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INNOVATIONS AND TECHNIQUES - APPLICATION TO EARTH STRUCTURES IN THE FUTURE

A PIARC TECHNICAL REPORT

TECHNICAL COMMITTEE 4.3 *EARTHWORKS*

STATEMENTS

The World Road Association (PIARC) is a nonprofit organisation 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 organisations or agencies.

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TC 4.3 was chaired by Patrick Boisson (France). The secretaries were Yasmina Boussafir (France), Paul Nowak (United Kingdom), and Natalia Perez (Mexico) for the French, English, and Spanish languages, respectively.

TC 4.3 Earthworks is focused on resiliency of earthworks and earth structures, and the WG2 focused on one of the topics, namely "Techniques and Innovations in Earthworks".

This work was devoloped with the contributions of several members of WG2, and the principal team responsible for this document is listed in the table below.

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EXECUTIVE SUMMARY

2023R36EN

INNOVATIONS AND TECHNIQUES - APPLICATION TO EARTH STRUCTURES IN THE FUTURE

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As we move further into the 21st century, it is becoming increasingly more clear that climate change is the biggest concern that we must face. The effects of climate change, specifically the increasing frequency and intensity of natural hazards, are wreaking havoc on infrastructure, including earth structures, around the globe. The need for more resilient earth structures requires firm and bold action by owners, managers, stakeholders and the whole scientific community.

The purpose of this report is to expand upon the work found in the first report published by Working Group 2 (WG2) of Technical Committee 4.3 Earthworks (TC4.3) titled Techniques and Innovations in Earthworks – A PIARC Collection of Case Studies (2022R11EN). The case studies report included 36 case studies from countries all around the world showcasing innovative solutions and techniques related to various aspects of earthworks and earth structures. Innovation will be the key to fight the effects of climate change through more resilient and sustainable earth structures.

This report aims to be a "future vision" of the path we must follow in the sustainable management of earth structures throughout the life cycle. Making decisions and finding solutions in all phases of an earth structure's life cycle will be key in long lasting, sustainable, and resilient earth structures. This report includes a chapter focused on the various phases of the life cycle, followed by a chapter taking a deeper dive into the maintenance phase including a focus on drainage, a key component in the resilience of an earth structure. Resilience indicators, part of a new tool for estimating the value of an earth structure's resilience, are introduced and presented in the fifth chapter. This tool would be useful for an agency or owner looking to build an asset management program for their earth structures.

The report concludes by identifying current and future challenges and some recommendations for future work to be undertaken by PIARC in hopes of progressing this topic among nations of all sizes.

CONTENTS

1. INTRODUCTION

As we move further into the 21st century, it is becoming increasingly more clear that climate change is the biggest concern that we must face. The effects of climate change, specifically the increasing frequency and intensity of natural hazards, are wreaking havoc on infrastructure, including earth structures, around the globe. The need for more resilient earth structures requires firm and bold action by owners, managers, stakeholders and the whole scientific community.

The scientific community has developed international, national, and regional climate change scenarios. These scenarios have been created by scientists to provide a tool for engineers and scientists to plan for the future. The design of earth structures from previous years needs to be improved through innovation and forward thinking to be able to withstand future natural hazards.

1.1. Purpose of the Report

The purpose of this report is to expand upon the work done in the first report published by Working Group 2 (WG2) of Technical Committee 4.3 Earthworks (TC4.3) entitled Techniques and Innovations in Earthworks – A PIARC Collection of Case Studies (2022R11EN). The case studies report includes 36 cases from countries all around the world showcasing innovative solutions and techniques related to various aspects of earthworks and earth structures. There are case studies on testing of materials and other means for collecting information, repairs of earth structures, maintenance of in-service earth structures, and combinations of all of these.

This report is focused on the following for now and the future, as illustrated in Figure 1:

1) Emphasizing the importance of innovation in the life cycle of earth structures and how the innovations in those case studies can be used at various stages in the life cycle;
2) Answering the questions and challenges to leverage resilience to natural hazards, moving toward the sustainability of the life cycle; and
3) Determining why we need to Innovation

Figure 1 – The goals for Design Phase

If we want to innovate, we have to set this as a goal in the design phase!

1.2. Framework of the Report

This report aims to be a "future vision" of the path we must follow in the sustainable management of earth structures throughout the life cycle. It consists of, beyond the introductory chapter, five more chapters. The second chapter describes the life cycle of earth structures. The third is dedicated to earthworks and drainage – a future approach in the design and construction phases. Maintenence works and monitoring during the operation phase are part of Chapter 4. Resilience indicators, part of a new tool for estimating the value of an earth structure's resilience, are presented in the fifth chapter. And in the sixth and final chapter, conclusions and future challenges are presented.

2. LIFE CYCLE OF EARTH STRUCTURES

The premise of a life cycle is similar across all types of assets. This life cycle consists of a design phase, construction phase, maintenance and operation phase, and repair and rehabilitation phase, likely with multiple iterations of maintenance and operation phases and repair and rehabilitation phases. Figure 1 shows the general life cycle of a structure, such as a bridge or building.

Included in the initial construction phase is the design, where critical decisions are made that can contribute to the efficiency and success of the remainder of the life cycle of the structure.

The life cycle of earth structures is similar but can have a distinct difference. Some earth structures, such as a natural embankment or side slopes of a hill or mountain, may begin in the middle of the life cycle. Thus, the life cycle of an earth structure often looks more like a circle (Figure 2). This distinct difference is important, as it requires the asset owner to manage the life cycle of the earth structure not from a true starting point, such as initial construction, but in the middle, such as the maintenance or operation phase.

Figure 2 – Life Cycle of an Asset

The resilience of the earth structure can be improved with steps taken during each phase. For example, consideration of material types during design may improve the overall resilience of the earth structure during its operation phase. Routine preventative maintenance actions taken during its operation phase, such as clearing drainage paths and inspection, can provide a longer lasting structure. Each phase of the life cycle has an influence over the longevity of the earth structure.

3. EARTHWORK AND DRAINAGE – FUTURE APPROACH

3.1. DESIGN PHASE, HOW CAN WE PREPARE BETTER DESIGNS?

The design phase of an earth structure is where decisions are made that ultimately affect its entire life cycle. The focus of future earth structures will undoubtedly be on resilience and sustainability. Resilience, as has been defined by another PIARC TC4.3 Report titled "PIARC LITERATURE REVIEW INCREASING RESILIENCE OF EARTH STRUCTURES TO NATURAL HAZARDS". A good definition of sustainability is fulfilling the needs of today's generations without compromising the needs of future generations while ensuring a balance between the economy, the environment, and society. Resilience is an underlying theme in sustainability – for infrastructure to be "sustainable", it must be "resilient" to natural hazards and a changing climate. As such, it is mandatory to develop the design in accordance with following pyramid (Figure 3), which considers sustainability at every step in the design proces. With this methodology, the earth structure will be on the right path to a resilient life cycle.

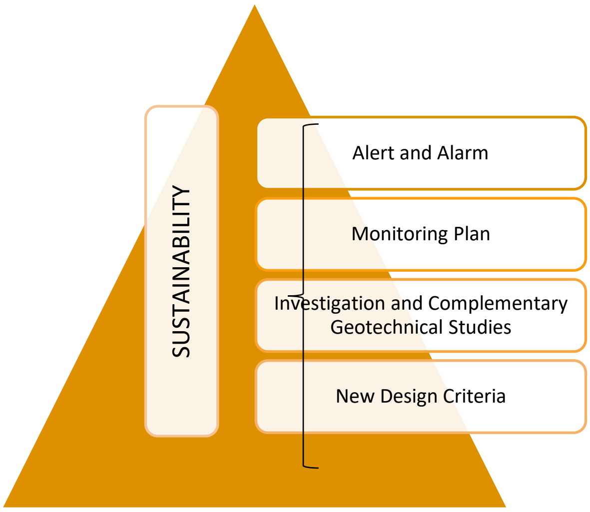


Figure 3 – Sustainability in the Design Phase

3.1.1. New Design Criteria

The project team should be multidisciplinary, consisting of a wide range of technicians – engineers, geologists, biologists, and landscape architects, among others, who work as a team to develop a more sustainable study in the technical, economic, social, and environmental aspects. In this stage, we must thoroughly evaluate the functionality of the structure, not just today but in the future, as well as consider the potential risks that the structure will see during its entire life cycle. It is much simpler to address potential risks and challenges to the earth structure during the design phase than during its in-service condition.

Due to climate change, it is very important to collect all weather data and extreme phenomena. In addition to this analysis, a historical search should be carried out on incidents or events that may have affected the site. In the case of rehabilitation or reinforcement projects of earth structures, it is also important to carry out a collection of:

- property information/ inventory and historic information from year of construction up to the project date;
- identification of all maintenance and repair activities;
- visual inspections and instrumentation reading,

- identifying the current state of maintenance and conservation and properly size the structure, with attention to the sizing of the drainage system.

The project should also reflect the functionality for which the structure is sized, ensuring its integrity, the level of service established and the security of the environment throughout the life cycle of the asset.

The design criteria are summarized in Figure 4.

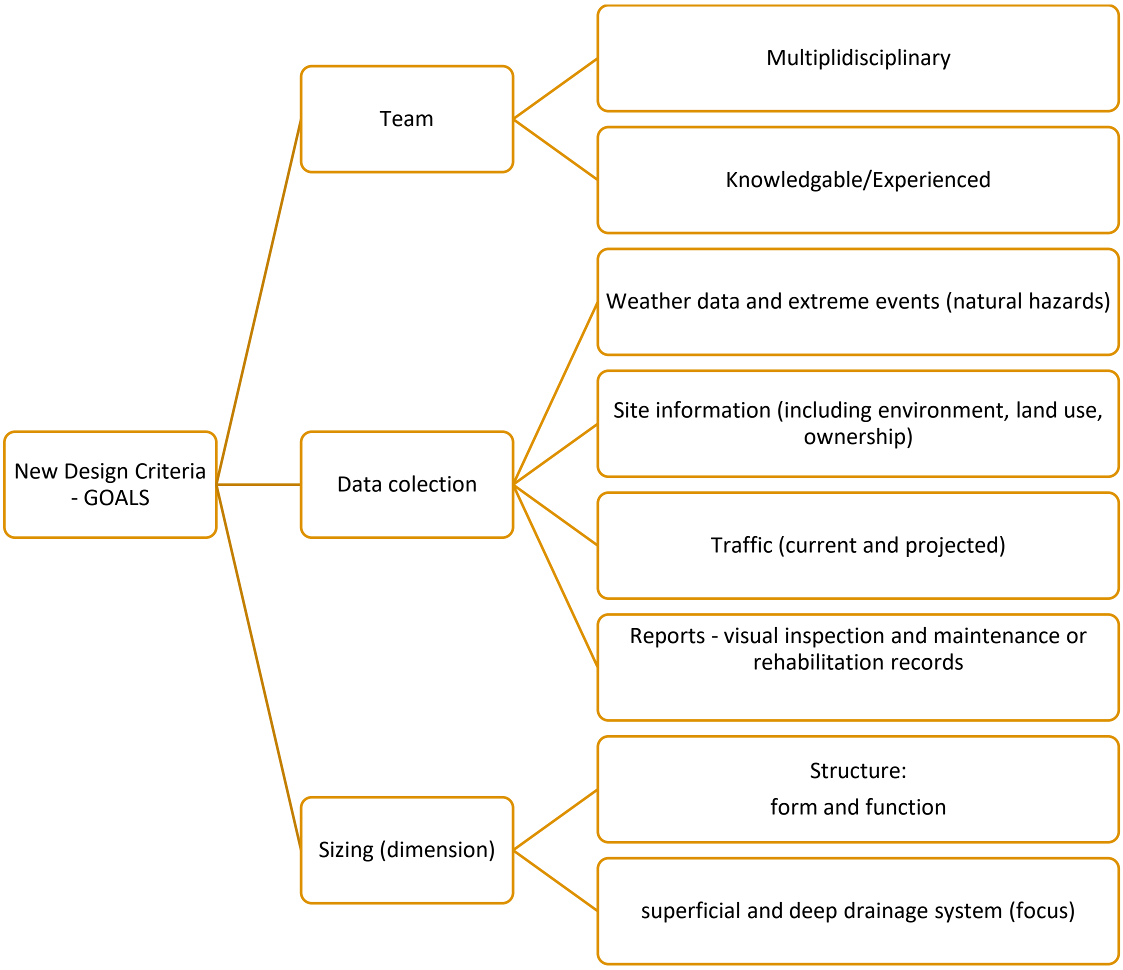


Figure 4 – Design Criteria

It is important, at the project stage, to study the scenarios of climatic vunerability RCP4.5 and RCP8.5, and the effects of climate change. This approach gives the sensibility for the team designer and the owner to be able to choose the most appropriate solution for each case study and earth structure.

What is RPC, RCP 4.5 and RPC8.5?

Definitions:

IPCC - Intergovernmental Panel on Climate Change. IPCC is the United Nations' body for assessing the science related to climate change.

RPC - Representative Concentration Pathway. RCP is a greenhouse gas concentration (not emissions) trajectory adopted by the IPCC. The pathways describe different climate futures, all of which are considered possible depending on the volume of greenhouse gases (GHG) emitted in the years to come. To understand how our climate may change in future, we need to predict how we will behave.

RCP 4.5 is described by the IPCC as an intermediate scenario. Emissions in RCP 4.5 peak around 2040, then decline. According to resource specialists IPCC emission scenarios are biased towards exaggerated availability of fossil fuels reserves; RCP 4.5 is the most probable baseline scenario (no climate policies) taking into account the exhaustible character of non-renewable fuels.

RCP 8.5 is generally taken as the basis for worst-case climate change scenarios and was based on what has proven to be an overestimation of projected coal outputs. It is still used for predicting mid-century (and earlier) emissions based on current and stated policies.

Figure 5 shows the scenarios for Representative Concentration Pathways.

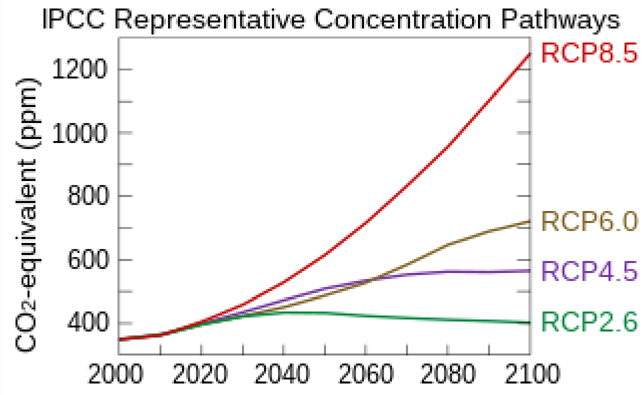


Figure 5 – Representative Concentration Pathways

All forcing agents' atmospheric CO_2-equivalent concentrations (in parts-per-million-by-volume (ppmv)), according to the four RCPs, are used by the fifth IPCC Assessment Report to make predictions.

In Figure 6, the three intervals for each scenario and the parameters evaluated are shown.

RCP4.5	RCP8.5	Parameters
•2011-2040 •2041-2070 •2071-2100	•2011-2040 •2041-2070 •2071-2100	•Temperature •Precipitation •Relative Intensity •Relative humidity •Global radiation •Thermal amplitude •Drought index •Evapotranspiration •Fire risk index •Climate classification

Figure 6 – RPC, intervals and parameters

From where do RCPs come?

The RCPs were used in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) in 2014 as a basis for the report’s findings. Previous IPCC assessment reports used a set of scenarios know as SRES (Special Report on Emissions Scenarios), which start with socioeconomic circumstances from which emissions trajectories and climate impacts are projected. In contrast, RCPs fix the emissions trajectory and rather than the socioeconomic circumstances as shown in Figure 7.

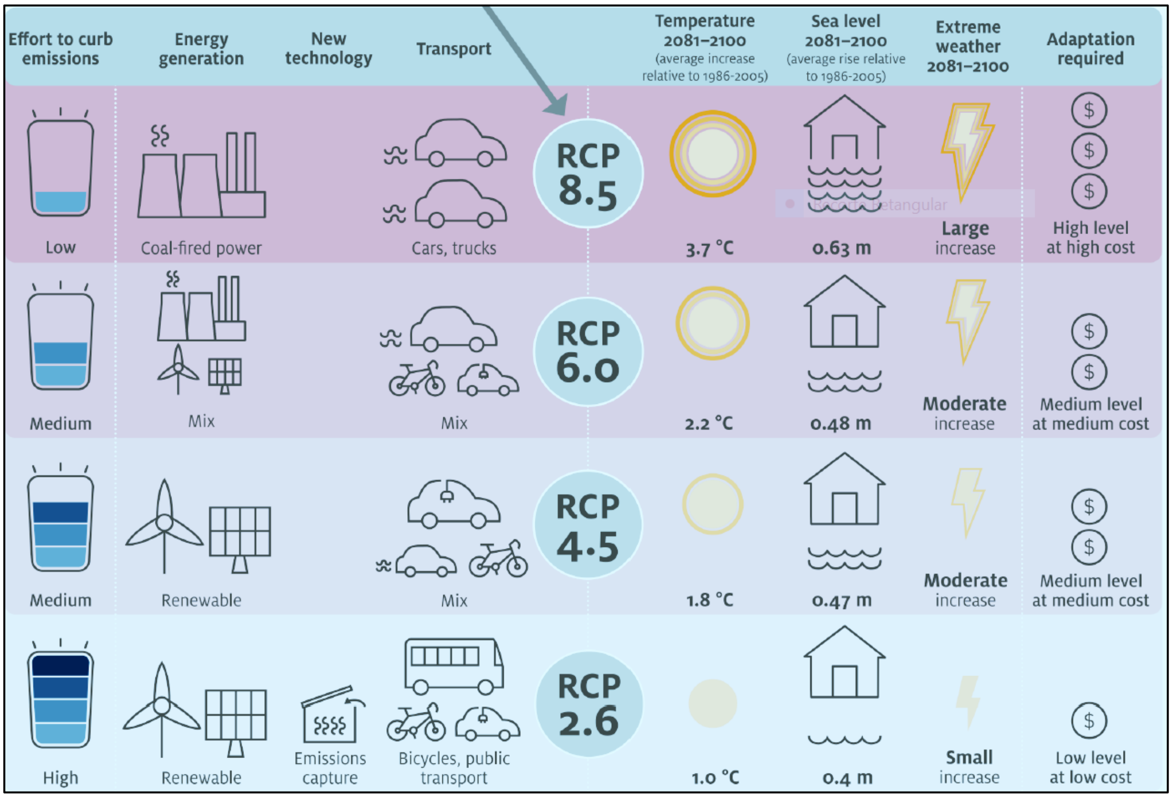
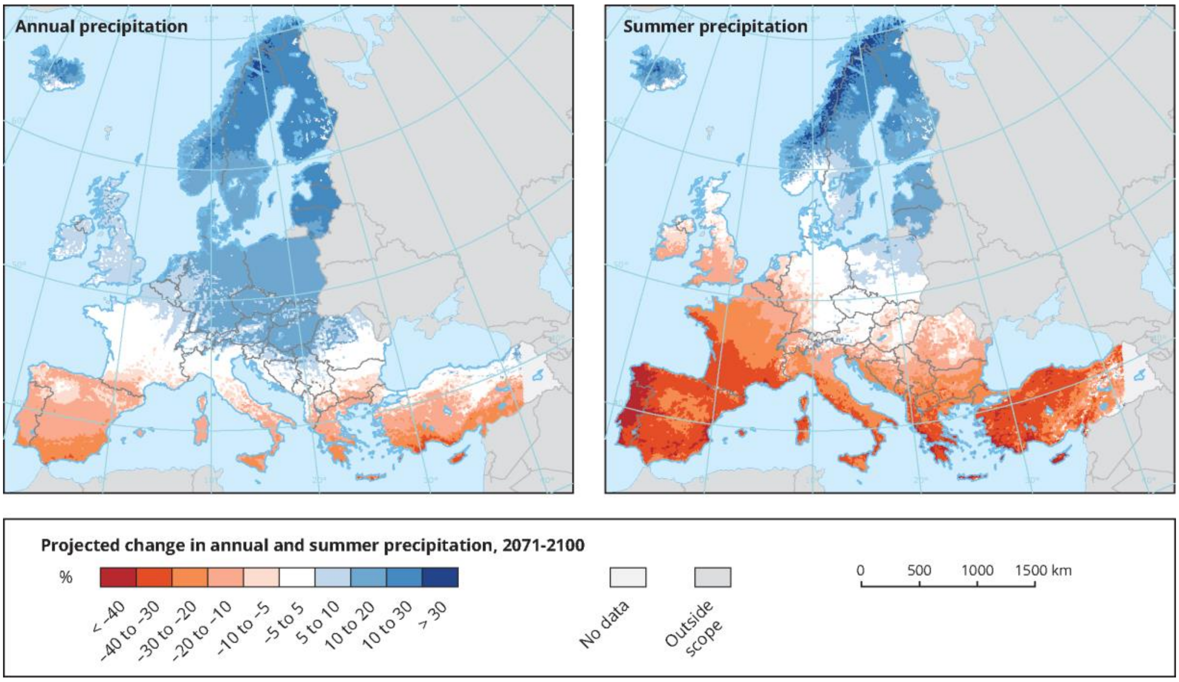


Figure 7 – Breakdown of RCPs

As an example, some illustrative maps of the RCP scenarios are presented in Figure 8:



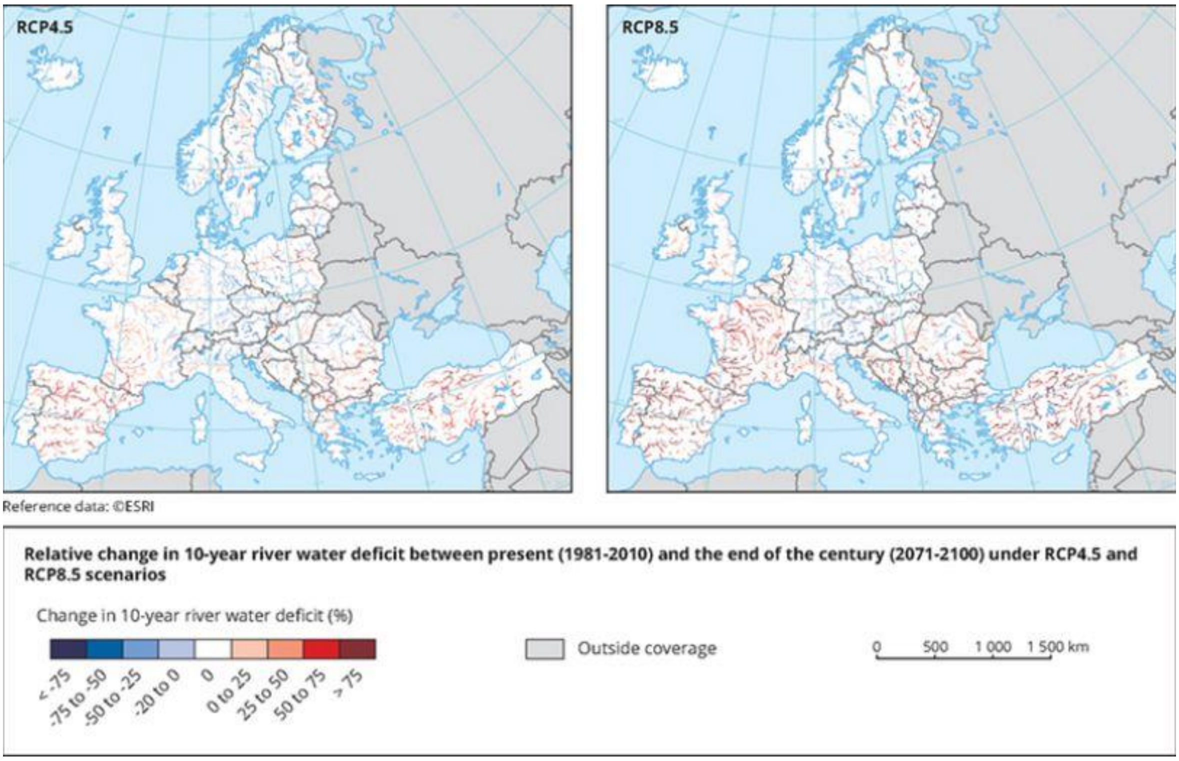


Figure 8 – Maps for RCP Scenarios

In addition to the sensitivity analysis resulting from the PRC scenarios, it is also important to evaluate the increased resilience that the solution will have in the earth structure.

3.1.2. Investigation and Complementary Geotechnical Studies

The investigation and complementary geotechnical studies program provides important information to support design decisions.

How should we increase these studies? What are the success factors?

Balance the benefits, cost and time spent for executing this program. In addition to this fact, another of no less relevance are the scenarios to be studied, and several should always be studied, ensuring that they cover the the risks to be taken. The keys for success are summarized in Figure 9.

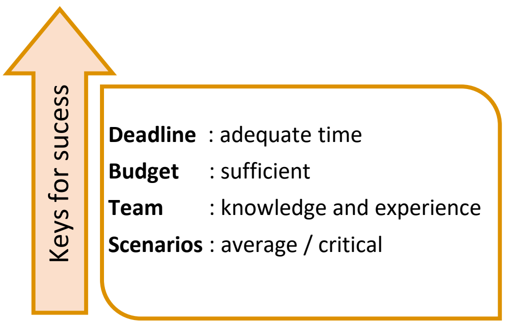


Figure 9 – Success Factors for Investigation and Complementary Geotechnical Studies

3.1.3. Monitoring Plan

The Monitoring Plan is a document that must be developed by the designer during the design phase, and applied during the asset lifecycle. This plan should be detailed and objective and elaborated experienced technicians with the input of the project team, as shown in Figure 10.

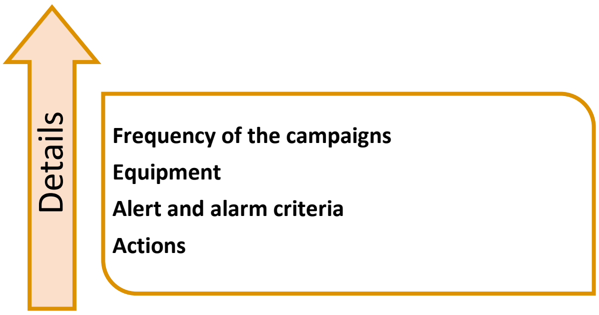


Figure 10 – Details for Monitoring Plan

3.1.4. Alert and Alarm Criteria

The alert and alarm limits require special attention, as they may indicate the occurrence of anomalies with serious implications for asset stability with safety implications for the surrounding area. Of course, this criteria just applies for some of earth structures – larger, critical or complex earth structures.

What is the methodology for an affirmative definition of criteria?

The alert and alarm criteria must be studied in the design phase and defined for the earth structure. In Table 1 presents an example for an embankment slope:

Level	Criteria for Embankment Slopes		
	Top./Inclin.	Cracks/Scars	Deformation Rates (Top./Inclin.)
1 (Stable)	$\delta_H < 40\ mm$ $\delta_V < 15\ mm$	$\Delta_{mm} < 40\ mm$	$\Delta\delta_H < 1.5\ mm/day$ $\Delta\delta_V < 0.5\ mm/day$
2 (Alert)	$80\ mm > \delta_H > 40\ mm$ $30\ mm > \delta_V > 15\ mm$	$80\ mm > \Delta_{mm} > 40\ mm$	$3.0\ mm/day > \Delta\delta_H > 1.5\ mm/day$ $1.0\ mm/day > \Delta\delta_V > 0.5\ mm/day$
3 (Alarm)	$\delta_H > 80\ mm$ $\delta_V > 30\ mm$	$\Delta_{mm} > 80\ mm$	$\Delta\delta_H > 3.0\ mm/day$ $\Delta\delta_V > 1.0\ mm/day$

Table 1 – Alert and Alarm Criteria

δ_H, δ_V– horizontal and vertical displacements, respectively [mm];

Δ_{mm} – opening of cracks/scars [mm];

$\Delta\delta$ - deformation rate of excavation and backfill slopes [mm/day].

How to use this indicators?

Define actions for the three possible scenarios:

- Stable
- Alert
- Alarm

Table 2 presents the actions for each level.

Level	Action
1 (Stable)	Stable – no action required
2 (Alert)	Communication to the entities involved, reinforced monitoring, verification of readings, preparation of an action plan
3 (Alarm)	Communication to the entities involved, verification of readings, increase the frequency of readings, application of immediate safety measures

Table 2 – Response Action Based on Notification Level

3.2. Construction Phase

Decisions are made and activities take place during initial construction that have a huge effect on the resilience of the earth structure. During this phase, the owner needs to establish what the problem is, investigate background information to help with design decisions, design the solution to the problem, and construct the solution. As we saw in the recently published Techniques and Innovations in Earthworks – A PIARC Collection of Case Studies (2022R11EN), there are many innovations from around the world that will help in the various steps of design and construction to build a resilient earth structure. But its also important to note that the place and asset to innovate must be carefully chosen – with less risk, for example in a secondary road.

What is innovation?

Definition - action or effect of innovation, that is, modifying old “customs”, processes, equipment, materials, etc.; with the effect of renewal or creation of a novelty. This includes not just what is new or what appeared recently, but also the application of a material or the adoption of a technology used in other structures or activities.

How can we innovate with positive input?

The current global situation and the challenges that arise, require innovation in the construction, adaptation and maintenance of assets. This process begins with the development of the project, extending throughout the life cycle of the structure. But it is not enough to innovate, it is important to do so in a positive way - avoiding waste, reducing the consumption of materials and resources, opting for natural techniques and less polluting, selecting recycled materials, integrating local materials, promoting biodiversity, replacing and preserving ecosystems.

This approach has positive effects, with four that must be adequately handled in the construction phase, that are summarized in Figure 11:

Figure 11 – Positive Inputs

Innovations can be found in the materials used to construct earth structures in both a resilient and sustainable manner. For example, the moisture content of the soil along a stretch of the Beni Walid Road is generally extremely low (1-3%). During a project to construct the roadway, the project team used a lower moisture content than w_{opt} to reduce the amount of water consumed for compation of the subgrade. Details of the project and engineering can be found in PIARC Report Techniques and Innovations in Earthworks, developed by TC4.3 in the triennium 2020-2023, but this is a good example of using more sustainable practices to build a more resilient earth structure.

Another innovative solution with respect to materials was utilized in the United Kingdom. The widening of the M25 motorway required a substantial amount of additional material, which was not available on-site due to project phasing and weather susceptible soils. As a result, the contractor used recycled crushed glass for these fill areas. The crushed glass was a waste product that would have otherwise been disposed, so reuse of this material was both budget-friendly and sustainable.

And finally, one more innovation on material was reported in France where the tires were reused as fill in an embankment. The tires provided a lighterweight embankment, reducing the amount of settlement caused from the new embankment. Additionally, the tires allowed for a steeper slope, reducing the footprint of the embankment when completed. The reuse of the tires kept them from taking up space in a landfill. Tables 3 to 8 present the case studies.

Performance (compaction)

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 3 – Performance Case Studies

Materials

Case Study	Name of the project	Problem	Country
3	Rehabilitation of the Espiridião de Sousa street (lightweight aggregate)	Existing wall movement needed 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 4 – Materials Case Studies

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 information	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 5 – Technologies Case Studies

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.	Many small cavities in the ground; need to prevent road collapse	Spain
15	Cavities risk management - Gypsum dissolution phenomenon	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 6 – Design Solutions Case Studies

Environmental - social

Case Study	Name of the projet	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 embankment with damaged by fire - located at EN 351 – center of Portugal	Embankment and georeinforced alls damaged by fire	Portugal

Table 7 – Environmental/Social Case Studies

Techniques/Methodologies – Reinforcement

Case Study	Name of the projet	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 from limestone; 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
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	Slope protection using modular Pyramid-shaped steel framed Retaining Elements – Fortezza-San Candido international railway	Emergency restoration of embankment without removing existing embankment	Italy
31	Reinstatement of the failed segmental retaining wall(SRW)	Wall collapsed - water pressures	South Korea
32	Control of Debris Flows with steel mesh	Protection against falling rocks and debris flow	Peru

Case Study	Name of the projet	Problem	Country
33	Stabilization work to control landslides in urban Areas	Slope stabilization	Bolivia
34	Rehabilitation of Tunnel 1, Mendoza	Protection against falling rocks	Argentina
35	Slope stabilization against seismic Events, 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 8 – Techniques/Methodologies Case Studies

4. OPERATION PHASE – FUTURE APPROACH

Earth structures exposed to climactic actions and natural hazards tend to degrade. The resulting pathologies are recorded during the inspections and auscultation campaigns. The information collected is handled in the office – maintenance and conservation states are assigned and reports are produced. These inputs feed planning and annual budget development. Adaptation projects and lists of maintenance and conservation actions are expanded. After the completion of maintenance and conservation work, the inventory is updated, ensuring the permanent updating of the asset and history.

Figure 12 shows the schematics that have an annual cycle.

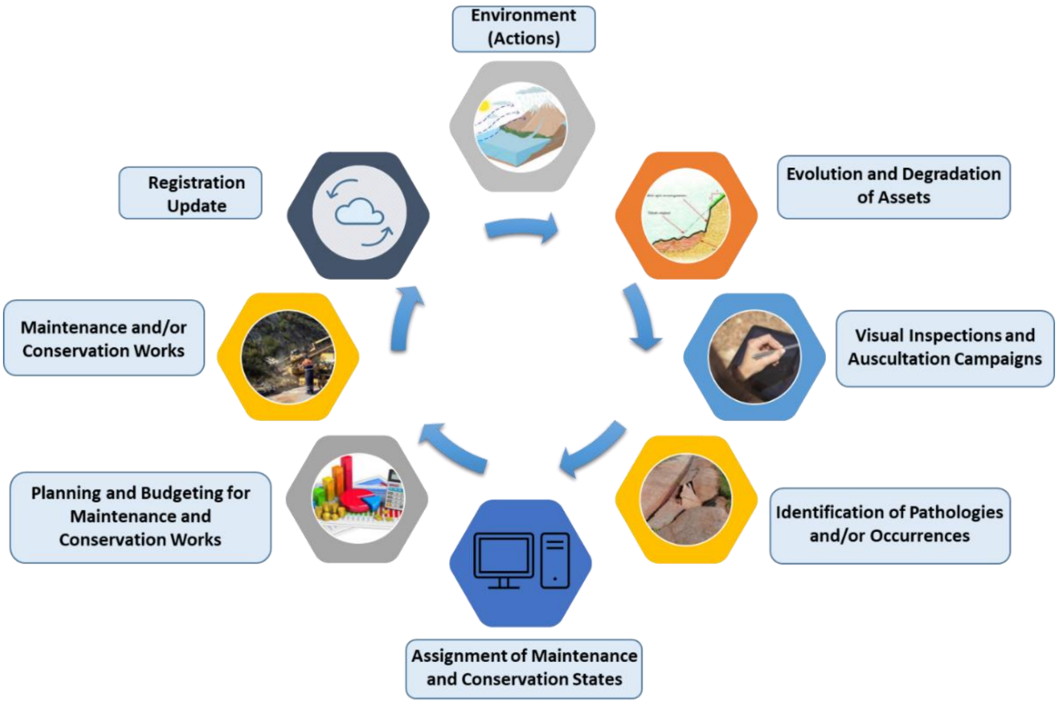


Figure 12 – Annual Life Cycle

4.1. Maintenance Works, How can we innovate?

Maintenance is complementary to monitoring throughout the life cycle of the earth structure. Maintenance activities are low in cost and technical complexity. This should not jeopardize the proper planning of such activities, nor the assessment of access and security conditions. Figure 13 summarizes the three phases enunciated.

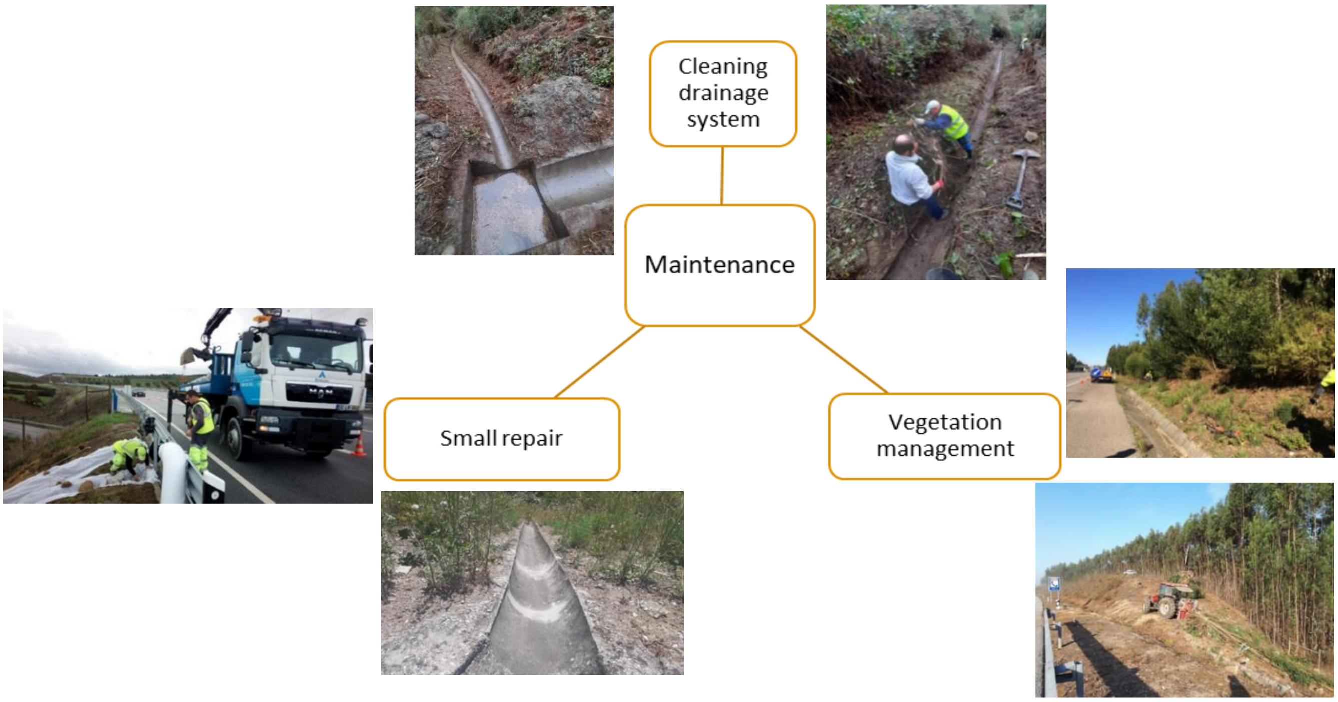


Figure 13 – Three Phases of Maintenance

How can we innovate to make it better?

The management of the longest phase of the asset's life cycle – operation – must be carried out using a management platform that combines all activities.

Innovation must be enhanced and law, rules and standards should not be an obstacle. Figures 14 and 15 summarize the three phases enunciated.

Solution	Integration in SIG	Management and control
1. Able to collect georeferenced multimedia *data in situ* and automatically store its information in a database 2. Find and access directly to the collected media data from a map.	1.Crossing the list of jobs with the database; 2.Creating a web map for tablet/mobile use	•Interactive management dashboards that combine the location of assets with the information obtained.

Figure 14 – Management platform for Operation Phase

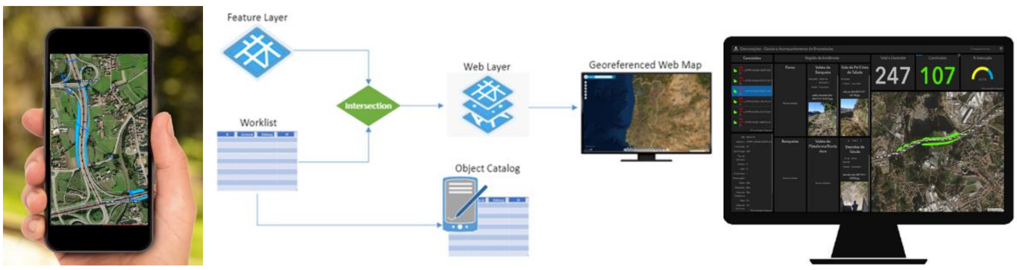


Figure 15 – Management Platform for Operation Phase

Use of geographic information technology and digital transition tools to:

1. optimize management;
2. create maps and registration applications with greater operational profitability (real time)
3. *create interactive management* and control *Dashborads*.

Health / Functionality / Resilience

4.2. MONITORING, WHAT IS THE FUTURE?

What's the future?

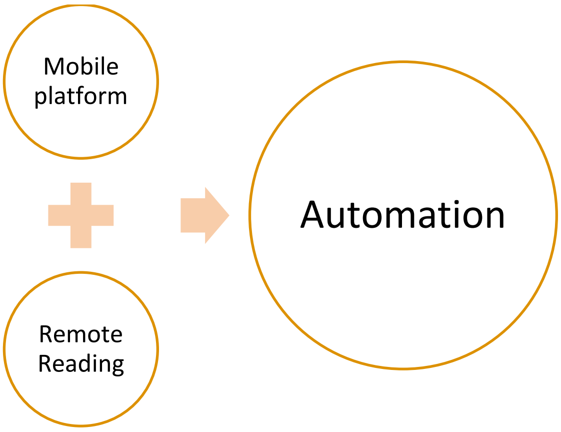


Figure 16 – Automation in Monitoring

Where do we want to go?

The future of monitoring is likely in integrated and automated systems that provide real-time data integrated in risk maps is a Geographical Information System (GIS). The equipment should be remotely accessible with adjustable frequency so that changes can be made from the office without having to visit the site each time a change needs to be made. Other technologies, such as Lidar and satellite imagery, will be used to supplement traditional inspection systems. Building Information Modeling (BIM) is the future in designing, constructing, and maintaining infrastructure, including earth structures. The term "Building" in BIM is not meant as a building structure, rather it is the act of building or constructing information models. These models are more than just designing in 3D. The models include information necessary for constructing, maintaining, and operating the infrastructure.

Monitoring should also be based on information provided by satellite register, including displacements, obtained by the Lidar system. Traditional systems should be maintained, associated and complemented with new technologies and platforms. Two examples are presented in Figures 17 and 18.

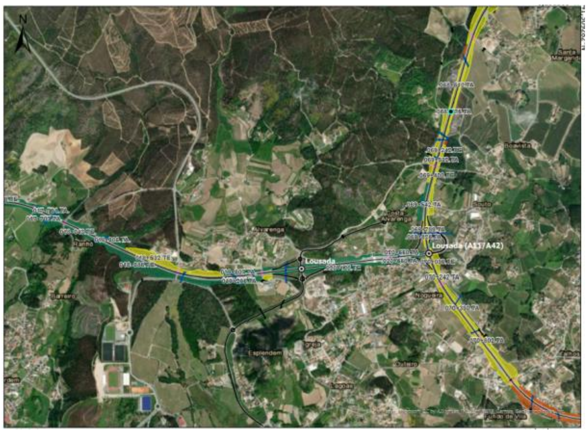


Figure 17 - GIS Risk Maps

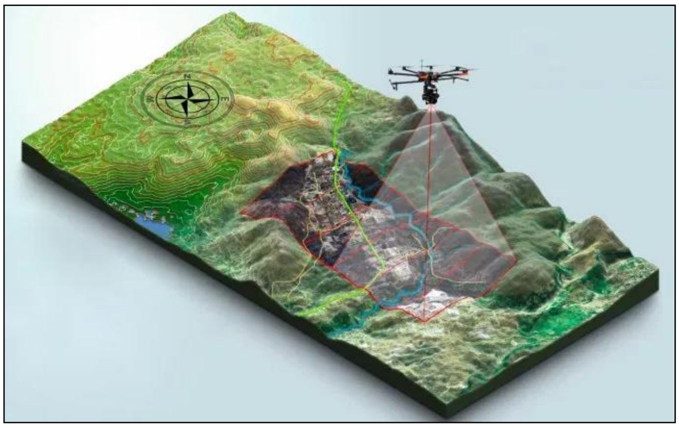


Figure 18 - LiDAR

What are the goals to achieve?

Careful assessment of the accessibility conditions of the asset in order to ensure the safety conditions of the Inspectors and whether it is possible to carry out a thorough inspection and reading of all installed equipment.

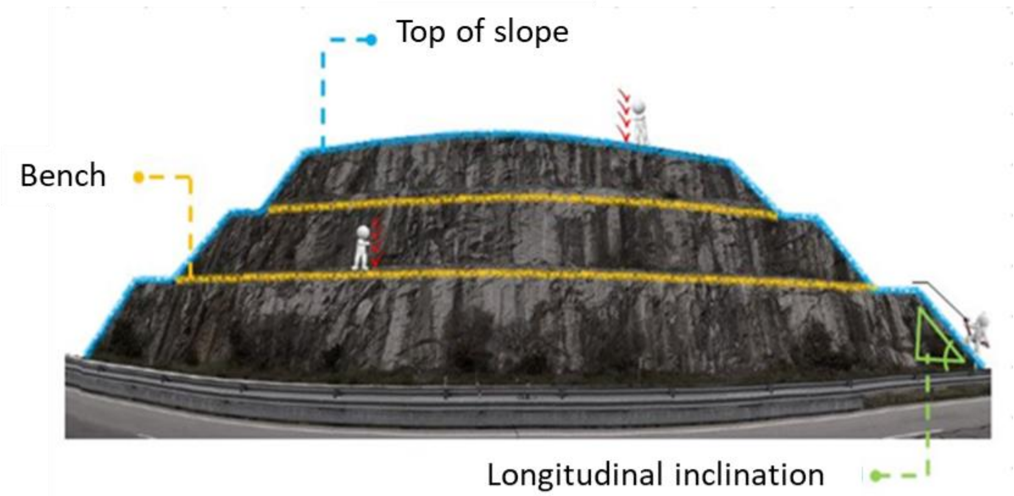


Figure 19 – Earth Structure

This valuation should be recorded and updated whenever the asset status is changed or intervened.

Example of a registration sheet of accessibility conditions presented in tables 9 and 10:

*BENCH | TOP | FOOT

ID	OBJET	MEASUREMENT CRITERIA		CLASSIFICATION 1	2	3
1	WIDTH	≤ 1.0 m				
		[1.0 -3.0]				
		> 3.0 m				
2	TRANSVERSE TILT	Interior				
		Exterior				
3	DIFFICULTIES	Walls				
		Acoustic Barriers				
		Landslides				
		Fence				
4	CIRCUBILITY	Good				
		Reasonable				
		Bad				

*ACESS BY HIGHER PK

ID	OBJET	MEASUREMENT CRITERIA		CLASSIFICATION 1	2	3
5	WIDTH	≤ 1.0 m				
		[1.0 -3.0]				
		> 3.0 m				
6	TRANSVERSE TILT	Interior				
		Exterior				
7	DIFFICULTIES	Walls				
		Acoustic Barriers				
		Landslides				
		Fence				
8	CIRCUBILITY	Good				
		Reasonable				
		Bad				

*ACESS BY LOWER PK

13 EXTERIOR ACESS	Grid door/Ba	
	Parallel path	
	Stairs	

Tables 9 and 10 – Record of the Assessment of Safety Conditions

Based on the analysis of the elements collected and, if necessary, identified security measures, which may include installations of stairs, safeguards, lifelines, or lifting plataforms. In the specific case of visual inspections, it can be concluded that it is impossible to create access conditions by promoting an air inspection.

These measures also provide adequate safety conditions for carrying out the maintenance activities described in point 4.1 Maintenance Works.

At the project stage, the designer should also be aware of this aspect, and should develop the project providing adequate conditions of access and circulation to all locations. A good example is the increase in the size of the berm/stool that ensures the circulation of equipment and people.

Figures 20 to 22 show the implementation of security measures.



Figure 20. Safeguards - Figure 21. Access Stairs - Figure 22. Elevator Platform

The following schema summarizes the analysis flow of accessibility conditions (Figure 23):

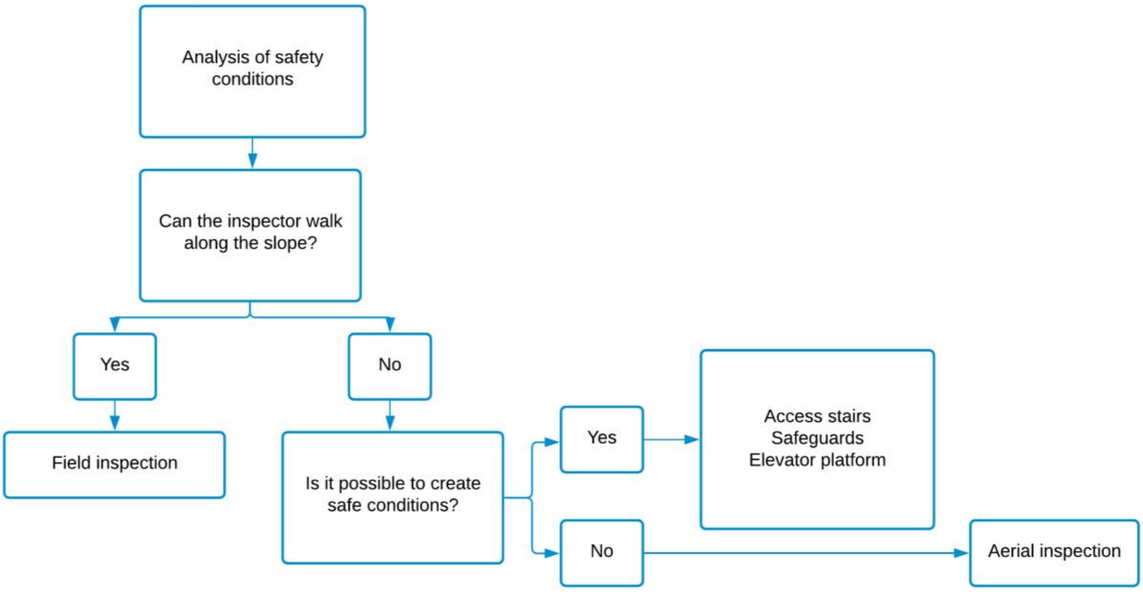


Figure 23 – Framework to Evaluate the safety procedures

4.2.1. Inspection and Observation

Inspections are of great importance, especially those carried out in the operation phase, since they allow for detection of deterioration that may affect the safety and functionality of the earth structure (Silva, 2002).

The inspections are scheduled according to the frequency established in the plan, and carried out by a team of qualified inspectors, engineers, and/or geologists. Table 11 summarizes the type of inspections.

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

Table 11 – Breakdown of Types of Inspections (CS = Conservation State ; MS = Maintenance State)

Visual inspection is developed in four main stages: Preparation Phase, Field Inspection, Data Analysis and State Calculation, and Final Report. This process is shown in the workflow in Figure 24.

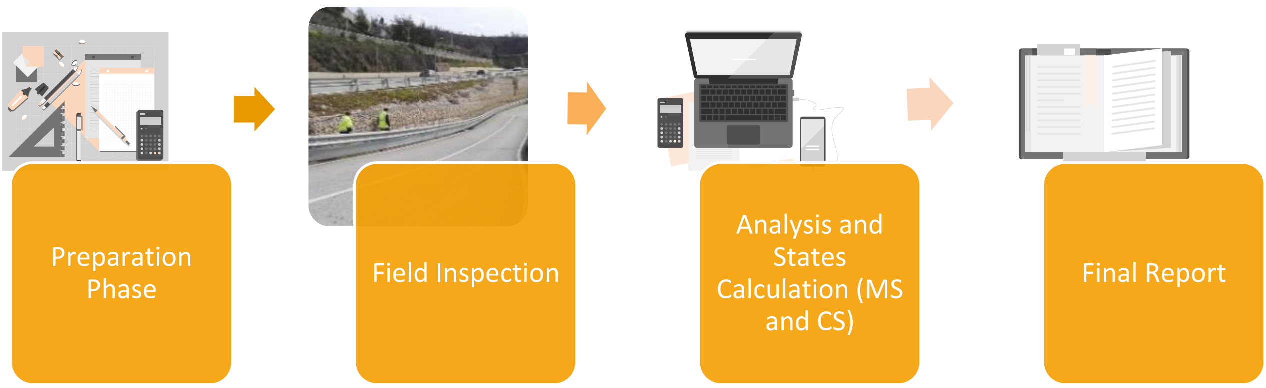


Figure 24 – Inspection Workflow

The most appropriate is that this campaign is carried out using an an equipment on a mobile platform (tablet or smart phone). This procedure is intended to reduce errors in information recording and to overcome the inspector's subjectivity in identifying components and classifying the pathologies. After completing the visual inspection of the infrastructures, the Inspector uploads the information with the possibility of immediately viewing the inspection sheet generated. An image of the pathologies registered during the visual inspection campaign is shown in Figure 25.

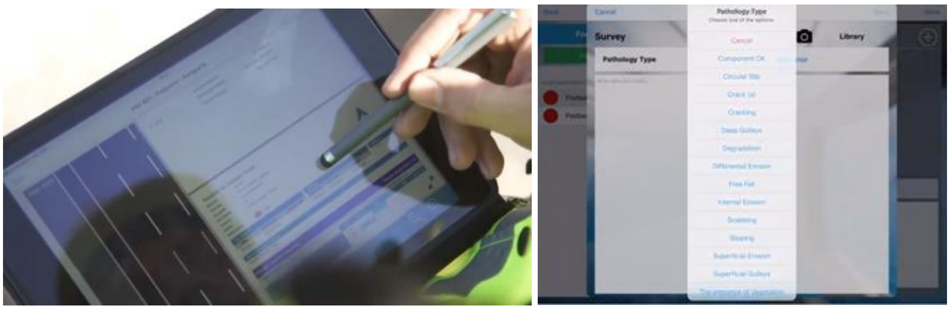


Figure 25 – Register of Pathologies

4.2.2. Health Check and Investigation

The instrumentation encompasses the set of techniques and equipment that are used and/or instituted in geotechnical structures in order to obtain data of their behavior. Currently, the instrumentation devices range from simple mechanical measurement equipment, where data is recorded manually, to complex electronic systems, where data is recorded through a datalogger that allows access and download of data remotely.

It should be planned to use equipment and monitoring methods with innovative technologies in order to monitor the behavior of geotechnical structures:

- Global Navigation Satellite System (GNSS);
- Synthetic Aperture Radar (SAR);
- Laser scans;
- Photogrammetry;
- Unmanned aerial vehicles (UAV);
- Fiber optic sensors.

5. INDICATORS

Asset Management, what is the best approach?

Asset management starts during the exploration phase, and risk assessment through the calculation of indicators is an important tool for decision-making by managers and stakeholders in investment and prioritization of interventions. This approach contributes to preventive action and increased resilience to natural hazards.

The methodology defined in ISO 31000 identifies that asset management should be based on assessment and risk management and should follow procedures established in ISO 55000:

- implementation of the global risk indicator,
- evaluation,
- prioritization of interventions.

In ISO 55000 the "risk" is one of the fundamental elements in the management, evaluation and valuation of an asset, following the development of the asset management system.

The implementation of a management methodology by the allocation of indicators is a predictive approach that requires an adequate choice of methods and indicators to maximize the qualitative information obtained for rapid and assertive decision-making.

Exposure to risk and the vunerability of the earth structure are directly related to resilience/adaptability to a Natural Hazard.

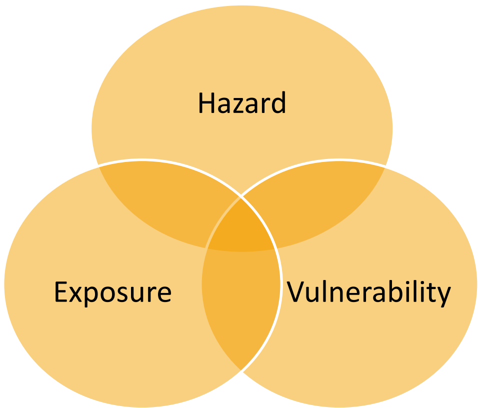


Figure 26 – Management Methodology

What is the framework?

The understanding of the importance of the indicators and the elaboration of risk maps is important for the asset manager, for stakeholders, and for society in general, since it allows a recognition of risk in advance, creating conditions for action in stability and security, mitigating the risk of damage and in the end financial, social, and environmental issues.

What is the definition of "indicator”?

Indicator – statistical data that provides clues about the condition of an asset, and the description is shown in Figure 27.

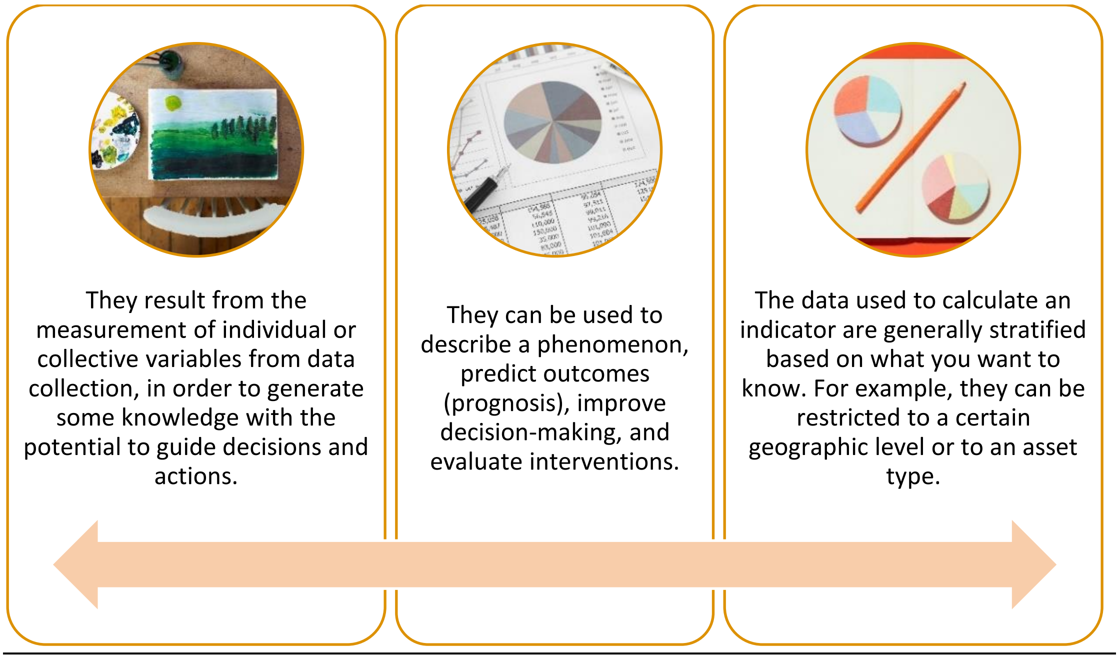


Figure 27 – Description of Indicators

What are the criteria and properties of an indicator?

Features of an indicator are presented in Figure 28:

Measurable	Feasible	Calculable	Reproducible	Understandable
• available and accessible data for their calculation	• be able to measure what is proposed, which depends on the accuracy of the data used and good coverage of the data	• can be calculated in a timely manner for the decision to be taken	• allowing for continuous collection of the data	• so that it can be properly interpreted

Figure 28 – Five Features of a good Indicator

What is the approach to take?

Based on the established principles, some indicators are presented that can be adopted in a global methodology of risk assessment and preparation of risk maps in the management of earth structures.

A) Risk matrix in the surrounding areas of an earth structure

This indicator allows you to assess the risk in the area surrounding the structure resulting from an accident and/or incident caused by a human action or a natural hazard.

Parameters to quantify: Size and Risk

With the quantification of the parameters (size and risk), the indicator is calculated with direct application in the matrices presented in tables 12 to 15.

Parameter - Size			
Slope height (m)	Score	Slope length (m)	Score
1 – 10	1	<50	1
10 – 20	2	50 – 100	2
20 – 30	3	100 – 250	3
30 – 50	4	250 – 500	4
>50	5	>500	5

Slope height (m)/length (m)	<50	50 – 100	100 – 250	250 – 500	≥500
1 – 10	1	2	3	4	5
10 – 20	2	3	4	5	5
20 – 30	3	3	4	5	5
30 – 50	4	4	5	5	5
>50	5	5	5	5	5

Parameter - Risk				
Surroundings	yes	no	Proximity	Score
residential area	5	1	really close	5
industrial zone	4	1	next	4
forest	3	1	little close	3
farm	3	1	way	2
road infraestructure	4	1	far way	1
port infraestructure	4	1		
water resource	3	1		

Surroundings /Proximity	really close	next	little close	way	far way
residential area	5	4	3	2	1
industrial zone	5	4	3	2	1
forest	2	2	1	1	1
farm	3	3	2	1	1
road infraestructure	4	4	3	2	1
port infraestructure	4	4	3	2	1
water resource	3	3	2	1	1

Tables 12 to 15 – Matrices

Risk in the surroundings is measured by impact, with a score of 1 to 5 described in Table 16:

IMPACT	
1	Very low
2	Low
3	Medium
4	High
5	Very high

Table 16 - Impact

Assuming the same contribution for each of the parameters, the impact indicator is calculated:

$\boxed{I = \sum (0{,}5 \times Score(Size) + 0{,}5 \times Score(Risk))}$

B) Conservation and Maintenance States

The earth structures are composed by components that in turn has subcomponents. Determining the states of conservation and maintenance starts at the subcomponent level and ends in the structure. Thus, the association of the pathologies occurs at the level of the subcomponents and the definition of the states is formed as we move towards to the structure. Note that each pathology has one conservation state and one maintenance state.

B.1) Conservation State

This indicator is obtained through the individual evaluation and quantification of each of the pathologies for each of the components of the Earth Structure (face of the embankment, bench, drainage, ...).

The conservation state, could range from very good to very bad, in function of the dimension and the impact or risk of the pathologies, and is calculation is given by a weighted average about the structural components that exists. The weights used on the calculation of the conservation State can be customized.

The parameters are the same – Size and Risk – and are scored from 1 to 5, as presented in Tables 17 and 18.

CRITERIA FOR QUANTIFYING THE DIMENSION AND IMPACT					
DIMENSION			IMPACT (RISK)		
	(%)	score		Need for Intervention	score
Small	0 – 30	1	Null	n.a.	0
Medium	30 – 70	2	Moderate	Medium/Long Term	1
High	70 – 100	3	High	Short Term	2

CONSERVATION STATE	
1	VERY GOOD
2	GOOD
3	MEDIUM
4	BAD
5	VERY BAD

Tables 17 and 18 – Parameters for Conservation State

$\boxed{\text{Conservation State (CS) = Dimension (score) + Impact (score)}}$

B.2) Maintenance State

This indicator is obtained through the individual evaluation and quantification of each of the pathologies for each of the components of the Earth Structure (face of the embankment, bench, drainage, ...).

The parameter is the urgency in the maintenance action and is scored from 1 to 3, as presented in Tables 19 and 20.

The calculation of the maintenance state is simpler, could range between good to bad, and the maintenance state of each component is given by the higher state assigned at the subcomponents, and therefore the final maintenance state of the structure is given by the higher state of the components.

CRITERIA FOR QUANTIFYING	
Urgency of maintenance	Score
n.a.	1
Until 6 months	2
Until 3 months	3

MAINTENANCE STATE	
1	GOOD
2	MEDIUM
3	BAD

Tables 19 and 20 – Parameters for Maintenance State

Maintenance State (MS) = F (time needed to do the repairing works/actions)

MS (structure) = Higher MS defined at the level of components

The maintenance state give us the alert of the time we need to do the repairing maintenance actions.

C) Resilience indicator or quality index

This indicator assesses the condition of the asset - robustness, functionality and integrity, being an indicator of its ability to adapt to an extreme phenomenon.

The quantification of this indicator is based on the identification of the main factors and for each one the parameters that characterize it. Each factor is assigned a rated, and the sum of all factors is equal to 100%.

Figure 29 illustrates the base structure for the calculation of this indicator.

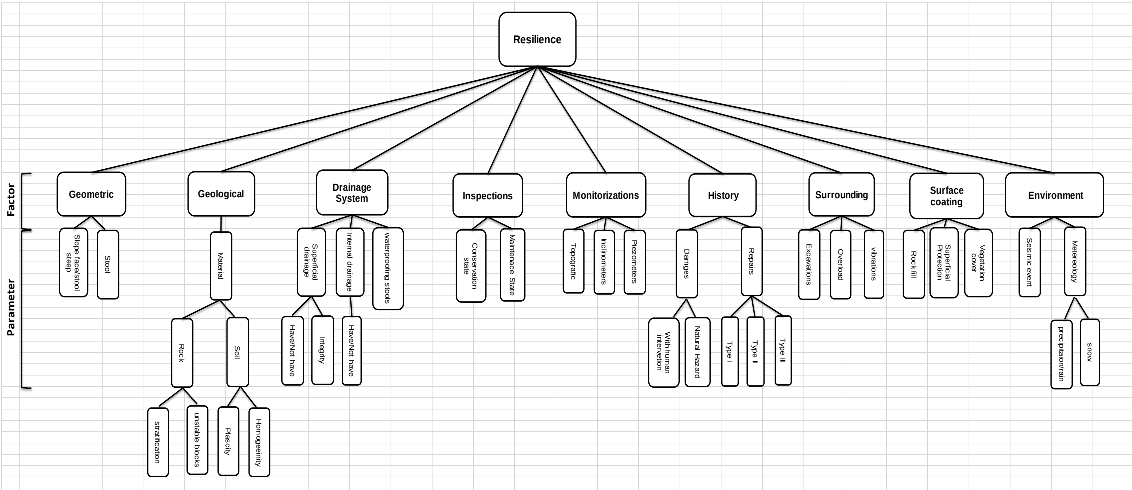


Figure 29 – Structure for Calculation of the IR

Factors can be static (it does not change or changes slowly in time) or dynamic (changes rapidly in time):

- Geometry
- Geology
- Drainage system
- Visual Inspection
- Monitorization
- History
- Environmental
- Surface coating
- Surounding.

The calculation of the resilience index is obtained by the sum of the affected factors of the assigned weight and is scored 1 to 3, as presented in Table 22:

Factor1 = ∑ (%P1.1*R1.1+%P1.2*R1.2+…)

IR = ∑ (%*F1+%*F2+…)

Where P = Parameter, R = rating, F = Factor

IR	RESILIENCE
1>IR<1,8	GOOD
1,8>IR<2,3	MEDIUM
2,3>IR<3	BAD

Table 22 – Resilience Index (IR)

D) Resilience Indicators

In order to establish a general method for quantitative and qualitative resilience evaluation, at project level, of highway earthworks and earth structure, we may assume that in any road project related to earthworks processes or to the construction of earth structures, there must achieve a balance between the main pillars of resilience: technical, social –economic, environmental and strategic aspects, as well as concepts on adaptation to climate change. Consquently, in any analysis of project resilience, at least the following five resilience criteria has to be considered and selected:

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

The identification and measurement of each of these five aspects must be performed in each stage of the life of earthworks or of earth structures, starting with the design and choice of materials and continuing with the execution, maintenance, and rehabilitation.

Detailed description is presented in the report « INCREASING RESILIENCE OF EARTH STRUCTURES TO NATURAL HAZARDS».

6. CONCLUSIONS AND FUTURE CHALLENGES

6.1. CONCLUSIONS

As we move further into the 21st century, it is becoming increasingly more clear that climate change is the biggest concern that we must face. The effects of climate change, specifically the increasing frequency and intensity of natural hazards, are wreaking havoc on infrastructure, including earth structures, around the globe. The need for more resilient earth structures requires firm and bold action by owners, managers, stakeholders, and the whole scientific community.

In a century when the challenges are “HUGE”, it is important to understand that not all innovations interest us. Before innovating, it is necessary to ask the right questions to get assertive answers to trace the future we want!

It is very important to clarify that good practices should not be confused with new practices. This means that geotechnical investigations are very important, but it is not necessarily more investigations that will get better information. New kinds of investigations in the design phase must be studied and considered. A resilient asset includes efficient drainage systems and maps of natural hazards. Construction must use the most green and sustainable technology and recycled materials whenever possible. Monitoring and maintenance are also very important during the operation and maintenance phase and must be based on a database in a integrated platform.

It is very important to assess whether the innovative solution chosen for a rehabilitation after a natural hazard was resilient. We should be aware that it is important to carry out an assessment of the innovation, answering the question “was the solution adequate or not?”

In the past, we have done innovations to solve specific problems - to work faster or cheaper or to produce better quality. We had individual ideas for innovation, but in the future, it is mandatory to have a broader mission and strategic plan for innovation. Innovations should be widely disseminated to the scientific community, managers and all the stakeholders.

Synthesizing the highlights of this report, we present briefly for each of the Phases:

DESIGN PHASE	
How can we prepare better designs?	New design criteria: Team, Data Collection, Carbon Footprint, Sizing (dimension) Sensibility - the team designer and the owner to be able to choose the most appropriate solution for each case study and earth structure - RPC scenarios assessment. The investigation and complementary geotechnical studies program are manditory because they provide important information to support sustainable design decisions.
	Monitoring Plan - integrated and automated systems that provide real-time data integrated in risk maps and a GIS. The equipment should be remotely accessible with adjustable frequency so that changes can be made from the office without having to visit the site each time a change needs to be made.

	Carbon footprint - solutions with smaller carbon fotprints should be considered as part of the selection criteria
	Alert and Alarm criteria - must be studied in the design phase and defined for the earth structure.
CONSTRUCTION PHASE	
1) What is innovation?	It means modifying old "customs", processes, equipment, materials, etc.; with the effect of renewal or creation of a novelty. This includes not just what is new or what appeared recently, but also the application of a material or the adoption of a technology used in other structures or activities.
2) How can we innovate with positive input?	It is not enough to innovate, it is pressing to do so in a positive way: avoiding waste, reducing the consumption of materials and resources, opting for natural techniques and less polluting, selecting recycled materials, integrating local materials, promoting biodiversity, replacing and preserving ecosystems.
3) Decisions can be made during this phase?	Decisions are made and activities take place during initial construction that have a huge effect on the resilience of the earth structure. During this phase, the owner needs to establish what the problem is, investigate background information to help with design decisions, design the solution to the problem, and construct the solution.
OPERATION PHASE	
1) Maintenance, how can we innovate?	The management of the longest phase of the asset's life cycle – operation – must be carried out using a management platform that combines all activities. Innovation must be enhanced and laws, rules, and standards should not be an obstacle.
2) Monitoring, what is the future?	The future of monitoring is likely in integrated and automated systems that provide real-time data integrated in risk maps is a Geographical Information System (GIS). Automation: visual inspection using mobile platform + remote instrumentation streaming.
	Careful assessment of the accessibility conditions of the asset to ensure the safety conditions of the Inspectors and whether it is possible to carry out a thorough inspection and reading of all installed equipment.

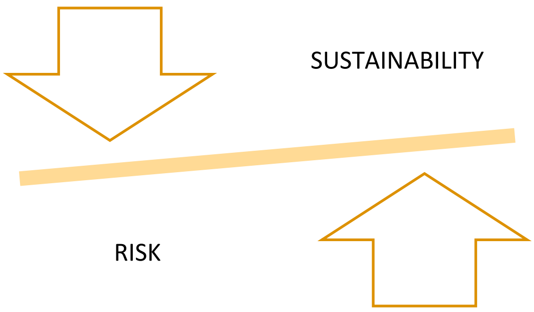
LMIC	
Recommendation and approach	• Asset management • Risk Management • Prioritization of intervention - with the identification of the most vunerability area.
	• Simple methodologies and easy application - enabling adequate and adequate asset management based on preventive action
	Focus in: • observation and monitoring; • low cost solution and nature based solutions; • minor works and management activities

In summary, the Innovation proposed in this section focuses on a predictive approach – focusing on increasing relocation and the adoption of asset management platforms, with risk analysis and prioritization of actions throughout all phases of the life cycle of earth structures, ensuring sustainable management that favors local and recycled materials, green technologies, preserving ecosystems and promoting biodiversity.

This methodology should provide solutions that have already proven their effectiveness and the implementation of an Asset Management that favors observation, monitoring and auscultation and current maintenance activities, all of low cost, whose effectiveness in the timely detection of pathologies contributes to a reduction in interventions, costs and accidents.

6.2. FUTURE CHALLENGES

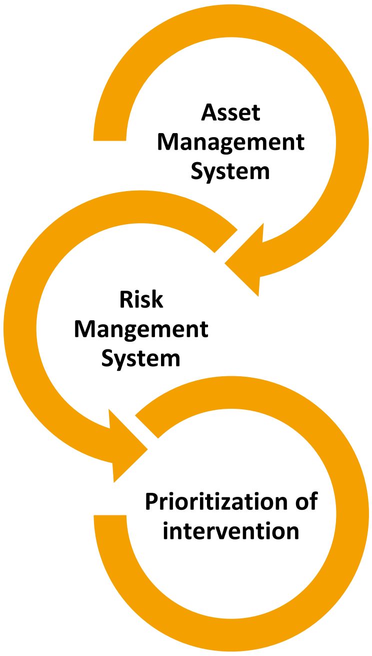
Structures become older and this is a big challenge. One such challenge that must be overcome from the design phase – drawing up an Observation and Monitoring and Maintenance Plan – increases its resilience to natural hazards. This condition requires that during the O&M Period, an effective asset management program is carried out, establishing a commitment between that the owner intends to assume the maintenance and conservation in a sustainable manner and confirming that commitment with all stakeholders and the community.



The balance to be found and the relationship between risk and sustainable management of earth structures requires choosing the most appropriate practices for each geographical location, i.e.:

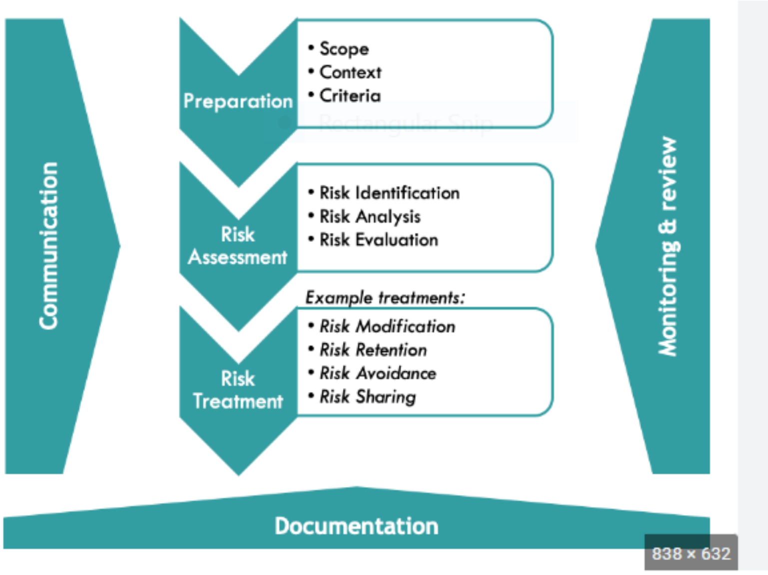
1. focusing on the adoption of low-energy methodologies, using green energies where possible;
2. reducing the consumption of natural resources, preventing the recycling of materials;
3. adoption of innovative techniques provided that they have already proven their effectiveness;
4. implementation of new technologies, efficient and user friendly;
5. implementation of an asset management system that covers the entire life cycle of the structure;
6. risk assessment: external actions and risk exposure.

The way is Sustainable Life Cycle Management of Earth Structures. This approach requires implementation methodology that follows a predictive approach:



It is very important to define a Global Risk Index (GRI) that allows the area of more vunerability to be zoned in a Geographical Information System (GIS) before a natural hazard.

The adoption of ISO 33000 is a practice that creates and protects value in organizations, managing risks, making decisions, setting goals and improving performance. Risk management is based on the principles, framework and process illustrated in the figure. These components may already exist in whole or in part within the organization; however, they may need to be adapted or improved for risk management to be efficient, effective, and consistent.



Final Remarks

Earth structures represent about 80% of a road project, so they are an important and fundamental asset. The maintenance of an adequate state of conservation and maintenance has a high impact from a social, environmental, and economic standpoint.

Climate change requires the resilience of assets to natural hazards, and the path forward is sustainable management of the life cycle of earth structures. Sustainability is based on three pillars: people, environment, and economy. The challenge is to achieve the balance of the three while ensuring a healthy and green environment, enhancing a prosperous economy, and people's happiness.

Changes are made with small but firm steps. We have to work on the mission and values presented in this report to build the future we want, reducing the carbon footprint and building a better world for humanity.

For low and moderate income countries (LMICs), we propose an initially more simplistic yet progressive approach, applying the proposed methodology with the development of simplified asset management and risk management that enables sustainable management of the all phases of life cycle.

7. RECOMMENDATIONS FOR PIARC

7.1. Recommendation A - Earth Structures

Convince stakeholders that earth structures is one of the biggest problems they will have in the future, and it is mandatory to have a broader mission and strategic plan for innovation.

7.2. Recommendation B - Catalog

Develop a catalog of innovations or unique solutions for a variety of natural hazards with a search function to allow easy selection of the solution appropriate for the situation.

7.3. Recommendation C - Repeat Compilation of Innovations & Unique Solutions

With the outstanding abundance of innovative solutions provided herein as well as the increasing speed at which technology continues to advance, we suggest that PIARC dedicate another future work cycle in 8-10 years to compiling innovative and unique solutions.

7.4. Recommendation D - Asset Management of Earth Structures

As noted in the Conclusions, one of the keys to resilience of earth structures is a strong inspection, monitoring, and maitenance program. We recommend PIARC consider for a future work cycle to develop an asset management manual for earth structures that would be focused on maintaining and monitoring the earth structure.

7.5. Recommendation E - Water Management of Earth Structures

Water is the single most damaging element to earthworks and earth structures. Obviously, flooding events cause major damage to earth structures, including culverts, through direct impact, erosion, debris, and landslides. However, water also causes internal damage through water table fluctuations, underground cavities, and deterioration of the infrastructure. We recommend PIARC to consider developing a manual focused on best practices of water management to help maintain or improve the resilience of earth structures.

7.6. Recommendation F - Biodiversity of Earth Structures

The first report published by Working Group 2 (WG2) of Technical Committee 4.3 Earthworks (TC4.3) titled Techniques and Innovations in Earthworks – A PIARC Collection of Case Studies (2022R11EN) included few innovations that used biodiversity to solve the earthworks problem that was present. Using green solutions reduces the carbon footprint while resolving the issue and potentially increasing the resilience of the earth structure. We recommend PIARC to consider further evaluating the potential of this field of innovative and unique solutions to give more environmentally friendly options to infrastructure owners in the future.

World Road Association (PIARC)

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