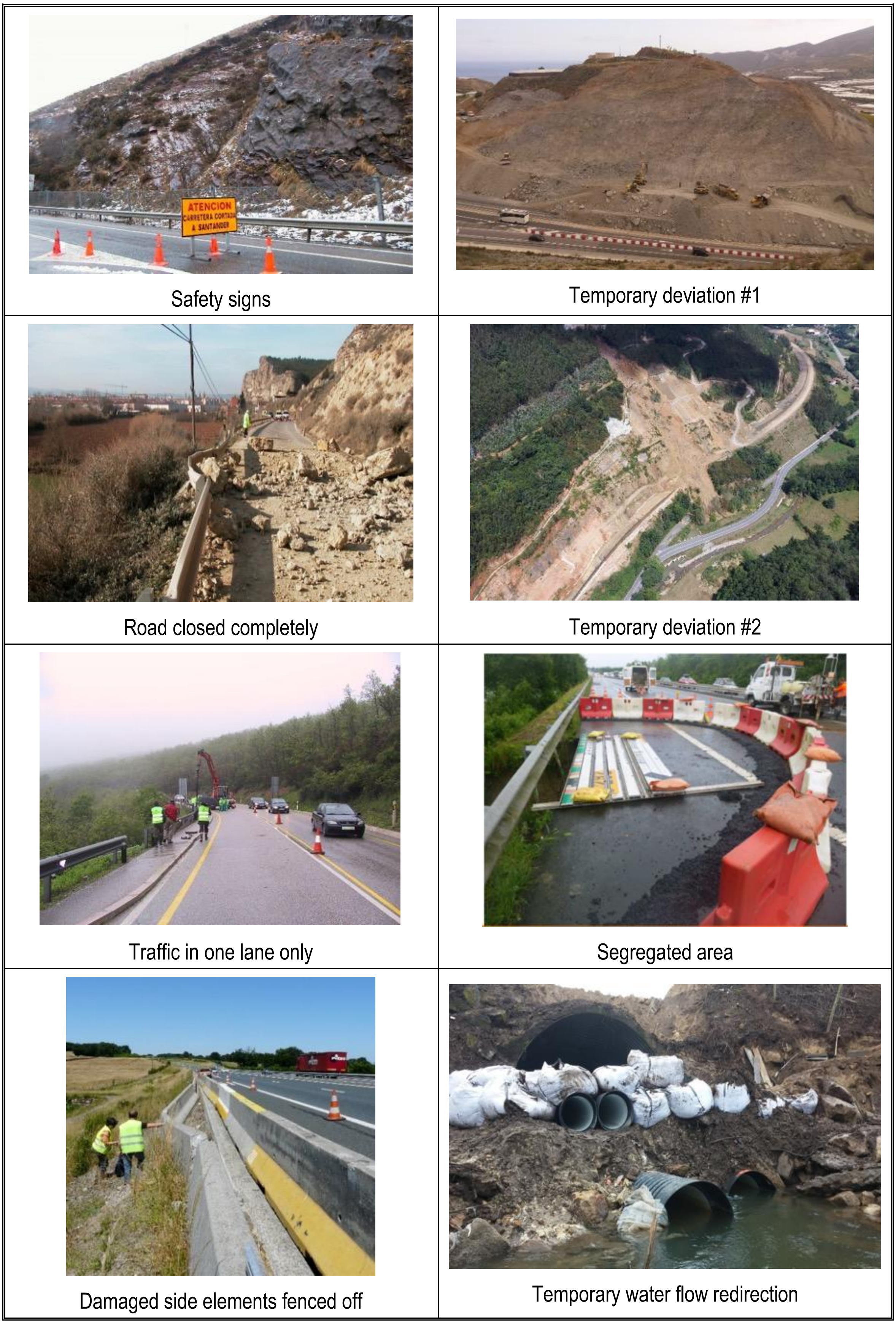


Figure 45. Miscellaneous adaptation cases

10. RECOMMENDATIONS

10.1. RECOMMENDATIONS FOR DECISIONS MAKERS

The state of each earth structures (part of a road infrastructure) has to be health-checked through regular inspections. After each inspection, experts can decide whether further work is required (maintenance, cleaning, minor works, etc.). The comparison with the initial state is of great importance to evaluate dynamics of ground movement or site transformation, and then decide on the appropriate level of intervention. The timeframe of inspections depends on the importance of the infrastructure and can vary from annual to every five years or more in case of no events (frequency of inspections must be adapted after damage-producing events).

The development of a catalogue of repair techniques that allows application of predefined measures immediately after an event, can greatly reduces the intervention time in the case of damage (preparedness).

After events, even if no damage has occurred, the stakeholder needs to organize and plan future works, based on a geotechnical study, location coordinates, data coming from monitoring, health check of the structures and the identification of associated natural hazards, after having updated thematic maps with information collected after event. In case of earth structures damage or collapse, it is highly advisable to inspect and identify other earth structures in similar conditions than the one that has failed, and programme and prioritise adaptation and improvement works for the following years (“lesson learned” – or observational approach).

It is important to observe that monitoring helps both **asset and risk management**, permitting to delay intervention and to improve applied solution.

10.2. RECOMMENDATIONS FOR PIARC

One of the keys to resilience of earth structures is a rigorous inspection, monitoring, and maintenance program. For future work cycles, we recommend PIARC to consider the development of an asset management manual adapted for earth structures.

11. CONCLUSIONS

Earth structures generally represent the main part of road infrastructure. Depending on the condition of the location, as they can represent more than 80% of the total length. With this consideration in mind, it is very important to ensure that they are properly maintained.

As earth structures are very sensitive when it comes to weather and its impacts (rainfall, flooding, erosion, winds), climate change is likely to considerably greatly increase the impact of the "weak link" of earth structures inside a road infrastructure.

It is, therefore, of utmost importance to define an earthworks' infrastructure asset management model that is based on an adaptive and resilient approach, using techniques derived from risk analysis. In this way, effects of expected and even unexpected events related to natural hazard can be easily faced by asset manager organisations.

<u>In this sense, adapted design and maintenance are the keys for a efficient asset management</u>.

Resilient design is based on:

- Correct design data, taking into account climate change effects.
- The ease of repair the earth structure.
- The complexity of access to the site and the expected timeframe for emergency response: if the access if difficult, companies will take time to move machinery and materials.
- The type of failure and deformation: some structures are very rigid, others are more flexible; this means that some earth structures will accept greater strain without failure whereas with others collapse may occur in a brittle manner after the development of a small number of cracks.
- The level of the global asset management of the infrastructure: well known risks, correctly prepared budgets, availability of by-passes, trained maintenance teams; all these criteria will ease the final decision.

Maintenance is based on:

- Periodic inspection of structures,
- Monitoring of structures and their surrounding natural environment,
- Cleaning of drainage systems,
- Minor works in order to keep assets in perfect order.

A resilient approach can only be applied when a specific hazard has been previously identified and addressed. It is, therefore, highly recommended to map the hazards and the corresponding expected damage and failure affecting earth structures. Information can be saved on a computer with specific software (SustIMS in Ascendi in Portugal and HAGDMS in the UK are consistent examples).

In any case, unexpected events can occur at any moment, especially if they are related to climate change.

<u>A resilient approach is based on the acceptance of the possibility of occurrence of unforeseen events</u>.

Preparedness of organisations, therefore, permits response to unexpected events in a way to reduce out of service periods and, above all, to ensure the safety of users.

An adaptive and resilient approach, based on highlighted features, is certainly effective to reduce, mitigate, and minimise the risk of damage, increasing at the same time both the ability of earth structures to withstand natural hazards and safety of all kinds of users, even in case of adverse unexpected events. Of course, this methodology has to be adapted to specific geographical and geological conditions.

A resilient approach should be as much oriented to environmental sustainability as practicable to permit cost reduction (prevention is less expensive than repair) and minimization of intervention and resources consumption.

It should be pointed out that maintenance and visual inspection are the minimum to guarantee an adequate performance in terms of safety and stability on a short-term basis only. This conclusion is particularly interesting for LMICs where budget is very often a significant constraint.

In conclusion, resilience for earthworks is based on a methodology in which the whole life-cycle of the structure is taken into consideration (design, construction, maintenance, adaptation, repair, fig. 46) and every phase of the cycle is taken into account in its relationships with the following one: in such way, the responsibility of asset managers is not restricted to a part of the life-cycle only but it is extended and made effective, having in mind that it is mandatory to design, build and operate safe and useful infrastructures in every condition starting from HICs to LMICs.

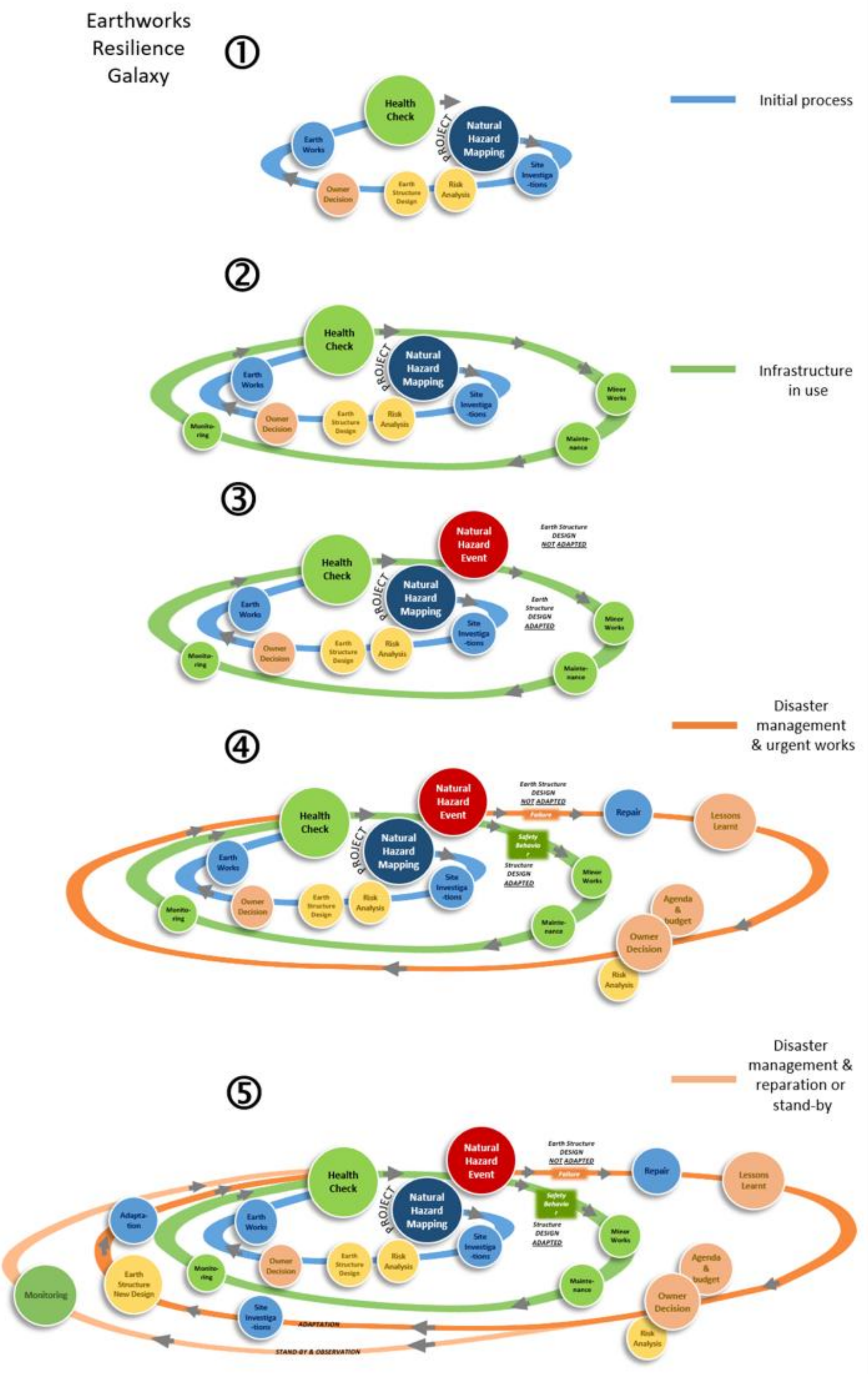


Figure 46. Resilience-enhancing methodology

12. GLOSSARY

Term	Definition
HIC	High Income Country
LMIC	Lower-Middle Income Country
LOF	Loss Of Functionality
TC	Technical Committee
UMIC	Upper-Middle Income Country

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ANNEX 1 - ENQUIRY ON RESILIENCE - RESULTS

To gather information regarding the concept of 'resilience' applied to the design, construction, and repair of earth structures subject to natural hazards (including those due to climate change) in different countries and to collect data on cases, techniques and practices employed, an enquiry was distributed among members of our TC.

The framework of the enquiry was as follows:

> ***Question 1:*** *In your opinion, what does the concept of 'resilience' mean when applied to geotechnical assets?*
>
> ***Question 2:*** *In your opinion, what are the main features or parameters to describe a resilient geotechnical system?*
>
> ***Question 3:*** *In your opinion, what are the possible benefits inferred from the application of a 'resilient' design approach to the geotechnical assets?*
>
> ***Question 4:*** *Are there standards/best practices in your country that explicitly implement design approaches or technical maintenance strategies to guarantee the resilience of a geotechnical asset?*

Questions were collected fro countries summarized in the following table 1.

	Country	Answers			
		Question 1	Question 2	Question 3	Question 4
1	Benin	Y	Y	Y	-
1	China	Y	Y	Y	Y
2	France	Y	Y	Y	Y
3	Italy	Y	Y	Y	Y
5	South Korea	Y	Y	Y	Y
6	Spain	Y	Y	Y	Y

	Country	Answers			
		Question 1	Question 2	Question 3	Question 4
7	United Kingdom	Y	Y	Y	Y

Table 1: Countries that gave contributions to enquiry

Question by question, the answers collected are summarized in the following tables 2-5.

	Country	***Question 1 : In your opinion, what does the concept of 'resilience' mean when applied to geotechnical assets?***
1	Benin	Le concept de résilience appliqué aux ouvrages géotechniques est leur capacité à résister dans le temps aux effets de l'utilisation, de l'usure, aux éléments tels que l'eau, le vent, aux agents agressifs.
1	China	Means properties of materials, what materials, construction technology, construction methodology, construction quality. Resilience also means the earthwork could to a certain extent return to its usual shape after natural hazards (usually weather effects).
2	France	C'est la capacité pour un ouvrage de répondre à sa fonction de façon durable dans son environnement face à ses sollicitations naturelles ou anthropiques et en fonction de leurs évolutions, et en cas d'évènements exceptionnels et/ou majeurs.
3	Italy	Resilience is the intrinsic ability of a system to modify its functioning before, during and following a change or a perturbation, so as to be able to maintain its functionality both in foreseen conditions and in unforeseen conditions.
5	South Korea	Resilience means to "prepare and plan for (called "First part")" and "more successfully adapt to of recover from (called "Second part")" the adverse events of disruptions. The first part implies the preparation and plan in advance before anticipated disasters which includes mainly establishment of system or network to enhance resilience to geotechnical events. The second part means successful recovering from the disasters and regaining functionality of geotechnical assets by appropriate design approaches to enhance the resilience. In my opinion, most of the engineers (including myself) seem to focus more on the second part whereas the government officials, planners or bureaucrats do more on the first part.

	Country	Question 1 : In your opinion, what does the concept of 'resilience' mean when applied to geotechnical assets?
6	Spain	En ingeniería de materiales, RESILIENCIA es el área de la zona que queda bajo la rama elástica en un diagrama tensión-deformación (ensayo de tracción) que, por tanto, tiene ecuación dimensional de energía o trabajo, es decir fuerza multiplicada por desplazamiento por unidad de volumen y en el SI de unidades se mide en J/m^3. El ensayo que permite su determinación es el del péndulo de Charpy.  Por tanto, se corresponde con la energía que es capaz de absorber un material en su rango elástico de deformación, antes de sufrir plastificaciones. El término ha pasado con este significado cuasimetáforico a otros campos como el de la psicología o la biología, así en este último ámbito se entiende como *"Capacidad de adaptación de un ser vivo frente a un agente perturbador o un estado o situación adversos"* (definición del Diccionario de la Real Academia Española de la Lengua). De forma similar este concepto ha pasado al mundo de las infraestructuras, desde nuestro punto de vista, la definición del diccionario español es perfectamente extrapolable al mundo de las infraestructuras como: *"Capacidad de adaptación de* ***una infraestructura/activo geotécnico*** *frente a un agente perturbador o un estado o situación adversos"* Este agente externo puede comprender no solamente acciones climáticas, sino que puede extenderse a un sentido más amplio, como aumento de demanda de uso, de cargas, catástrofes naturales e incluso sabotajes.
7	United Kingdom	Resilience is *the ability of an asset, network or system to anticipate, absorb, adapt and/or rapidly recover from a disruptive event*. This definition can be applied at a variety of levels, for example, it may be applied at an operational level to a single geotechnical asset, such as an earthwork or natural slope or to a length or highway, or it may be applied at a strategic level to a highway network or transport system. A disruptive event may be a naturally occurring ground-related hazard, such as a landslide or solution

	Country	Question 1 : In your opinion, what does the concept of 'resilience' mean when applied to geotechnical assets?
		feature, or it may be a man-made event, such as ordnance being encountered.

Table 2: Answers to question 1

	Country	Question 2 : In your opinion, what are the main features or parameters to describe a resilient geotechnical system?
1	Benin	Ces caractéristiques sont la capacité de résistance aux charges, aux surcharges, à l'eau, au vent, aux variations climatiques.
1	China	Water stability, temperature stability, internal friction angle, control of water.
2	France	C'est un ouvrage robuste construit avec des matériaux nobles dans les règles de l'art comportant des dispositions constructives associées lui permettant de se protéger/préserver dans son environnement de facteurs externes évolutifs ou périodiques indépendant de sa fonction de base.
3	Italy	A geotechnical system is to be considered resilient if it has certain characteristics or capabilities: • ability to adapt to changes without major damage; • presence of a monitoring system to control and supervise the system performance to anticipate failures; • easiness to repair damages in order to shorten as much as reasonable periods of out of service; • possibility to easy introduce modifications that permit to cope with similar hazards in the future.
5	South Korea	The resilient geotechnical system has to be basically aimed at or applied for the permanent solution rather than for temporary measures. Thus the parameters for resilient system are to be on a long term basis, i.e. 30 years or 50 years, etc. with regard to design, construction and materials aspects. Safety, economy, environment and constructability are to be basic and main features. In more detailed terms, the main features or parameters for the resilience of geotechnical system can be categorized as below. (1) Design parameters

<table>
<tr><th colspan="2">Country</th><th>Question 2 : In your opinion, what are the main features or parameters to describe a resilient geotechnical system?</th></tr>
<tr><td></td><td></td><td>Geomorphological and geological characteristics, Geotechnical properties, Underground water conditions and Rainfall data.

(2) <u>Construction method</u>
Simple and easily constructive method are recommended to reduce recovering time. In selection of construction method, the accessibility, mobility and availability of plant and equipment, working space are to be examined.

(3) <u>Materials</u>
- Easily available or secured from nearby area.
- Eco-friendly materials
- Durable materials
- Favorable for maintenance

(4) <u>Maintenance</u>
Efficient maintenance works requiring less physical inspection and, if possible, with remote monitoring system.</td></tr>
<tr><td>6</td><td>Spain</td><td>Indicadores que permitan evaluar la respuesta del sistema frente a cada agente. Tanto los indicadores como los agentes deben ser concretos.

Por ejemplo: movimiento vertical (asiento) en la coronación de un terraplén ligado a un episodio de lluvia excepcional (superior a un umbral a definir en cada caso), así podría ser: Asiento de 10 mm (hito nº x) para una lluvia de 125 mm/día (T_{ret}=75 años).</td></tr>
<tr><td>7</td><td>United Kingdom</td><td>The first part of a resilience assessment, at a geotechnical asset level, is to develop an understanding of the role the geotechnical asset in any wider network or system and it needs to understand the performance requirements and objectives at asset, network and system levels. The assessment needs to have access to an inventory of assets, including non-geotechnical assets and other infrastructure (including third-party assets) that are linked to or reliant on geotechnical performance, and an understanding of their inter-relationships. In addition, the assessment should consider asset condition, alongside an understanding of whole-life performance and deterioration, as well as asset and network criticality.

The next part of a resilience assessment is to develop knowledge and understanding of the hazards that may impact the asset, system or network. Natural and man-made hazards need to be identified and the mechanisms of occurrence need to be understood, alongside the possible impact of their occurrence, which should be informed by an understanding</td></tr>
</table>

	Country	Question 2 : In your opinion, what are the main features or parameters to describe a resilient geotechnical system?
		of asset vulnerability. These items need to be measurable, either quantitatively of qualitatively, to inform assessments of likelihood, consequence and risk, which are all needed prior to considering resilience and response. Levels of acceptable, tolerable and unacceptable risk also need to be determined. The ability to respond to a hazard event needs to be understood as this will impact any measure of consequence and this will be improved by implementing proactive monitoring, mitigation and preventative measures. These will include physical techniques and methods as well as organisational processes and procedures, for example network and asset management plans, emergency response plans, resource and supply chain availability, diversion routes etc. Once these criteria are understood, it is important to identify actions to improve resilience and these will likely focus on an element's ability to resist a hazard, its reliability, any redundancy in the network to function without an element, as well as response and recovery.

Table 3: Answers to question 2

	Country	Question 3: In your opinion, what are the possible benefits inferred from the application of a 'resilient' design approach to the geotechnical assets?
1	Benin	Les avantages sont la tenue dans le temps, le confort des usagers et l'atteinte des objectifs de la conception.
1	China	Improve the ability to resist natural disasters. When suffering from natural disasters, speed up the progress of restoration and reduce the cost of restoration.
2	France	Économie d'entretien sur la durée de vie de l'ouvrage (ralentissement du vieillissement, diminution des interventions hors entretien courant), maintient de l'intérêt socio-économique que représente l'ouvrage (continuité du réseau).
3	Italy	• Less vulnerability of geotechnical assets against natural phenomena, even extreme ones; • Cost savings through tested and improved recovery techniques, if damages occur; • Time savings in restoring the damaged part, if any;

	Country	Question 3: In your opinion, what are the possible benefits inferred from the application of a 'resilient' design approach to the geotechnical assets?
		• Increasing of asset life through more efficient and easier maintenance.
5	South Korea	• Save time in restoring the damaged part systematically. • Cost saving through improved recovery techniques or preplanned methods. • Increase asset life through efficient maintenance.
6	Spain	• Mantenimiento de la vialidad de infraestructuras críticas (carreteras) en caso de catástrofe o situación excepcional. • Menores costes de conservación del activo geotécnico y de explotación de la carretera en su conjunto. • Mejor evaluación de activos para priorización y optimización de inversiones.
7	United Kingdom	Design is only a small part of an asset's life-cycle and it is crucial that designers understand their role in the whole lifetime of an asset. A resilient design demonstrates an understanding of condition, performance and deterioration over the asset's lifetime and must allow for proactive inspection, maintenance activities and interventions that will not adversely affect the asset's ability to perform.

Table 4: Answers to question 3

	Country	Question 4: Are there standards/best practices in your country that explicitly implement design approaches or technical maintenance strategies to guarantee the resilience of a geotechnical asset?
1	Benin	(no answer)
1	China	There are different design standards for different geological conditions.
2	France	A priori pas de guide « direct » sur le sujet. La notion de résilience et cependant implicite à de nombreux guides du Cerema ou de l'IFSTTAR que j'utilise. En effet, cela manque peut-être. Tous guides sur la pathologie et la réparation des ouvrages. Voir nos sites du RST.

	Country	Question 4: Are there standards/best practices in your country that explicitly implement design approaches or technical maintenance strategies to guarantee the resilience of a geotechnical asset?
3	Italy	Not yet specific standards but elements are present in National Building Code (2018) and EuroCode. Best practices are generally prepared in specific cases and make part of projects of new works and maintenance works.
5	South Korea	We don't have standards/practices or technical maintenance strategies that explicitly implement design approaches to guarantee the resilience of a geotechnical asset. Although there have been many concerns on climate change impacts and related disasters, thus counter measures and practical strategies being studied and developed by government subsidized organizations or private institutes, the system or network for enhancing resilience to geotechnical events have not been established yet. In general, the term "Resilience" is deemed not so familiar in our geotechnical engineering /construction society who, therefore, are not ready for enhancing resilience to geotechnical events proactively.
6	Spain	Las prácticas (obras y otras actuaciones) de la Subdirección General de Conservación de la Dirección de Carreteras (y equivalente del resto de administraciones españolas) están enfocadas, entre otros aspectos, a garantizar la resiliencia (entendida en sentido amplio, como se ha indicado en la pregunta 1) de las carreteras. Reparaciones, adecuaciones a nuevas situaciones de aumento de carga de tráfico, caudales de drenaje…etc., todo ello sobre carreteras en servicio. Desde el punto de vista normativo y a modo de ejemplo, en el campo de la hidráulica aplicada a la carretera, la nueva *5.2 IC Drenaje Superficial* (de 2016, sobre una versión previa de 1990) ha actualizado los criterios y parámetros de diseño relacionados con este particular.
7	United Kingdom	We have standards and best practice guidance, but these do not guarantee the resilience of a geotechnical asset on their own. The standards and guidance provide asset managers, engineers and other specialists with knowledge, tools and techniques so that resilience can be assessed, measured and improved. For instance, CD 622 and CS 641 (within the Design Manual for Roads & Bridges) outline processes for managing geotechnical risk and highway geotechnical asset maintenance, respectively. Guidance on Highway's England's Resilience Assessment Framework, which is split into two parts,

Country		***Question 4: Are there standards/best practices in your country that explicitly implement design approaches or technical maintenance strategies to guarantee the resilience of a geotechnical asset?***
		is available to our supply chain through the HA GDMS reports repository (references 31685 and 31686).

Table 5: Answers to question 4

World Road Association (PIARC)

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