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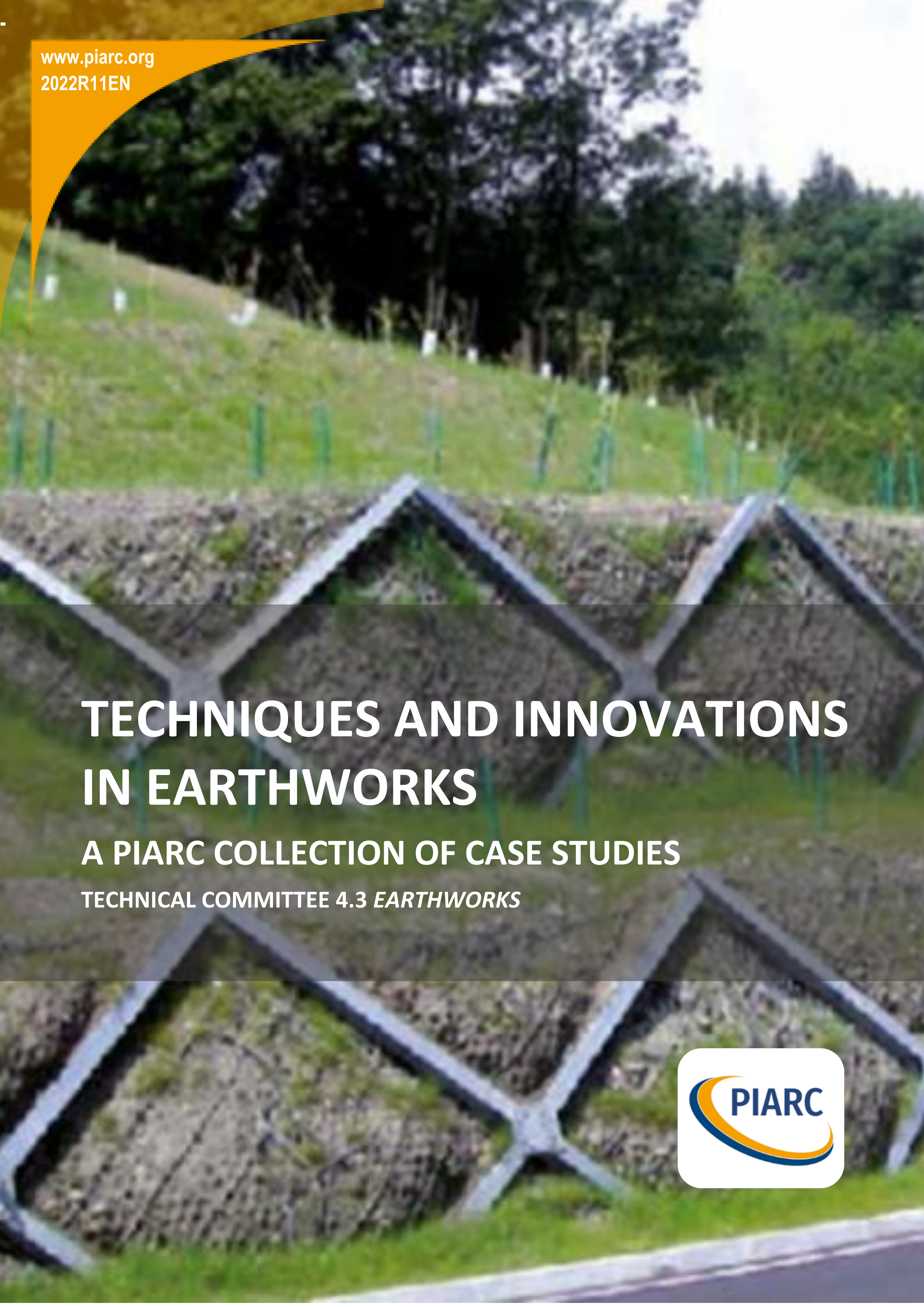

TECHNIQUES AND INNOVATIONS IN EARTHWORKS

A PIARC COLLECTION OF CASE STUDIES

TECHNICAL COMMITTEE 4.3 *EARTHWORKS*

PIARC

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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A PIARC COLLECTION OF CASE STUDIES

TECHNICAL COMMITTEE 4.3 EARTHWORKS

AUTHORS/ ACKNOWLEDGEMENTS

This report was prepared by Working Group 2 (WG2) of the World Road Association's (PIARC) Technical Committee 4.3 (TC 4.3) on "Earthworks" for the work cycle 2020-2023.

TC 4.3 was chaired by Patrick Boisson (France). The secretaries were Yasmina Boussafir (France), Paul Nowak (United Kingdom), and Natalia Pérez (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 developed with the contributions of several members of WG2, and the principal team was responsible for this document is named on the table below.

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Jason Hastings	United States	Author/ language review/WG Co-chair
Yasmina Boussafir	France	language review
Paul Nowak	UK	language review
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EXECUTIVE SUMMARY

2022R11EN

TECHNIQUES AND INNOVATIONS IN EARTHWORKS

A COLLECTION OF CASE STUDIES

This report presents the summary of thirty-six cases studies compiled by Working Group 2 of Technical Committee 4.3 under the theme “Techniques and Innovations in Earthworks“. This document will be further developed as part of the 2020-2023 Work Cycle and is expected to be accompanied by one additional document in publication, a full report. The information contained herein provides general insight, innovative techniques, and unique solutions to problems related to earthworks and earth structures from around the world, with the focus on making these elements of infrastructure more resilient. This document describes interesting solutions to solve damage occurring due to natural adversaries, specifically water and fire, in a several diverse geologies and geotechnical conditions. A map view of the distribution of contributions by countries and continents is presented in Figure 1.

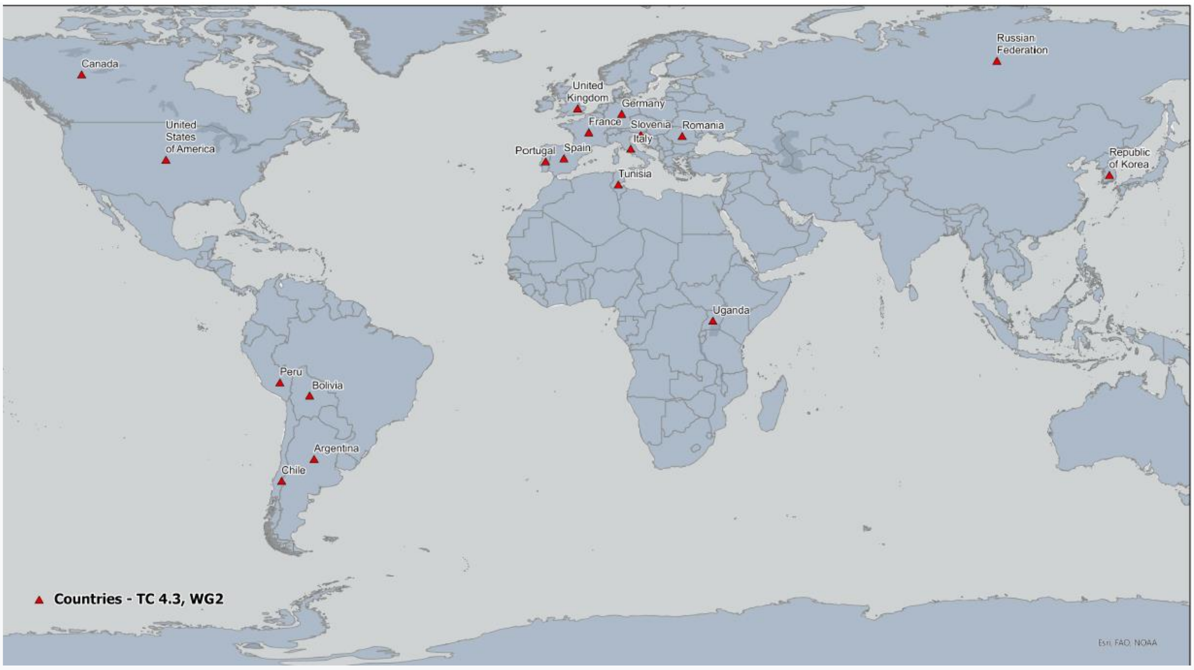


Figure 1 – Map

The case studies address a wide range of issues across five of the seven continents : Europe, Africa, Asia, and North and South America. The issues addressed several areas, including advanced materials, unique techniques and methodologies, innovative technologies, and project specific solutions, all focused on repairing a geotechnical structure after a damage while improving its resilience. The number and the percentage of each group are shown in Figures 2 and 3.

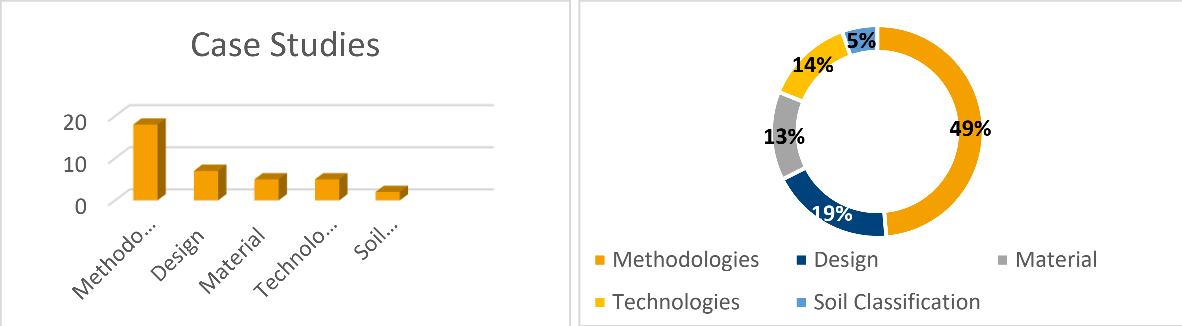


Figure 2&3 : Breakdown of Case Studies By Grouping

CONTENTS

1. INTRODUCTION

In the "Increasing Resilience of Earth Structures to Natural Hazards" Literature Review report elaborated by Working Group 1, several technical definitions of resilience are presented. A metaphoric definition of resilience is provided by Boris Cyrulnik, who defines resilience as follows: *a pearl is the result of the oyster's reaction to the aggression of a grain of sand*. In general terms, resilience is the ability of something or someone to resist adversity. In engineering terms, it is the response of a material or structure to the application of large amounts of energy from a natural or man-made event.

Many of the problems with earthworks are old, but many of the solutions, materials, technologies, and methodologies that we use to solve these problems presently were innovative at one time, and we continue to develop innovative techniques and solutions today. Since the Romans built the first roads, we have taken gigant leaps in improving the cost effectiveness and efficiency of these earthwork practices, but a greater focus on improving their environmental sensitivity and resilience has moved to the forefront.

Climate change is one of the greatest environmental threats of the 21st century, with profound consequences for various areas of society: economic, social, and environmental. Climate change has been systematically recorded over the existence of Planet Earth. However, in the last century, the pace of climatic variations has accelerated sharply. The occurrence of heat waves and droughts, the higher sea levels, and the increased intensity of rainfalls and storm events are becoming more and more frequent, representing a real threat to geotechnical infrastructure. The increased risk of catastrophe that humanity faces today, be it of natural or human induced origin, poses a huge set of challenges to the managers of geotechnical structures.

We believe that increasing the resilience of earth structures, choosing the best solution for the design, treatment, and reinforcement, reduces risk and consequences associated with these disasters. With this theme, we developed our work, asking all the Technical Committee 4.3 (TC4.3) members to provide case studies from their respective countries of good examples of: i) more adequate materials, ii) unique techniques/methodologies, iii) innovative technologies, iv) sustanaible solution and v) the best solutions for the projects, for application in earthworks and earth retaining structures.

This report compiles summaries of the thirty-six case studies received from the members of Working Group 2 (WG2). The case studies cover a wide range of diverse problems and diverse solutions to address these challenges with geotechnical structures. Figures 2 and 3 indentify the countries and the continents that contributed case studies.

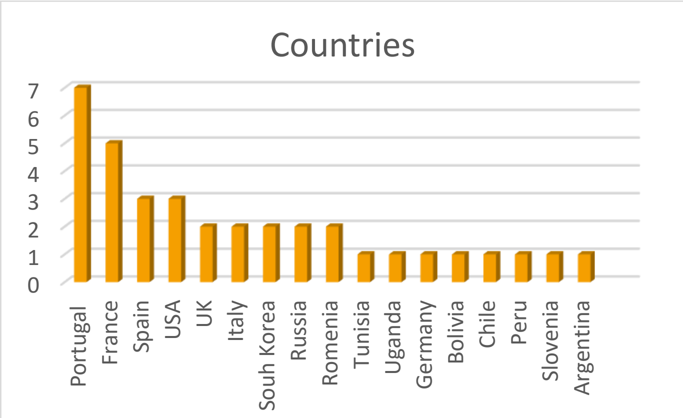


Figure 2: Contributions by Country

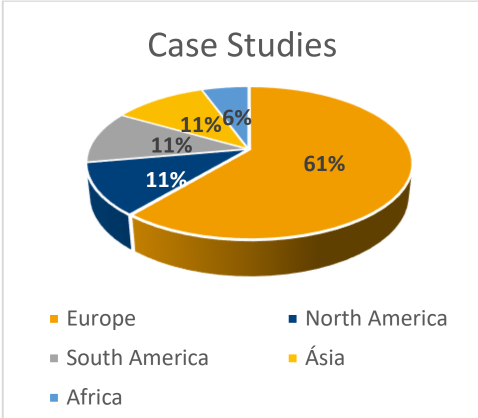


Figure 3 – Contributions by Continent

It is important to note that visual inspection, cleaning, and maintenance are all important activities to help any earthwork solution to remain resilient against future natural or man-made hazards. Although these items are not discussed in the case study summaries, the costs of these activities are low and the benefits are high, so these should be considered after the implementation of any of the solutions presented in this report.

1.1. FRAMEWORK

This document is divided into four chapters. The first and second are dedicated to the introduction and presentation of the methodology used; the third chapter compiles the summaries of the case studies; and the last focuses on the conclusions and final considerations.

1.2. THE PURPOSE OF THE REPORT

The challenge presented to Technical Committee 4.3 (TC4.3) was to study the problem of resilience in earthworks and earth structures. TC4.3 formed three working groups, with Working Group 2 (WG2) focused on “Techniques and Innovations in Earthwork”.

This report summarizes the compilation of the case studies presented by TC 4.3 members from their respective countries. The case studies represent innovations, unsual techniques or methodologies, appropriate design solutions, and cost-effective approaches. It becomes important to clarify what is meant by some concepts that are intrinsic to this work:

- Earthworks – the procedures and techniques that are necessary to build earth structures.
- Innovation – at the project level, construction techniques, equipment and materials.
- Unsual techniques – design solutions, construction methods or materials, which are not the ones usually used in solutions for repair, rehabilitation or reinforcement of geotechnical infrastructures.
- Sustainable solution – solutions that use recycled materials and/or are applied with low energy, producing carbon emissions - in other words, “friendly for all ecosystems”.
- Appropriate design solutions – the most appropriate solutions with respect to technical, economic, environmental, and contractual aspects of the project.
- Cost-effective approaches – the most appropriate solution in a global assessment from a cost standpoint.

All of these elements were evaluated with sustainability and resilience in mind.

The principal objective of this document is to compile the summaries of thirty-six case studies, describing interesting solutions to solve damages occurring due to natural and man-made hazards, particularly water and fire, in a wide range of diverse geologic and geotechnical conditions.

2. METHODOLOGY

The 2020-2023 work cycle for TC4.3 is focused on resilience of earthworks and earth structures. WG2 of the technical committee is working on identifying, compiling, and disseminating best practices and innovative solutions to earthworks and earth structures from around the world. To accomplish this, we collected: i) projects, ii) innovative solutions, iii) unusual techniques, and iv) cost effective methods from several countries. The case studies presented in this report are considered unique or innovative solutions to earthwork problems in their respective countries, used to solve damage and improve the resilience in geotechnical structures.

The production of this report was carried out in three principal phases: first, collecting case studies through an enquiry distributed to all TC4.3 members, second, organizing the content into groups by common theme, and finally, developing conclusions based on the solutions provided withint he case studies.

The enquiry included a questionnaire asking for the following information:

- Brief summary of the problem and solution
- Background Information
    - Project name (if applicable), timeline, and location (including country)
    - Point of contact – project manager, author of published document, etc.
- Detailed description of the project, problem, and solution
    - The initial condition including problem identified and any constraints
    - The proposed solution including materials, equipment, design considerations, design challenges, etc.
    - The project delivery method such as design-build, design-bid-build, maintenance forces, etc.
    - The construction phase including any construction challenges, field changes, ease or difficulty of construction, etc.
    - Photos, plans, specifications, or any other documentation related to the project
- Lessons learned
    - Did the solution solve the problem as expected?
    - Is the solution still performing as expected?
    - Was the solution cost-effective?
    - Were there unanticipated construction issues?
    - What would the project team do differently based on the lessons learned?
- Any additional information

The enquiry was distributed by e-mail to all members of TC4.3. Many of the members responded with case studies from their own experience. However, many members also provided case studies of other work from their country in which they were not directly involved.

The second phase was collecting the enquiry responses and organizing them into four groups: materials, techniques/methodologies, innovative technologies, and design solutions. The authors provided a summary of the case study broken into 3 parts : summary of the problem, summary of the solution, and lessons learned. The lessons learned part of the summary provided information on any changes the author would make, how the solution is performing today, and if the solution was cost effective.

The final phase was developing this document, which included the production of conclusions and final considerations. Although a full report is anticipated of the cases studies is anticipated to be published later in the 2020-2023 work cycle, this document provides the user with thirty-six innovative or unique solutions to help to solve resilience issues in earthworks or earth structures in his/her country.

3. CASE STUDIES

The case studies were organized into five large groups and came from eighteen countries.

List of Case Studies

The tables below list the provided case studies broken down into five groups – soil classification, materials, techniques/methodologies, technologies, and project solutions – representing fifteen countries and four continents from TC4.3.

Soil classification

Case Study	Name of the project	Problem	Country
1 (page 15)	Dry Compaction	Soil classification system Reusing very wet or very dry soils	Romania
2 (page 17)	Decision tool and software for soil identification and harmonization of various classification systems	Soil classification system	Romania

Material

Case Study	Name of the project	Problem	Country
3 (page 19)	Rehabilitation of the Espiridião de Sousa street (lightweight aggregate)	Existing wall movement needed earth pressure to be reduced	Portugal
4 (page 21)	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 (page 23)	©Pneu sol	Unstable slope requiring steeper slope; opportunity for environmental solution by using old tires	France
6 (page 25)	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

TECHNOLOGIES

Case Study	Name of the project	Aplicability	Country
7 (page 27)	The Restore the Corridor Wilmington Rehabilitation Project	Identification depth of rock in advance of construction	USA
8 (page 29)	Lidar Robot	Cheaper and faster method for collecting topographic information	France
9 (page 31)	Reinforcement system including detection, survey, and warning system (PREDITECT®)	Observation and monitoring of earth structures	France
10 (page 33)	Comprehensive geotechnical monitoring of the landslide processes and the retaining structures in the city of sochi	Observation and monitoring of earth structures	Russia
11 (page 35)	Development of smart compaction management system for earthwork	Soil compaction	South Korea

DESIGN SOLUTIONS

Case Study	Name of the project	Problem	Country
12 (page 37)	ER238, PK 25+200 – excavation slope rehabilitation	Geology incompatible with geometry of excavation	Portugal
13 (page 39)	A17 Motorway Slope Failure	Erosion and infiltration causing slope failure; find cheaper and easier solution	Portugal
14 (page 41)	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 (page 43)	Cavities risk management - Gypsum dissolution phenomenon	Many small cavities in the ground; need to prevent road collapse	Tunisia
16 (page 45)	Castilla La Mancha A-40 dual carriageway construction project.	Bottom of excavation intercepted water table	Spain

Case Study	Name of the project	Problem	Country
17 (page 47)	Temporary and permanent culvert construction	Soft soils with large settlement; need to maintain culvert under embankment	USA
18 (page 49)	**Geosynthetic reinforced soil (GRS)** bridge abutments with stage constructed full height rigid facings	Soft soils under embankment	Slovenia

Techniques/Methodologies - Erosion

Case Study	Name of the project	Problem	Country
19 (page 51)	Regional Road no. 578 Rieti-Torano (Central Italy) – Vegetative solution protection nets environmental appearance improvement	Erosion causing falling rocks	Italy
20 (page 53)	Use of bioengineering for slope stabilisation	Erosion	Uganda
21 (page 55)	Reinforced embankment damaged by fire - located at EN 351 – center of Portugal	Embankment and georeinforced walls damaged by fire	Portugal

Techniques/Methodologies – Reinforcement

Case Study	Name of the project	Problem	Country
22 (page 57)	A4 - large embankment construction	Stability of very high embankments	Portugal
23 (page 60)	A16 Gabion Wall	Reinforcement of a gabion wall sagging and settling without removing	Portugal
24 (page 62)	Ground treatment solutions using jet grouting	Overall stability of gabion wall and slope	Portugal

Case Study	Name of the project	Problem	Country
25 (page 64)	© Cavibag	Many large cavities from limestone; need to prevent road collapse	France
26 (page 66)	Liquid lime-soil mixing treatment inclusion	Large cracks in clayey soils caused by drought	France
27 (page 68)	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 (page 70)	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 (page 72)	Technology of construction of anti-landslide structures in cramped conditions.	Large layer of very soft soil with major utilities under proposed embankment	Russia
30 (page 75)	Rete Ferroviaria Italiana – RFI – Fortezza-San Candido international railway (Alto Adige-Sudtirol - Northern Italy) – Restoration of damaged railway embankments	Emergency restoration of embankment without removing existing embankment	Italy
31 (page 77)	Reinstatement of the failed segmental retaining wall (SRW)	Wall collapsed - water pressures	South Korea
32 (page 79)	Control of debris flows with steel mesh	Protection against falling rocks and debris flow	Peru
33 (page 81)	Stabilization work to control landslides in urban areas	Slope stabilization	Bolivia
34 (page 83)	Rehabilitation of tunnel 1 cacheuta	Slope stabilization	Argentina

Case Study	Name of the project	Problem	Country
35 (page 86)	Slope stabilization route T350 Valdivia-Niebla	Slope stabilization	Chile
36 (page. 88)	Soil improvement of organic soil in the substructure of a road or railway line with The Cut-Mixing-Injection- Method	Slope stabilization	Germany

3.1. Case Study 1 – Dry Compaction Technology implemented in the construction of Tarhuna beni-Walid Road Project

Author – Radu Andrei, Technical University " Gh. Asachi" of Iasi, Romania

Location – Tarhuna - Beni Walid, Libya

3.1.1. Brief Summary of the Problem

The Tarhuna – Beni Walid Road is a two-lane asphalt concrete highway that connects the cities of Tarhuna and Beni Walid in northern Libya. Built during 1975 – 1980, the roadway crosses more than 97 km through an extremely arid desert environment and it is the only transportation route between the two cities. Water in the area is scarce and finding and hauling large amounts of water for soil compaction operations during the construction of the project was a major challenge.

3.1.2. Brief Summary of the Solution

The great majority of the subgrade soils along the construction route were granular (coarse-grained) with natural moisture contents between 1% and 3%. A great number of Modified Proctor laboratory compaction curves involving ten different soil samples and more than five hundred standard compaction tests, were developed for both coarse-grained and fine grained soils encountered along the road route. Thus, for the AASHTO course-grains soils A-1, A-2 and A-3, an unusual local maximum was observed at very low moisture, as illustrated qualitatively in Figure 1.

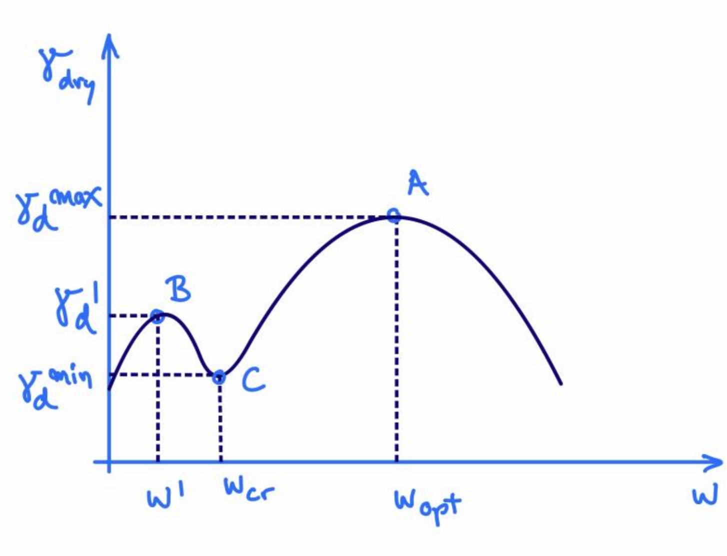


Figure 1: Schematic of Modified Proctor compaction curve for granular soil showing local maximum at low moisture (Point B) and the traditional maximum dry density at optimum moisture content (Point A). Also this curve shows a minimum dry density correspoing to a critical moisture content wcr (Point C)

For the fine-grained soils such as AASHTO A-4, A-5, A-6, the Proctor curves were presented similar irregular shapes , with the particularity that the local maximum at low moisture content(point B) was located on the ordinate , corresponding to a complet dry condition (moisture content w' = 0)

To reduce the amount of water required for compaction, the solution was to take advantage of the observed local maximum in dry unit weight (point B on the compaction curve) and to compact the soils at the site at the corresponding lower moisture content w’. Although γ_d’ is lower than γ_{dmax}, the required relative compaction of 95% of γ_{dmax} was generally achieved without any difficulties in the field, using only vibratory rollers.

The dry density curve also shows a minimum at point C, corresponding to a critical moisture content wcr. Compaction at this moisture content should be avoided.

The detailed results of laboratory and site investigations, the definitions of the new compaction parameters such as minimum density and wcr and the analyses of the suitability of investigated soils, are given in Annex 1, conceived as a “Practical Guide for Compaction of Soils at Dry or Very Low Moisture Contents“

3.1.3. Lessons Learned

1. As at this stage , the phenomena occuring during soil compaction are not fully understood, taking into consideration the limited research facilities of a site laboratory, and considering mainly the Proctor’s capillarity and lubrication theory , the aim of our research was foccused to find out , by examining from a macroscopic level, what are the main geotechnical characteristics of soil, such its grading , the moisture content, the liquid limit, plasticity index , which may affect the shape of its moisture –density compaction curve.
2. The extensive laboratory investigation involving ten different soil samples and more than five hundred standard compaction tests revealed many irregularly shaped compaction curves. The majority of coarse –grained soils , having a liquid limit less than 25, clearly reveal the existence of double peaks, as shown in Fig.1. A number of different irregular shapes was found to be characteristic for some sandy, silty and clayey soil specimens. The soil samples tested, with a liquid limit higher than 25, usually yield typical 1&1/2 or single peaks compaction curves.
3. Based on the laboratory and field research, involving complete Proctor curves, as shown in Fig.1, it was found that most of coarse-grained soils, (AASTHO classification A-1, A-2, and some of A-3) are suitable for dry compaction.
4. The investigated fine grained soils (AASHTO classification A-4, A-5, A-6), were found to be unsuitable for application of dry compaction. However, for these soils, even in non desert areas, it is recommended to perform complete laboratory Proctor tests, in order to find out the value of critical moisture content (wcr) , which is a very important parameter for the earthworks engineer, indicating how to avoid the inneficient use of the compaction equipment, on soils having such moisture. (For this reason, this recommendation, valuable for all types of soils, has been included in the Romanian standards for earthworks. (STAS 1913-13 -83 « Fondation soil. Determination of Compaction Characteristics. Proctor test »)

3.2. CASE STUDY 2 - – DECISION TOOL AND SOFTWARE FOR SOIL IDENTIFICATION AND HARMONIZATION OF VARIOUS CLASSIFICATION SYSTEMS

Authors:

- Radu Andrei, Technical University "Gh. Asachi" of Iasi, Romania
- Adi Andrei, Technosophics Ltd, London, UK

3.2.1. Brief Summary of the Problem

The experience of the American Association of State Highway and Transportation Officials (AASHTO), Unified Soil Classification System (USCS), of the French Recommendation pour les Terrassements Routiers (RTR) and of Romanian Standards for soil classification systems, that allows for coherent and complete soil classifications, based on a relatively limited number of well-justified representative parameters requires a critical assessment of the existing standards in various countries of the world, especially in developing nations, in order to improve, to complete, or to simplify them as appropriate. These problems became more evident during the development of Technical Recommendations for the Earthworks Construction of Trans-European North-South Motorway (TEM), with the aim that these recommendations would be used by all of the involved countries. At that time, the RTR classification system was agreed upon and adopted for TEM, but the problem of correlation and harmonization of various classification system was still unsolved.

3.2.2. Brief summary of the solution

The comparative analysis of the criteria and of the representative parameters used in the various classification systems analyzed identified the existence of a small number of common criteria, and especially, a very small number of common parameters, which could justify the need and usefulness of the study undertaken. Given the wide range of criteria and parameters involved in the classification of soils in the different systems we looked at, it follows that, although there is no "correlation" in the strict sense of the word, there is some "correspondence" between classes of soils specific to different classification systems. We developed Uniteras, a computer program capable of identifying the type of soil according to each standard, as well as of finding such possible "correspondences" between different classes of soils belonging to different soil classification systems. Using the geotechnical data available for a particular soil, Uniteras identifies the classification in any of the four classification systems, namely: AASHTO, USCS, RTR, and the Romanian Standards. The download location, a short user guide as well as some running examples and results of application are given in the Appendix.

3.2.3. Lessons Learned

The following conclusions have been formulated in relation with the results of the research undertaken for this purpose:

1. The comparative analysis of the criteria and of the representative parameters used in the classification systems analysed highlighted the existence of a small number of common criteria, and especially a very small number of common parameters, which could justify the need and usefulness of the study undertaken.
2. Given the reduced number of common criteria (granularity, plasticity, organic matter content) and the wide variety of all parameters involved (36 parameters), it follows that even

a "correlation" of these systems cannot be achieved in the strict sense of the notion. It is also possible to establish "correspondences" between some classes of soils, specific to the systems analysed, and for this purpose it is recommended to use the Uniteras program, a program in which the input data provides/assures the consideration of any one of those 36 representative parameters described in Table 1, covering all the possible situations of the investigated classification systems.

3. Such "correspondences", which may be established by using the program, could lead to a better knowledge and assessment of the performances of any investigated soil, being known that other classification systems may more fully describe the different categories of soil, and may present more complete methods and criteria for their identifications in the field (USCS, AASHTO) and in the laboratory (RTR, USCS). Finding and getting more knowledge of such correspondences may help the practitioners and the decision-makers benefit from these advantages offered by the other potentially more advanced systems, concerning the appropriate use of various soils (e.g. only in embankments, not in subgrades, etc.). Also, such correspondnces (for example the correspondance , found between the AASHTO Class A-2-4 and the RTR soil B4, as shown in the Appendix, def demo3-RTR_B4 & AASHO-A-2-4.doc), may help the AASHTO user to benefit from the detailed RTR practical guide for the extraction, laying, treating (if necessary), and compaction of that soil. Finally , such correspondences may help the adoption of more efficient construction technologies (e.g : dry , normal or very wet compaction), function of the real geo-climatic conditions, and guidance on the optimization of earthworks construction.
4. The experience of the advanced AASHTO, USCS, and RTR classification systems, which allow coherent and complete classifications, based on a relatively limited number of well-justified representative parameters, require a critical assessment of the existing standards in various countries of the world, and especially in the developing ones in order to improve, to complete or to simplify them, as appropriate.
5. The Uniteras software can be diversified and extended in the future, in order to cover other classification systems. It could also be enhanced with the addition of links and other external resources. As an example, in the case of using the RTR system, after finding the specific class of soil (e.g., soil RTR class A-4), the program can be extended to provide a web link for a specific "RTR Construction Case" providing a detailed practical guide for extraction, laying, treating (if necessary), and compaction of that soil. At this stage we are working on these extentions.

3.3. Case Study 3 - Rehabilitation of the Retaining Wall Using Expanded Clay Aggregate Backfill

Authors – Domingos Moreira, VEconcept; Pedro Tovar, VEconcept

Location – Vila Nova de Gaia, Portugal

3.3.1. Brief Summary of the Problem

The existing wall along Espiridião de Sousa Street consisted of rigid stone blocks with the exterior face lined with concrete located in an urban environment. The wall has an approximate constant height of 5.20 meters and a length of around 60 meters. At the back of the wall there is a one-lane road with a pedestrian walkway and parking lining the road on both sides. On the opposite side of the road there is a 7-story residential building.

The surrounding area began to show signs of movement of the wall, specifically the appearance of tension cracks in the sidewalks parallel to the wall and in the granite block pavement, as well as a vertical subsidence of 10-20 centimeters in the sidewalk, parking, and road behind the wall.

3.3.2. Brief Summary of the Solution

A test pit was excavated next to the wall to confirm the state of the wall in depth on its backside and the backfill soil. The good structural condition of the wall was verified, but the embankment soil contained low-permeability material with a high percentage of fine-grained particles, which created increased pressure on the wall.

The evaluation started with an option to reduce the applied pressures that cause the wall to slide and not to increase its rigidity, which would be much less efficient. The preferred solution was to replace the soil in the wedge of active soil pressure with material with higher drainage capacity and lower density. The choice fell on expanded clay aggregate with an effective drainage system at the base of the wall on the backfill side. Thus, the reduction of soil pressure on the wall allowed the end of its movements with a low-cost solution, structurally efficient and environmentally more sustainable.

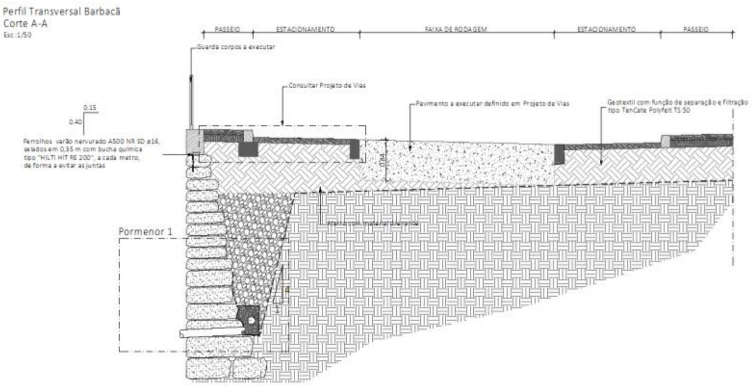
The drainage system was executed by wrapping the expanded clay aggregate with geotextile for filtration and installing a perforated pipe along the back of the wall in the base of the aggregate. Along its length, the underdrain pipe had two connections to drainpipes protruding through the wall, reducing hydrostatic pressure at the back of the wall. This came to be a simple construction solution with standard materials, procedures, and equipment resulted in a low-cost, structurally efficient, and environmentally sustainable solution that stopped the movement of the wall.

3.3.3. Lessons Learned

The following lessons were learned by the project team - The chosen solution was developed using simple materials, procedures, and equipment and produced a low-cost, structurally efficient, and environmentally sustainable solution that was effective in stopping the movement of the wall.

1.1 - Sidewalk and parking on top of the wall

1.2 - Front view of the wall



1.3 – Drawing detail of the applied solution

1.4 – Landfill during construction

1.5 – Landfill during construction

3.4. CASE STUDY 4 - USE OF GLASS SAND FOR HIGHWAY EMBANKMENT CONSTRUCTION

Author – Paul Nowak, Atkins Ltd

Location – Buckinghamshire, UK

3.4.1. Brief Summary of the Problem

The M25 widening DBFO project involved the widening of the existing M25 motorway from dual 3 lanes to dual 4 lanes over a 32-kilometre section between junctions 16 and 23 north west of London. All solutions for widening of cuttings and embankments had to be affected within the existing motorway boundary as the client, Highways England, did not want to engage in further land purchase. Where possible, earthworks solutions were adopted to reduce the carbon footprint of the project. The M25 is one of the busiest motorways in the UK and construction had to be carried out using the hard shoulder and lane 1 only to maintain 3-lane traffic flow in both directions. During the construction the availability of the material from widening of cuttings did not always become available when required for embankment widening works. Embankment widening material had, therefore, to be imported. Additionally, some of the material won from cuttings was weather susceptible, which precluded its use over periods of wet weather.

3.4.2. Brief Summary of the Solution

Some 1.5 million m3 of crushed concrete was used in the widening of embankments on the contract. This had been stored locally by the contractor from a previous nearby motorway widening project that involved the demolition of a number of bridges.

Additional to the crushed concrete, embankment widening was also carried out using some 250,000 m3 of glass sand. This material was attractive economically, as it is classified as waste product and provided free of charge at source. The cost of the material was, therefore, only that of transport to site, which involved road haulage of some 20 miles. The glass sand comprises a well graded angular material of sand and fine gravel size and achieves a high angle of friction on compaction due to its angularity.

A majority of the glass sand was used to widen an embankment 8 metres in height. It performed well on compaction, although local ponding of water caused some temporary pumping and dilatancy until the water had drained through the compacted fill.

Figure 1: Embankment construction using glass sand

3.4.3. Lessons Learned

The following lessons were taken from the project:

- glass sand performs well as an engineered earthworks material
- it is an economic and sustainable source of fill although limited in its supply
- as it generally comprised crushed beer bottles it does not pose any harm to the environment due to long term leachate from the fill
- it has been used subsequently as granular backfill to retaining walls on the A465 Heads of the Valleys 2 project in South Wales.

3.5. Case Study 5 - Repairing collapsed embankment with old tires and the "pneusol" technique

Authors – Thierry Dubreucq, University Gustave Eiffel

Location – Rural road n°9, Cardesse, France-Pyrénées Atlantiques

3.5.1. Brief Summary of the Problem

Many techniques exist to repair damaged embankments, collapsed due an excess of water content in the underlying embankment material. In the case of Cardesse, the embankment failed at the outfall of a spring resurgence on a natural slope. The stakeholder was also concerned by a stock of old truck tires located 40 km from the site, which created negative impacts in the environment.

3.5.2. Brief Summary of the Solution

The use of old tires is a French technique developed by Dr NGUYEN THANH Long, with French Ministry connections (https://www.pneusol.eu.org/.) The French name is "Pneusol", which can be translated to "Tiresoil".

For this technique, only gravel, geotextiles, and tires are needed. The work does not require skilled labor, and only light drum rollers are necessary for compacting the material. Once the damaged soil is removed, tires are placed and strongly bonded one-to-another. Flexible geosynthetics sheets are laid between each row of tires and Figure 2). Prior to laying these sheets, each tire is then partially filled with gravel (Figure 3).

Figure 2 : Assembly line for Pneusol process – placement of tires and geosynthetic sheets and stockpile of gravel

Figure 3 : tire bonding operation and then fitting the geotextile into the tire hubs

Figure 4 : Placement of gravel and compaction at each inter-layer with light drum roller.

3.5.3. Lessons Learned

The design of an embankment using this technique allows:

- Reuse of waste in a high added value structure;
- Increase of the safety factor by 30% with respect to the external sliding;
- Reduction in the weight of the backfill ;
- Steepening the earth structure slope with respect to the internal sliding;
- Draining the internal natural groundwater table.

One year after the works, the road settlement was only around 1 centimeter. This repair was really a sustainable solution for the stakeholder at a normal cost for works.

3.6. Case Study 6 – Re-use of End-of-Life Tires as Backfill Material

Authors: José Estaire, Centro de Estudios y Experimentación de Obras Públicas (CEDEX) / Jerónimo Vicente Dueñas, Ministerio de Transportes, Movilidad y Agenda Urbana

Location: Spain, several locations. Branch 3 of Junction 1 of the AP-46 Motorway: Alto de Las Pedrizas (Málaga) and esplanade near the municipality of Villanueva del Arzobispo (Jaén).

3.6.1. Brief Summary of the Problem

This application is part of the activities aimed at improving the management of waste, specifically "end-of-life tires", whose correct management at the end of their useful life is the responsibility of the manufacturer and importer of the tire.

3.6.2. Brief Summary of the Solution

Among the possible alternative uses of end-of-life tires is their use in the construction of backfill in road works and in the construction of the backfill of retaining structures.

The objective of this document is to provide a series of guidelines, criteria and directives regarding the use of these materials in road fills, so that these types of solutions can be considered in the design of these elements when their conditions of use are appropriate. The criteria contained in the document are based on experimental studies carried out by the Centro de Estudios y Experimentación de Obras Públicas (CEDEX) and by the Dirección General de Carreteras of the Ministerio de Transportes, Movilidad y Agenda Urbana (Spain).

3.6.3. Lesson learned

The execution of this type of backfill presents conditioning factors that introduce additional operations and increase the difficulty of construction, with the consequent loss of performance compared to conventional earth backfills. However, this type of backfill has special characteristics (low density, low transmission of horizontal pressure on the back of a structure), which can make it particularly interesting for special applications (backfills on soft soils, special backfills for structures with limited lateral load-bearing capacity).

An additional advantage of the above solution is the transformation of waste into resources, an operation geared towards greater sustainability and a circular approach to economic activity.

Fig. 1. Construction of experimental embankments made of shredded end-of-life tires (SEOLTs)

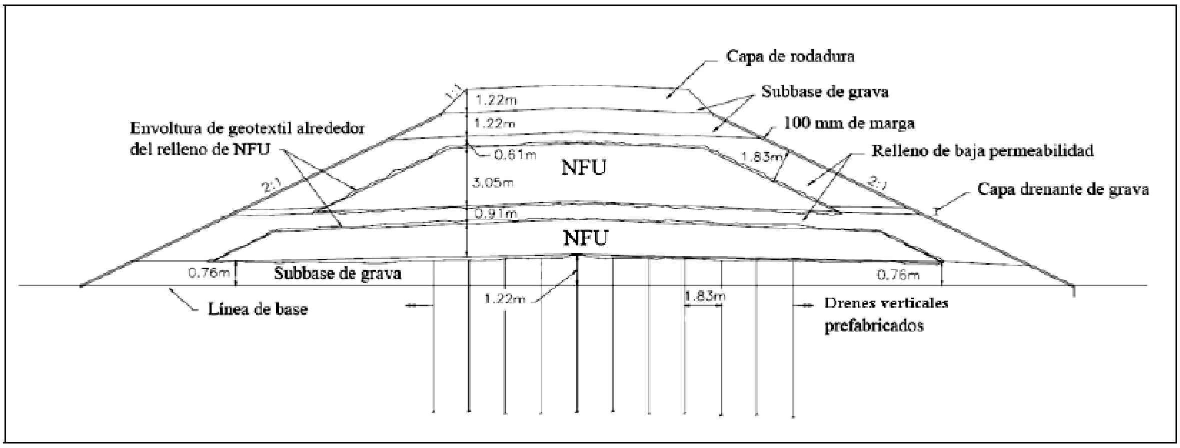


Fig.2. Cross-section of an embankment with two layers of shredded end-of-life tires (SEOLTs-NFU) (Humphrey et al, 2004).

3.7. Case Study 7 – Identification of Subsurface Rock Profile Using Ground Penetrating Radar

Authors – Ted Thomson (Pennoni Associates); Jason Hastings (Delaware DOT)

Location – Wilmington, Delaware, United States

3.7.1. Brief Summary of the Problem

Interstate 95 (I-95) is a major north-south highway on the east coast of the United States running from Maine to Florida and connecting major cities such as Boston, New York, Washington, and Miami. The segment running through Wilmington, Delaware, was built in 1964 and in need of major rehabilitation. A portion of the project limits involved the reconstruction of the existing pavement. This area is underlain by very hard rock, Brandywine Blue Gneiss, with a depth that varies wildly, from outcroppings to several feet below the ground surface. The rehabilitation project had a major impact on traffic and a tight budget, so the variability in depth to this very hard rock presented a significant challenge for the design team. Due to the large area of varying rock depth, the strict use of Standard Penetration Tests (SPT) and Cone Penetrometer Tests (CPT) alone would have a relatively high cost, would have significant impacts to traffic, and would cause damage to the existing roadway for the amount of testing needed to effectively map the rock depths, so an alternative approach was needed.

3.7.2. Brief Summary of the Solution

The solution was to use an exploration program consisting of geophysical exploration followed by test borings to confirm the geophysical exploration data. Geophysical exploration consisted of ground penetrating radar (GPR) using a 400 MHz and combination 300/800 MHz antenna. GPR was used to capture qualitative data over a wide area. The testing was able to be completed quickly, allowing for the work to occur with minimal impacts to traffic through rolling roadblocks and shoulder closures only. To supplement and help reinforce the results of the GPR data, SPT borings were performed in specific areas where rock was estimated to be within excavation zone following the completion of the GPR testing. SPT borings were performed at night to limit disruption of traffic.


Figure 1. Photographs of GPR Units.

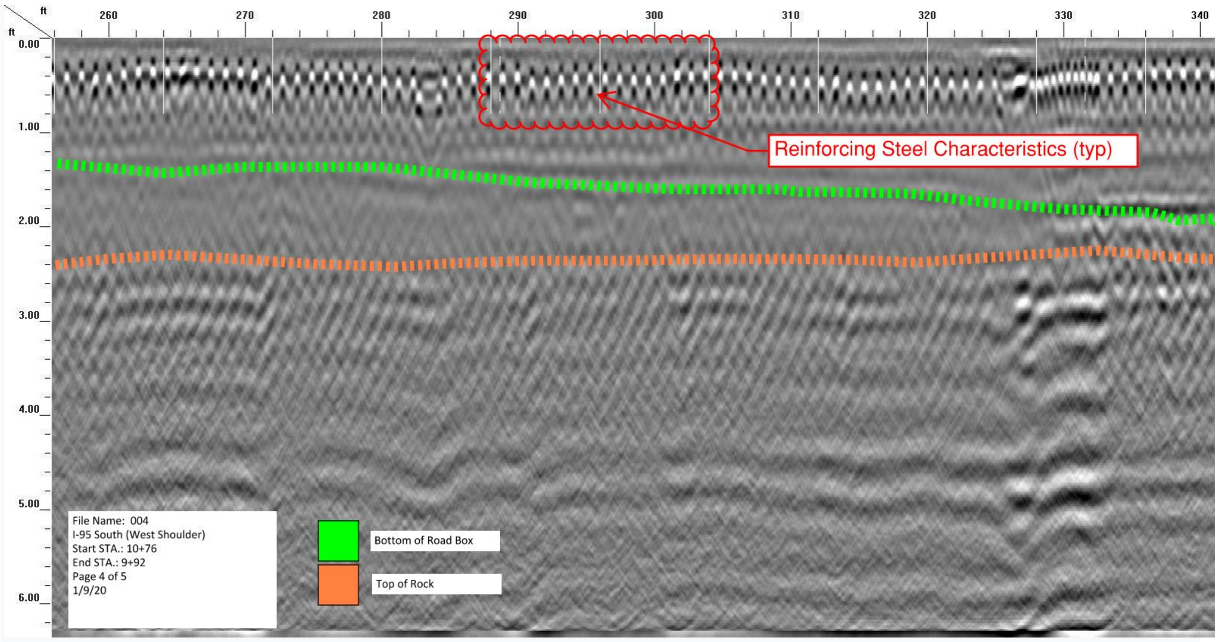


Figure 2: Typical GPR File.

The GPR testing was able to detect not just the top of rock but locations of rebar in the existing concrete pavement, producing an unanticipated benefit with additional useful information to provide to the contractor.

3.7.3. Lessons Learned

The following lessons were learned by the project team:

- GPR is a relatively low-cost method of providing qualitative data over a wide area.
- GPR can be performed with minimal impact to traffic.
- GPR can identify various subsurface features (e.g., reinforcing teel, concrete, rock surface, etc.) in certain situations.
- The advanced GPR exploration investment paid significant dividends for the advanced utility relocation work performed in the area, which included the relocation of three 36” diameter water mains and a natural gas line.

3.8. Case Study 8 - Adaptation of new technologies as Lidar and photogrammetry to earthwork

Authors – Yohann Rabot, Vinci Construction

Location – France

3.8.1. Brief Summary of the Problem

Topographic work is an essential part of earthworks, but it is sometimes time-consuming when the topography is complicated, such as with lot of vegetation, or is for a very long project. Evolution of the market for land surveyors and for companies naturally leads to an evolution of tools and equipment. This evolution of equipment has led the topography department of Vinci Construction to adapt Lidar and photogrammetry to their earthworks practice. The company proposes these new technologies to their clients at a competitive cost and for the same quality of work.

Figure 5: example of drone and on-board camera

3.8.2. Brief Summary of the Solution

Data is acquired with a simple camera supported by a drone for small areas (Figure 5) or Lidar supported by a helicopter for the largest. Thanks to those technologies, we are able to survey large areas in few hours with high resolution and accuracy as opposed to days or weeks using traditional field methods.

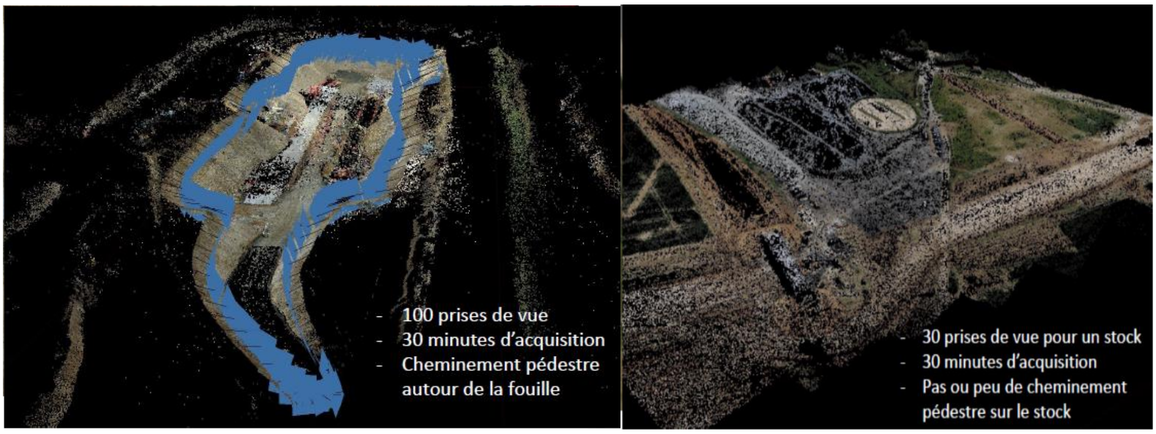


Figure 6: example of the result of a lidar acquisition

Those data are processed with specific software of trajectography, lasergrammetry, or photogrammetry to produce 3D points cloud, orthoimages, 3D models, or maps. Those deliverables are used to optimize the conception, follow the earthwork progress, or produce an as-built model.

3.8.3. Lessons Learned

Lidar and photogrammetry using drones and technologies for data post-treatment provide complementary responses to the evolution of the survey and topography market. We are now able to access accurate data quickly in large or inaccessible area. Thanks to the "communication" aspect, they enable the company's work to be more cost-effective. The public works industry must allow the use of these technologies and must evolve and adapt the rules and regulations governing the use of Lidar and photogrammetry by aerial means.

Advantages : speed of processing, security of data acquisition, less fieldwork to be done, automated data entry and repeatability, ability to access inaccessible areas.

It is also interesting because it provides real time follow-up of the site progression, digital archives for claims, and digital as built for Asset management and future new technologies as BIM in earthworks.

Disadvantages : For aerial works you have to follow local regulations. The technology is highly dependent on the weather – you cannot use it with rain or fog.

3.9. Case Study 9 - Reinforcement system including detection, survey, and warning system (PREDITECT®)

Authors – Mathilde Riot, Afitexinov

Location – France

3.9.1. Brief Summary of the Problem

Earthworks and earth structures occasionally face the risk of localized soil subsidence or collapse due to karst cavities and former underground mines both deep and shallow. The use of geosynthetic reinforcement to prevent localised failures linked to cavities is now relatively common. With that solution, the cavity still exists at the end of the earthworks and a risk of unfavorable conditions after several years of life still exists. One solution consists in integrating a monitoring system into the geo-synthetic reinforcement. This allows for a survey and warning system of the road with a reasonable cost. It offers to the earthworks owners an easy-to-use tool which can be easily adapted according to the intended monitoring objectives.

3.9.2. Brief Summary of the Solution

The proposed solution combines this reinforcement technique with a reliable measurement, detection, monitoring, and alert system (Figure 7).

Figure 7: (left) Principle of the PREDITECT® system ; (right) Example of innovative inverted bi-stiffness geosynthetics.

This solution has been developed within the REGIC research project (Reinforcement using Intelligent Geosynthetic over Natural or Anthropogenic Cavities). The project is localised in France, with French partners: Afitexinov (project leader), 3SR Laboratory (Grenoble university), INERIS (French National Institute for Industrial Environment and Risk). It was labelled by the TECHTERRA “Pole of Compe-titiveness” and funded by ADEME as part of the PIA projects “Road for the future”.

The first installation of the system was scheduled on the “Lino” project (Lille, France), where the project passes over an area of old abandoned wells (Figure 8). The upper soil is a 1.0 m thick clayey soil layer and the embankment is 1.5 m backfill. It has been previously validated in laboratory and full scale testing at INSA Lyon.

The solution includes:

- the use of the innovative inverted bi-stiffness geosynthetics to widen the measures of small deformations allowing the early detection of the cavities,

- coupled with the new technology "geo-auscultation" for risky earthworks that is supported by its integrated monitoring system, PREDITECT®

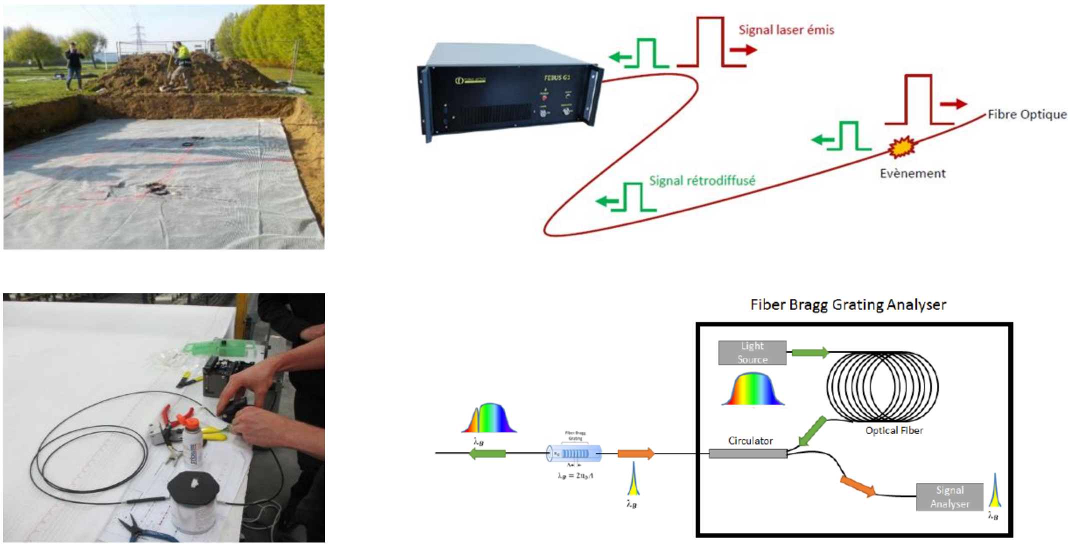


Figure 8: (above left) Typical installation of the system over an old career just above a localised cavity (Lille, France); (bottom left) Connection of the optical fibres included in the geosynthetic; Functioning principles of the optical fibres used in the "geo-auscultation": (above right) distributed optical fibre measurements and (bottom right) local optical fibre measurements

3.9.3. Lessons Learned

The construction of geosynthetic reinforced "simple" structures using instrumented geosynthetics is quite common and Afitexinov has an experience of more than 20 years in case of geosynthetic reinforced walls and slopes, and similarly in embankments on piles in soft soils.

The real challenge is in the adjustment to the specific requirements of the upwardly migrating cavities, including the wide settlement troughs with low amplitude. The design of an adequate optical fibre and eventually of the specifically designed geosynthetic, with the relevant PREDITECT ® is the main challenge. The production of the specific bi-axial geosynthetic, when needed, remains an important challenge where Afitexinov has reached a clear know-how.

As for more classical instrumentation of reinforced geosynthetics special care has to be focused on the layout of the fibre's patterns and on the realisation of the connections. The protection of the optical fibres has also to be correctly designed for the placement of the upper soil layer and its compaction.

Based on calculations on several actual structures, it can be estimated that instrumented reinforcing geosynthetic solutions may reduce the costs of cavity treatment by up to 40% compared to a traditional solution. The environmental impact has been evaluated by a "Life Cycle Analysis" study. Depending on the structure and on the solution chosen a reduction the up to 20% to 40% of the Global Warming GWP(100) is obtained.

3.10. CASE STUDY 10 - COMPREHENSIVE GEOTECHNICAL MONITORING OF THE LANDSLIDE PROCESSES AND THE RETAINING STRUCTURES IN THE CITY OF SOCHI

Authors - Matsiy Sergey Iosifovich, NTS GeoProjekt, Lyubarsky Nikolai Nikolaevich, NTS GeoProjekt

Location - Sochi, Russia

3.10.1. Brief summary of the problem

During preparations for the 2014 Olympics Games in Sochi, in order to reduce the traffic impact to the city's transportation network, an alternative route was built on the Kurortny Prospekt. The proposed road is located along the slope of the seacoast with access to the ridge that separates the seacoast from the valley of the Agura River.

One of its main points is located in the Agura-Bzugu interfluve, where the Bypass of the city of Sochi and the A-147 Dzhubga-Sochi highway intersect. This area is located in a low mountainous part of the sea coast in difficult geotechnical and geological conditions, where, according to the List of the State Monitoring Service, two ancient landslides № 214 and № 215 occurred.

The landslide № 214 has a slightly knobby surface, forested part. Small erosion insets in the clay soils are observed.

The landslide № 215 also has small stepped shapes; the landslide bodies consist of the deposits with an insignificant capture of the bedrock. They are at the stage of a long-term stabilization, which has resulted in a formation of the powerful landslide strata in the floor of the valley.

During construction, the large-scale hazard level of a microblock displacement activation hazard remained at the points of a coincidence of the surface inclines and the bedrock stratification. To protect against the effects of hazardous geological processes, the construction of a piled anchor landslide protection structure was envisaged (Figure 1).

Figure 1. Pile anchor landslide protection structure at the interchange in the area of the city of Sochi

3.10.2. Brief summary of the solution

The design of the protection measures included a comprehensive geotechnical monitoring system. Sixty-three (63) survey points have been installed to measure the displacement of structures. The geodetic base stations were arranged with the marks located on the boundaries of the deformation sections in pairs along one vertical line. Their position in plan from top to bottom was determined with an electronic tachometer on a month-to-month basis. The landslide accumulations were also mapped by using methods of seismic profiling and electric profiling.

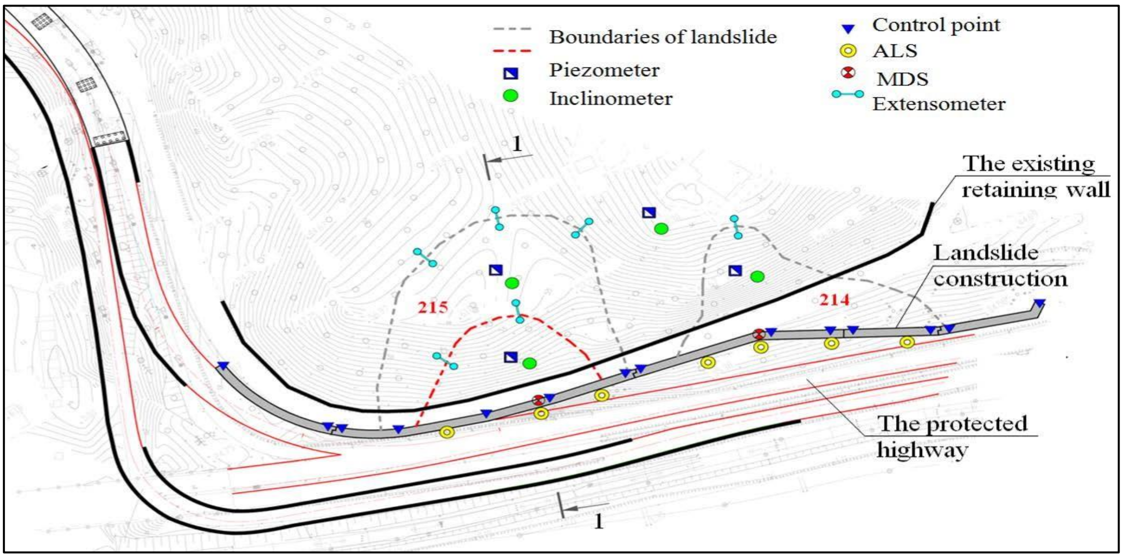


Figure 2. Layout of geotechnical equipment at “Agura” interchange

3.10.3. Lessons Learned

The vertical displacements of soil were observed using five-deviation recording wells, which have a depth of 14 to 18 m. They were arranged at the boundaries of the existing landslide systems as well as at the locations of their possible development. In order to control nearby ground water level, pressure observation wells were installed to a depth of 10 m. Due to the dense vegetation, it is nearly impossible to arrange a network of the monuments in order to trace the surface displacements at this part. For this purpose, a system of six (6) surface extensometers were used, each embedded 0.4 m in concrete. A landslide pressure influence on the structure was assessed using the mechanical deformation sensors (MDS), which were arranged in two most loaded piles. The sensors were placed in pairs in the sections, which are spaced at 4 m. The anchor load sensors (ALS) were mounted using bolted connections. When they were arranged, the anchors were tightened up to the design stress of 200 kN.

The results, which were obtained during the geophysical investigations, made it possible to specify the borders of the landslide parts and to define the area of filtration and increased fissuring. The seismic exploration data demonstrated the presence of irregularities and an increase of longitudinal wave velocity at the depth of 5.5 to 7 m in the area of the landslide No. 215; it proved instability and watering of the present zone.

3.11. CASE STUDY 11 – DEVELOPMENT OF SMART COMPACTION MANAGEMENT SYSTEM FOR EARTHWORK

Author: Dr. DO, Jongnam (Korea Expressway Corp.)

Location: South Korea

3.11.1. Brief summary of the problem

In road construction, compaction for earthworks and earth retaining structures is critical for the usability and stability during construction and service life of roads. Settlements and cavities in roads can occur due to the lack of quality compaction and may threaten the usability and the stability of structures and roads. The compaction work is difficult to do in the areas adjacent to structures during construction of the road embankment and earth retaining structures due to the narrow space. The quality control of the compaction in these vulnerable areas is very important.

While the compaction evaluation method using the plate loading test does not have a problem for compaction of general roads with a large space, compaction testing is difficult in narrow places around structures. The existing compaction evaluation method using the plate loading test has many challenges including difficulties in the arrangement of reaction equipment, too much time required to test, and difficult to test around bridge abutments, retaining walls, culvert backfills, and other areas with tight space.

3.11.2. Brief summary of the solution

Because compaction is such a critical element of constructing earthworks and earth retaining structures, a Smart Compaction Management System for Earthwork (SCMSE) was developed. The SCMSE consists of a global navigation satellite system, dynamic loading system, and motoring and data acquisition system and is mobile. The SCMSE was developed and tested in the field to verify its usability as a research project using the Korea Expressway Corporation's own research funding.

Through field tests, a correlation between the elastic modulus estimated by the existing plate loading test and the elastic modulus estimated by the SCMSE was derived. It was proved in the field verification test that the SCMSE can replace the existing plate loading test method using this correlation.

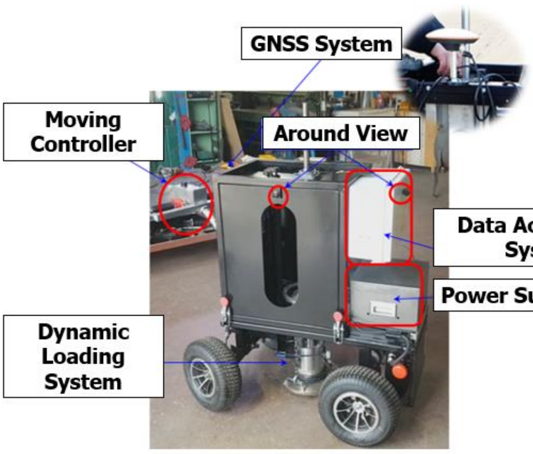


Figure 1: Photo of SCMSE

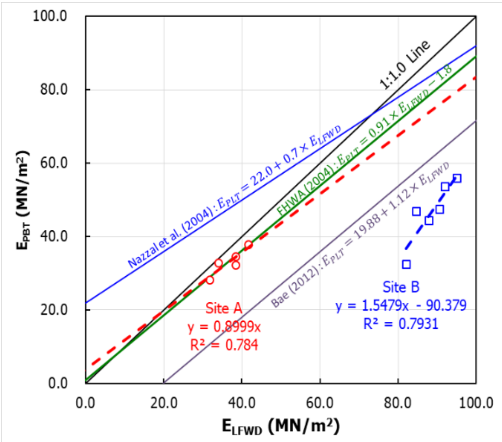


Figure 2: Correlation plate loading tests and SCMSE

3.11.3. Lessons learned

The development of SCMSE has significantly reduced the challenges of evaluating the quality of compaction in tight spaces and critical areas around earth retaining structures. The main achievements were the reduction of the working time by 90% (40 minutes/test → 3 minutes/test), and 97% reduction in cost ($10,000 US/test → $400 US/test). It is expected that the application of the SCMSE will improve the compaction quality and thereby improve the usability and stability of the road. However, the derived correlation has a certain variance, which will be supplemented through additional research and analysis.

3.12. CASE STUDY 12 - SLOPE REHABILITATION USING INTERNAL DRAINAGE SYSTEM

Authors - Agostinho Benta, Aveiro University; Alexandra Ferreira, ASCENDI

Location - Ferreira de Zezêre, Portugal

3.12.1. Brief Summary of the Problem

The slope had two landslides that occupied a large part of its length. The landslides originated from the combined action of water and the effect of ice and thaw on the existing fracture / schistosity system. The slope of the cutting consisted of two areas with different material types. In the lower area, the material consisted of fractured rock with an average spacing between fractures of 20 to 30 cm. Near the top of the lower zone, the fracture spacing deecreased to 10 cm. In the upper area, the material transitioned to soil covered by vegetation. It was found that the main unstable mass detached from the upper area - earth formation, dragging other materials to the foot of the slope.

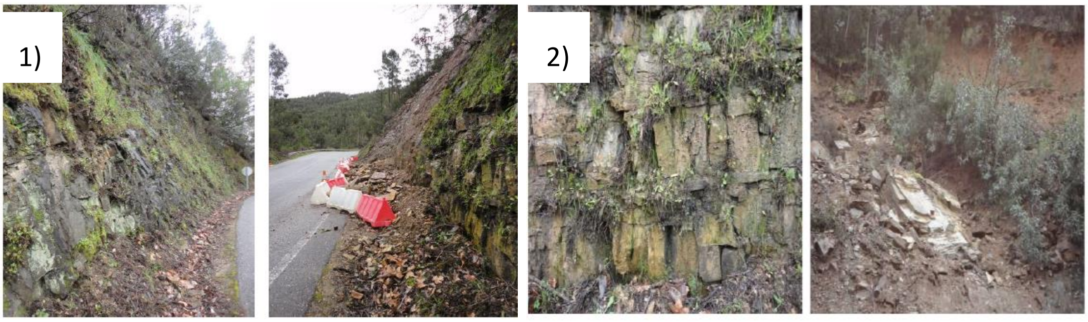


Figure 1: Photos 1) material deposited in the roadside ditch, 2) different views of the slope failure

3.12.2. Brief Summary of the Solution

The diagnostic was done with a visual inspection and two probes for rotation. The main conclusions drawn:

i)- the slope doesn´t have a drainage system and the platform ditch is blocked;

ii) assessment of the state of change, depth of each zone and respective geological-geotechnical characteristics.

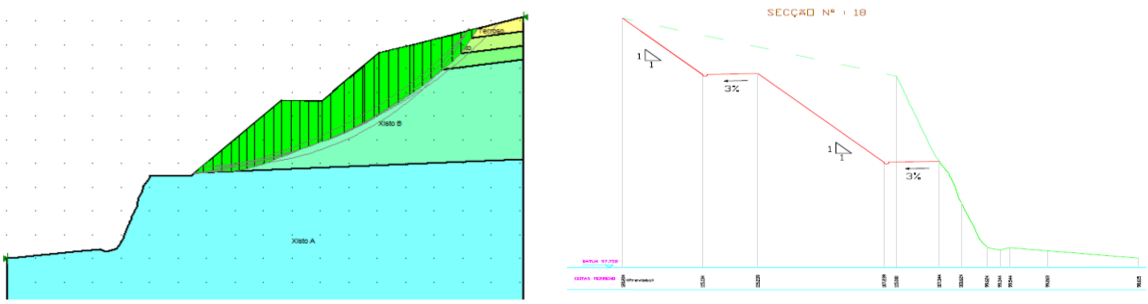


Figure 2 - representation of stability analysis - most unfavourable composite surface, and one example of the cross-section

The solution consisted of the following steps:

1. Deforestation of the cutting slope;
2. Earthmoving - Removal of unstable material and profiling of the cutting slope creation of intermediate shoulder;
3. Internal drainage - geodrains diameter of 50 mm, in PVC pipe crepined and wrapped in geotextile, 5% inclination to the outside. And implemented a superficial drainage system;
4. Application of metal mesh - triple torsion wire mesh.

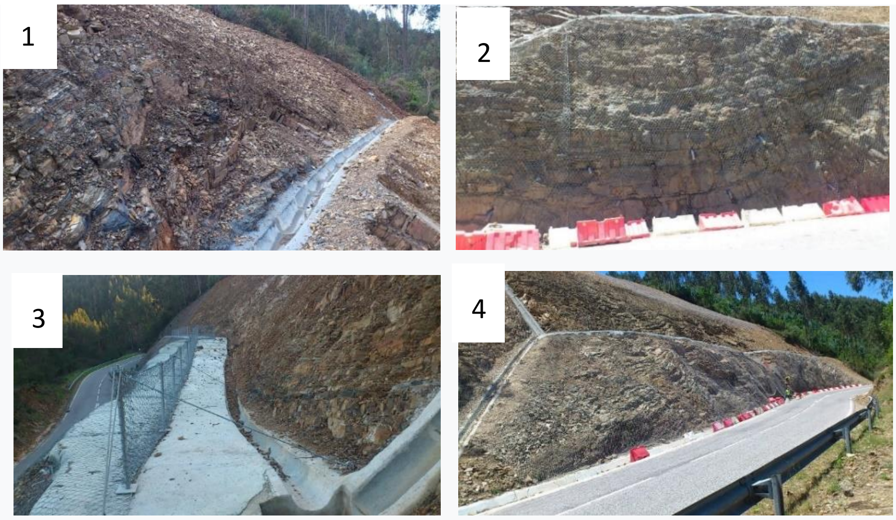


Figure 3 – Construction phase photos: 1) Earthmoving - Removal of unstable material and profiling of the cutting slope, 2) Application of metal mesh, 3) intermediate shoulder, 4) Final view.

3.12.3. Lessons Learned

The following lessons were learned by the project team:

- Seven year after completion of the work the solution remains effective.
- The geometry of the slopes must be suitable with the geological formation. The existence of intermediate shoulder is a stabilizing factor.
- The superficial and internal drainage are revealed to be fundamental in the stabilization of slopes, and must be properly dimensioned.
- The cleaning of the tree and shrub vegetation and mainly the maintenance of the integrity and unblocking of the drainage organs are maintenance activities to be carried out at least twice a year.
- The existence of an annual observation and monitoring plan for geotechnical infrastructures, with visual inspections, allows a monitoring of the effectiveness of the implemented measures, as well as preventive actions, in small pathologies that occur.

3.13. Case Study 13 – Slope Stabilzation Using Bituminous Concrete

Authors – Edurado M. Fernandes, Elsamex; Alexandra Fereira, ASCENDI

Location – Aveiro, Portugal

3.13.1. Brief Summary of the Problem

The A17 motorway, located in the center of Portugal, runs from north to south, connecting the district capitals of Aveiro and Leiria and connecting at the ends to the A25 and A8 motorways. The problem occurred in December 2019, on the excavation slope at PK 100, after the occurrence of very high rainfall in periods of very short duration.

On the 19th of December 2019, in a cutting slope on the A17 at PK 100, a very large mass of clay materials liquefied reaching the edge of the highway as a result of the partial rupture of the slope. Concrete barriers were immediately installed to protect the roadway and the roadway users, but the mass volume was significant and cracks were registered in the slope, a phenomenon that increased the percolation of water into the mass and further progressed the rupture.

Figure 1 – Damage: Photos: 1, 2 and 3)

3.13.2. Brief Summary of the Solution

The solution consisted of the following steps:

1. Removal of all vegetation, including removal of roots, on the slope and area related to landslides;
2. Removal of the landslide materials from the bottom of the excavation slope and its removal to the drain (between Pk 100 + 155 and Pk 100 + 185);
3. The installation of rockfill with indentations in the lower layer of the excavation slope, maintaining the existing slope of 1:2 (v:h);
4. Stripping the entire length and width of the bank, with a thickness of 10 cm;
5. Waterproofing the excavation slope stool by applying a 10 cm thick granular rock aggregate + 1.5 cm thick double bituminous coating + 6 / 10 mm gravel;
6. Repair of damaged drainage pipes.

The final surface was covered with 6 / 10 mm gravel, which has the function of protecting against Surface erosion, in an amount that covers the entire watered surface perfectly. The characteristics of the gravel complied with the Specifications for Roads of Portugal 2009.

Figure 2 – Construction Phase: Photos: 1) Removal of all vegetation and removal of the landslide materials from the bottom of the excavation slope; 2) The installation of rockfill, 3) Stripping the entire length and width of the bank, with a thickness of 10 cm and 4 and 5) Waterproofing the excavation slope stool by applying a 10 cm thick granular rock aggregate + 1.5 cm thick double bituminous coating + 6 / 10 mm gravel 6) Final view after the intervetion.

3.13.3. Lessons Learned

The following lessons were learned by the project team:

- One year after completion of the work and being in service through two rainy seasons (spring 2020 and winter 2020/2021), waterproofing the slope stool remains effective. Although the observation and monitoring period is still short (1 year), the solution appears to be adequate in preventing water from entering the mass.
- In Portugal, the usual solution for waterproofing slope stools is 10 cm thick concrete, with wire mesh AQ50 sol, on 1 cm thick PEAD geomembrane. Bearing in mind the cost-effective solutions, this one had a cost of 70% compare to the traditional solution.
- In conclusion, this methodology allows the waterproofing of shoulders or other components of a slope, preventing water from entering the mass, allowing geotechnical infrastructure to withstand adverse weather conditions with better performance.

3.14. Case Study 14 – Repair of Holes Formed at the Bottom of Earthwork Excavation

Authors: Álvaro Parrilla Alcaide / Jerónimo Vicente Dueñas / Jesús Iranzo Sanz ; Spanish Ministry of Transports

Location: Sarrión, Spain

3.14.1. Brief Summary of the Problem

After the excavation of a cutting, some small areas started to sink in both the bottom and the slopes of the cutting. These areas had a circular shape with an average diameter of approximately 1 m and a depth slightly smaller (these dimensions were the average values but there were big deviations).

They used to appear after rainy periods, and evolved very quickly (in one or two weeks a located area may suffer holes). The observation period took about 8 months, after that time it was decided to implement a definitive solution.

The affected zones by this phenomenon were three stretches of the bottom of a cutting with a length of 180, 40 and 240 m each.

3.14.2. Brief Summary of the Solution

At a first stage, a deep research of the phenomenon was done, including laboratory tests (granulometry and Atterberg limits, standard Proctor, carbonates content, swelling, collapse, dispersibility (pin-hole) and mineralogy by means of X-Ray diffraction) and in situ investigation (seismic refraction prospection, electrical vertical probing and borehole probing).

The designed and executed solution comprised the construction of a subterranean water drainage network, the over-excavation of the bottom of the cutting, a subsequent earth fill with rocky material with a thickness of 2.5 m, and some waterproofing measures on the superficial surfaces of the road. If any new hole could appear below the new bottom (2.5 m deeper than the previous one), it was considered that a fill of two layers of rock 2 to 2.5 times the size of the hole could be enough (by reordination of its fabric) to avoid reflection of holes in the pavement. If any, in such a case, at least it would be softer and able to avoid a sudden hole in the pavement.

3.14.3. Lesson learned

Before defining the solution, it was necessary to carry out a thorough investigation in order to understand the phenomenon. Analysing the performance of the solution we can confirm that it was effective and efficient, as it only considered conventional equipment and material that was available on site. The affected area comprised a total surface of 15,180 m2, and had a cost of approximately 700,000€.


Fig.1 (left) Aerial view of the cuttings affected by the phenomenon
Fig. 2 (right) Sink holes observed in the bottom of a cutting

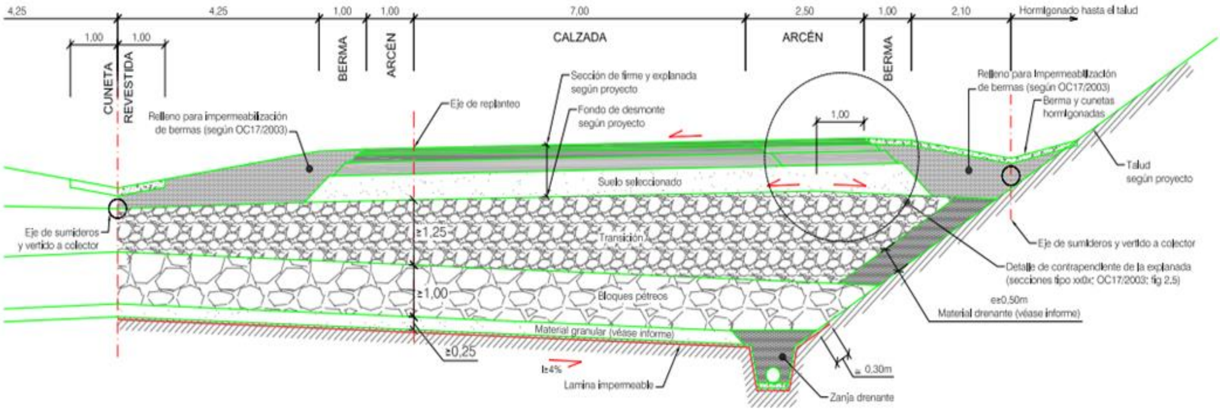


Fig. 3. Typical cross-section of the implemented solution

3.15. Case Study 15 - Risk Management Related to Underground Cavities from Karst

Authores: Kamel Zaghouani (Terrasol)

Country: Tunisia

3.15.1. Brief Summary of the Problem

Traditional solutions to solve karst cavities typically involve pumping grout into the cavities until completely filled. This solution can be expensive and time-consuming, and there is no guarantee that all the voids have been filled. During the construction of the A3 Motorway, the contractor detected karstic cavities within the proposed area of the new roadway.

Picture 1 *Picture 2*

The opening of the roadway was time sensitive, but it was important to fully mitigate these cavities to minimize the potential for catastrophe once the roadway was opened.

A major contributor to this problem was water. Water causes the dissolution of karst, creating the cavities, but this was exacerbated by the fractures prevalent in this area. These fractures allowed more water to enter the karstic areas. In addition to the fractures, stream flows contributed to the risk associated with karst cavities. On the upstream side, the drainage basin seemed dry but consisted of many sinkholes and there were many blackages caused by farmers protecting their animals, leading to stormwater rushing in during rain events. On the downstream side, high water elevations are present close to the project area.

To help identify the problem, 44 soil borings 25 meters in depth were performed. From these borings, it was determined there are two types of soil profiles interspersed throughout the project limits: the "good zone", consisting of compacted marl and gypsum, and a "bad zone", consisting of fractured gypsum with clay, sand, and marl filling the cracks.

3.15.2. Brief Summary of the Solution

The proposed risk management strategy considered cost and time and included the following:

- Inject existing voids in a grid pattern to provide some stability and support for the additional measures without the excessive overruns of traditional solutions
- Implement a protective layer of geotextiles to provide support in the event cavities do form in the future
- Limit infiltration of rainwater to reduce the potential for the karst to be dissolved by water

The proposed grid had a spacing of 10m by 10m and was limited in depth to 15m to avoid impacting groundwater. If a cavity was found at the spacing, additional injection measures were taken to ensure a column was created to provide extra support for the geotextile layer.

The geotextile layer was designed to consider cavities up to 3m in diameter while allowing an acceptable level of deflection.

The rainwater was prevented from infiltrating the subgrade by making the shoulders waterproof and collecting the rainwater outside the shoulders.

3.15.3. Lessons Learned

The project team learned the following from the project:

- The solution solved the problem as desired and was cost-effective.
- This same solution was implemented on another section of the motorway after this section was completed.
- It is clear that the solution has been working 15 years since implementation. There have been cavities formed in the same area outside of the roadway, but there have been no cavities observed within the motorway.

3.16. Case Study 16 – Correcting High Groundwater Table Using Drainage System

Authors - J. Díaz; E. Bermúdez; F.J.G. Cabezas; A.J. Díaz; C. Rodríguez.

Location: Castilla La Mancha, Spain

3.16.1. Brief Summary of the Problem

In the study and execution of the excavation of a cutting for a road platform, a series of problems of hydraulic nature were detected, which would lead to others of a geotechnical and pavement nature if they were not solved. The appearance of groundwater at levels which intersected or were above the gradient of the finished road required the establishment of the necessary technical solutions which would guarantee the adequate use and comfort of the future road.

3.16.2. Brief Summary of the Solution

Discarding the solution of raising the gradient of the finished road, due to the groundwater levels, a solution of deep drainage, soil replacement and placement of granular drainage material was chosen, variable according to the volume of water intercepted and its channelling and outflow. The soil of the excavation, of Miocene origin, was composed of brown and reddish sands with clayey and silty intercalations. Occasionally, levels of sand with considerable gravel content appeared. Due to the foreseeable deformability of the most superficial layers at the bottom of the cuttings, as they were in contact with the phreatic water, it was decided to replace variable thicknesses of the supporting soil with free draining granular material protected with geosynthetic and filled with material with improved characteristics. With the dual function of reducing possible deformations and channelling the water to the lateral collectors of the road. In some areas, work was also carried out on the slopes of the cuttings by protecting them with rockfill where, due to these levels of sand and gravel, cohesion was reduced and instabilities appeared.

3.16.3. Lessons learned

The solution solved the problem and is still performing as expected after 8 years of service. There have been no reported pathologies in the section.

The solution can be considered effective and efficient. Its aproximate cost was about 1.1 million € for 1.2 km of a highway section.

The conclusion of the report is that the proposed solution can be useful for similar cases where the water table intercepts the line of the road. The years that have passed since the implementation of the solution ratifies the good functioning of the design. Therefore, we believe that its diffusion could be of special interest.

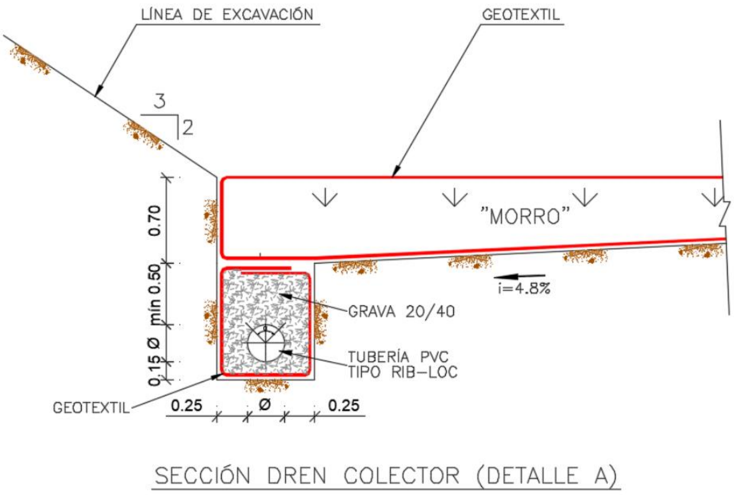


Figure 1. Detail of collector drain section.

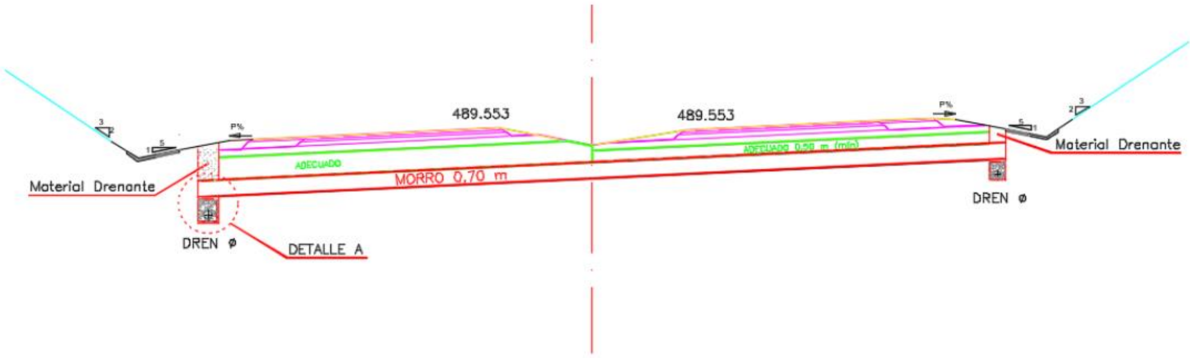


Figure 2. Section plan with detail of Figure 1 kilometre points: 19+620-20+800.

Figure 3. Granular drainage layer, geotextile and backfill layer

3.17. Case Study 17 - Temporary And Permanent Culvert Construction Under Tall Embankment over Soft Soils

Author – Jeffrey Basford, Whitman Requardt & Associates

Location – Newport News, Virginia, United States

3.17.1. Brief Summary of the Problem

The Atkinson Boulevard Project is a new alignment four-lane divided roadway that connects two major throughways on the Newport News Peninsula. The Project includes a 2,000-foot long bridge crossing the I-64 Highway, railroad, and several hundred feet of wetlands for a total project length of just over one mile. The typical section includes two lanes in each direction, a grass median, and parallel multi-use trails for a total width of 90 feet. Approach embankments to the bridge required up to 35 feet of fill over forested wetlands. The West Approach Embankment required a large triple box culvert to convey the waters of a small stream through the 250-foot-wide embankment footprint which is the focus of this case study.

The problem at hand was to install triple concrete box culverts to convey the flow from a small stream under the 35-foot tall roadway embankment being constructed that was estimated to settle 55 inches. The majority of the settlement is attributed to a 40 ft thick soft clay deposit below the embankment. Part of the challenge was not only constructing a culvert at the appropriate grade to function and be structurally sound, but also maintain the flow from this stream throughout construction. The objective was to develop a solution which was compatible with a staged embankment concept such that a pile foundation or a pile supported embankment would not be necessary.

3.17.2. Brief Summary of the Solution

The solution consisted of staged construction of the roadway embankment (including a surcharge fill) allowing settlement to occur, then excavating through the embankment to install the permanent box culverts. Although a simple concept, several innovative techniques were utilized to facilitate this installation. These techniques included:

Depressing wick drains and high strength embankment stabilization geotextiles (for global stability during the post settlement excavation process)

Installation of temporary sacrificial culverts (using numerous short sections of pipe with specially designed flexible joints).

Burring temporary geosynthetic reinforced walls into the embankment construction to use as temporary excavation support after the embankment has settled for installation of the permanent culverts.

Figure 1 Installation of Temparary Culvert Pipes

Figure 2 GSE Walls Being Used as Excavation Support.

Figure 3 Placement of Precast Concrete Culvert Section

Figure 4 Completed and Bacfilled Culvert.

3.17.3. Lessons Learned

The following lessons were learned by the project team:

The project team found that pipe manufacturers were unable to provide pipe of the specified diameter that could handle both the burial depth pressure, considering there was no trench arching effects, and supply an off the shelf joint which could accommodate the necessary deflection. There were joints that could be set initially at the specified three degrees of deflection but could not be set straight and deflect to the three-degree requirement. Hence, the project specific joint was developed.

The project team found that the wire baskets tend to push out under the compaction equipment loads. Although that alone was not an issue, the construction crew set the next basket relative to the deflected underlying basket instead of setting the next row of baskets relative to a surveyed baseline. Due to concern that the walls were battering inward in sections, a wall setback was added in Stage 2 of the embankment construction.

The project team intended to monitor stability using inclinometers set within the geosynthetic reinforced earth (GSE) wall reinforcement. These inclinometer casings were carried up through the geogrid reinforcement and cut as each layer was placed. Due to the settlement these casings became unusable. Due to concerns related to drilling back down through the reinforcement, the project team resorted to monitoring the movement of the GSE walls through survey monitoring points installed as the excavation progressed.

CASE STUDY 18 – GEOSYNTHETIC REINFORCED SOIL (GRS) BRIDGE ABUTMENTS WITH STAGE CONSTRUCTION USING FULL HEIGHT RIGID FACINGS

Author – Stanislav Lenart, Slovenian National Building and Civil Engineering Institute (ZAG)

Location – Žerovinci, Slovenia

3.18.1. Brief Summary of the Problem

Due to the insufficient water flow capacity and the deteriorated condition of the existing road bridge across the Pavlovski Potok stream, a new short span (5.5 m) bridge was needed in the village of Žerovinci in north-eastern Slovenia (Lenart et al., 2016). Its design was developed with limited preliminary geological and geotechnical information, but poor conditions were expected. Available data and results from investigations performed for the geotechnical works in the neighbourhood indicated low bearing capacity ground conditions with a deep layer of soft foundation soil. Furthermore, very short deadlines were defined by the local authority, who ordered the design of a new bridge at the beginning of November 2014 and expressed the expectation to open the bridge for traffic before Christmas of the same year.

3.18.2. Brief Summary of the Solution

Low shear strength and significant compressibility of the sub-soil were exhibited during the construction of another bridge located 50 m upstream, which included reinforced concrete (RC) abutments founded on 24 m deep pile foundations. Due to short deadlines and a limited budget, an alternative solution was recognized in shallow foundations made of compacted fill material reinforced with geosynthetics.

It was proposed that a prefabricated reinforced concrete slab, integrated onto a pair of geosynthetic reinforced soil (GRS) bridge abutments should be built. This type of construction is effective for the reduction of construction time and costs, while simultaneously eliminating the need for the use of heavy construction machinery. GRS bridge abutments also alleviate the bumps in front of and behind the bridge, which is expected to occur due to differential settlements in this kind of subsurface soil conditions if deep foundations of bridge abutments are used.

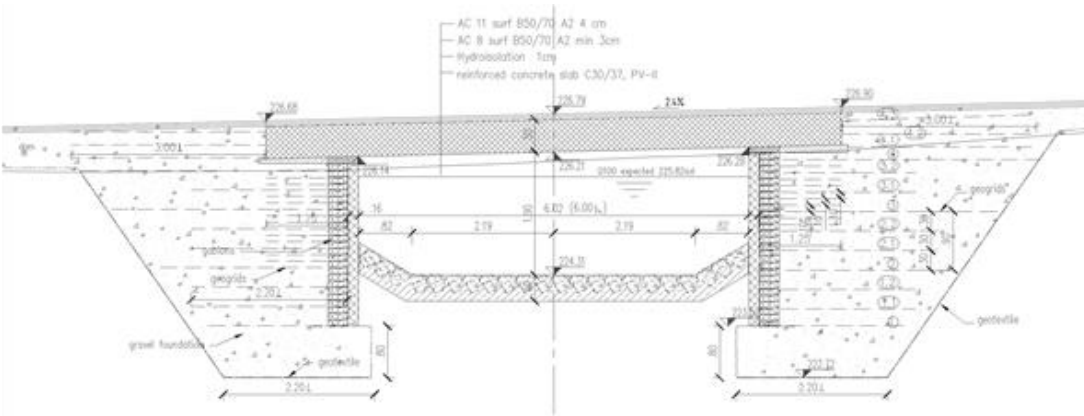


Figure 1 – tranversal section

After site preparation (temporary excavation works), soil bags (gabions) were placed at the shoulder of each soil layer during the construction process. The soil bags function as a temporary but stable facing structure during the construction works, since they resist the earth pressure generated by the compaction works and by further backfilling at higher levels. After sufficient deformation of the subsoil and the backfill has occurred during the construction of the geosynthetic-reinforced backfill, the full height rigid facings were constructed by means of cast-in-place concrete in the space between the formwork and the wall face which is wrapped around with geosynthetic (geogrid) reinforcement. As fresh concrete can easily get inside the gravel-filled bags through the apertures of the geogrids, which are wrapped around the gravel bags, there is a strong connection between the facings and the reinforcement layers. In addition to better load distribution, high scour resistance of this kind of facing has also been proven (Lenart et al., 2017).

Both GRS bridge abutments were built within a period of less than 10 days due to the simplicity of the construction processes involved. The concrete face and the concrete bridge slab were then built using appropriate formwork and cast-in-place concrete.

Photos 1,2 and 3 – construction phase

3.18.3. Lessons Learned

The following lessons were learned by the project team:

- GRS bridge abutments show several advantages (e.g. shorter construction time, lower costs, elimination of differential settlement problems) compared to conventional reinforced concrete cantilevered abutments.
- Approximately 60% less concrete needed compared to conventional reinforced concrete abutments.
- The solution is beneficial particularly for short span bridges with short construction deadlines.

3.19. Case Study 19 - Slope Protection Using Deep-Root Vegetative Solution

Author – Enrico Mittiga, Anas SpA – Gruppo FS Italiane

Location – Regional Road no. 578 Rieti-Torano (Central Italy)

3.19.1. Brief Summary of the Problem

Stable slopes lying over roads and highways often suffer from surface erosion due to heavy rain or wind action. Protection of slopes against erosion and scour can be achieved by using surface coating (especially geosynthetics, such as geocells, geonets, biomats, etc.), often combined with a cover of topsoil to permit grass to grow up, in order both to protect geosynthetics against elements and to improve their environmental appearance.

Geosynthetic coatings are subject to aging. This will occur in relatively short time if no protection against elements (rain, sunlight and heat) is provided, but it is very likely to occur even when they are hidden under a protective coat; for short, they need maintenance.

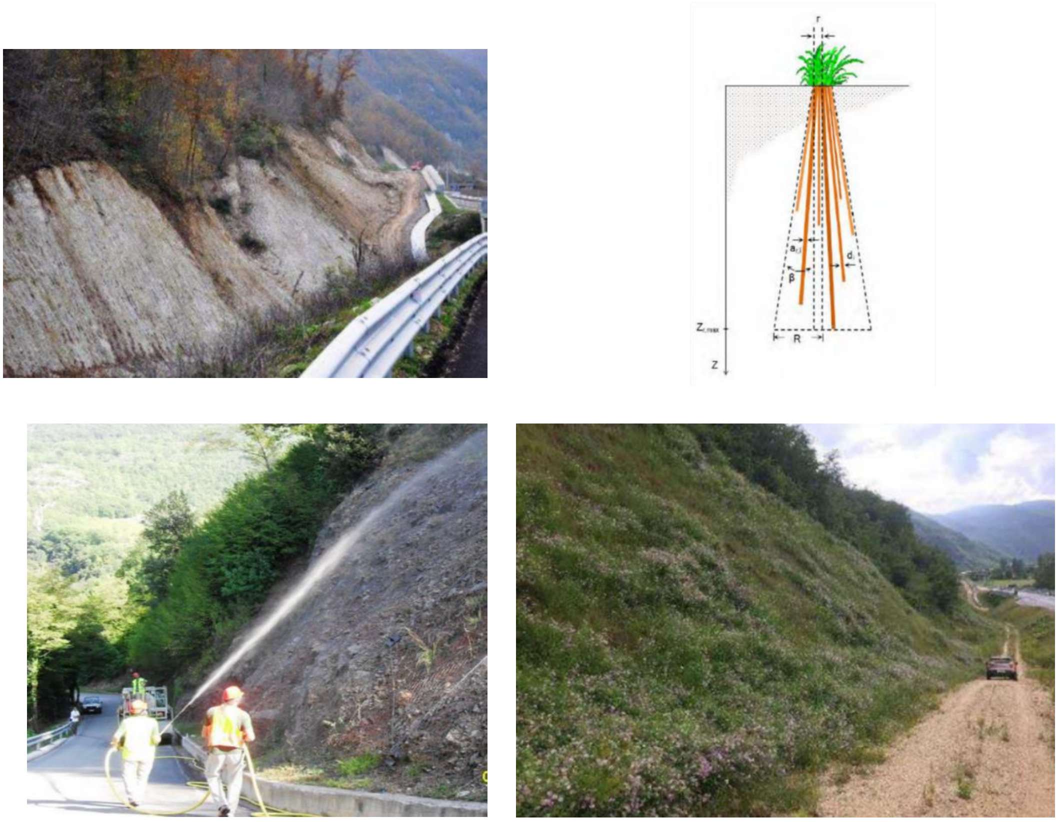
In the case described, slopes lying over the road, being cut in coarse soils and in highly fragmented rock, were highly prone to water erosion. Due to erosion, altered and fragmented rock elements are very likely to fall over the road and, even if relatively small, could cause severe damage to vehicles and/or road interruption and, in worst cases, casualties among car occupants. Considering the long extension of these slopes and their irregular shape, a geosynthetic coating was not identified as a fast and cost-efficient solution.

3.19.2. Brief Summary of the Solution

The solution consisted in the application of a vegetative cover by using an innovative technique that uses very specific types of herbaceous plants. This technique is a registered trademark, patented under the name of Prati Armati(™). The main characteristics of the technique are:

- Prati Armati(™) is an innovative green technology that uses deep rooting, perennial, non-invasive, locally native seeds of herbaceous plants able to contrast both water and wind soil erosion and desertification without using protective coating and/or other material.
- The protection of a stable slope against erosion is therefore assigned to deep rooting herbaceous vegetation without any other structural geo-element (metallic and/or plastic reinforcement bars, geogrids, etc.).
- Prati Armati(™) is able to reduce water infiltration into the ground and improve water removal from upper soil layers thanks to evapotranspiration.
- Plants are a perennial anti-erosion solution and they practically do not need any maintenance.
- No topsoil is needed.

Prati Armati(™) is a very environmental-friendly technique. Seeds are put in place by using hydroseeding from the bottom. Special equipment is required to reach the upper parts of high slopes only. Road can be left open to traffic during installation operations.



From top left clockwise: slopes before works, typical geometry of long roots, the slopes as they present after works, hydroseeding.

3.19.3. Lessons Learned

The following lessons were learned by the project team:

- Water erosion has virtually disappeared and slopes are completely under control and safe.
- It is remarkable that ditches under slopes are always clean even after heavy rain.
- After over five years no sign of erosion was recorded and Prati Armati(™) is still performing as new.
- Considering costs of maintenance (personnel, slope inspections, road interruptions) usually due to slope erosion problems, even if this technique has a relatively high initial cost, the solution can be defined cost-effective at all, as costs of maintenance are practically reduced to zero.
- Due to relatively high initial costs, Prati Armati(™) technique is preferably applicable for large areas to be treated.
- Even under these limitations, Prati Armati(™) technique is very effective for a wide range of geotechnical conditions.

3.20. Case Study 20 – Use of Bioengineering for slope stabilization

Authors – Angella Lekea, Uganda National Roads Authority

Location – Fort Portal-Bundibugyo, Uganda

3.20.1. Brief Summary of the Problem

The Fort Portal-Bundibugyo-Lamia (105km) road is located in the southwestern part of Uganda, commonly known as the Rwenzori/Semiliki region. The road traverses a sparsely inhabited land, passing through the Mt. Rwenzori range, and has been highly affected by landslides, including erosion on the exposed cut slopes.

Soil erosion usually occurs along exposed mountainous slopes of roads and stream river banks or where excess water flows over hill slopes. Conventionally, structural practices like rip rap, retaining walls, and sheet piles are used to control streamflow and water induced erosion. However, these methods are expensive or considered socially unacceptable. Bioengineering, which involves planting live plants alone or combined with dead or inorganic materials to produce living and functioning systems, provides a low cost and suitable alternative. The method uses a combination of structural practices and live vegetation to provide erosion protection for hillslopes and streambanks.

Consequently, a site visit was conducted to determine sections along the road suitable for conducting a bio-engineering demonstration considering the depth and size of the landslide. A section at km 19+800 was identified and a detailed site assessment as per Table 1 conducted. The objective of the demonstration training was to show the implementation steps and effectiveness of bioengineering in landslide management.

3.20.2. Brief Summary of the Solution

The demonstration showed the extent to which bio-engineering techniques contribute to effective mitigation of shallow landslides and erosion, considering technical, environmental, economic and livelihood sustainability criteria. These techniques included:

- Laying fascines which is of a bundle of live branches bound together, in a shallow dug ditch or trenches and covering with soil for sprouting.
- Placing palisades, a live sprouting cutting planted across the slope or small gully usually following the contour.
- Brush layering which consists of layering of live woody cuttings planted in line across the slope, usually following the contour.
- Planting grass over the slumps in different lines configurations (horizontal, vertical and diagonal) to protect the slope against sheet and surface erosion.
- Constructing a dry-stone toe wall and planting vegetation in the gaps to strengthen the wall. The dry stone wall is flexible but provides a strong revetment, without the cost of concrete mortar.

The steps involved are shown in Figures 1 to 8.

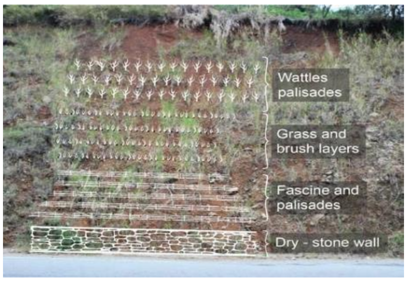


Figure 1 Proposed bio-engineering measures at the demonstration site km 19+800

Figure 9: Site preparation and grass planting tools

Figure 10: Live staking and fascines installation

Figure 11: Construction of dry-stone toe wall

Figure 12: After one month of planting

Figure 13: Grass and stone toe wall after three months

3.20.3. Lessons Learned

The following lessons were learned by the project team:

- Given the project time constraints, the demonstration training was conducted in the month of March 2020, which was followed by a dry spell that stunted plant growth over the first two months. The palisades were the most affected and needed replacement during the wet season; however, the grass weathered the dry season and grew once the rains started. A need for watering during the dry season was identified.
- The brush layers have been effective in providing a strong and low-cost barrier especially in controlling debris flow and thereby reducing erosion on the slope.
- For a successful demonstration project, it is recommended that the project is kept small approximately 100 to 500 feet in length to minimize the investment risk. The demonstration will also help in evaluating what methods and plant species performed best under similar conditions. A variety of plants should also be incorporated to compare differences. The project should be adequately maintained and closely monitored with good record keeping.

3.21. CASE STUDY 21 - EVALUATION AND REHABILITATION OF WALLS IN EMBANKMENTS REINFORCED WITH GEOGRIDS AFTER FIRE

Authores: Rui Barros, NORVIA; Alexandra Ferreira, ASCENDI

Country - Portugal

3.21.1. Brief Summary of the Problem

In August 2016, several forest fires occurred in the central region of Portugal. Three embankments with soil reinforced with geogrids walls were affected by these fires.

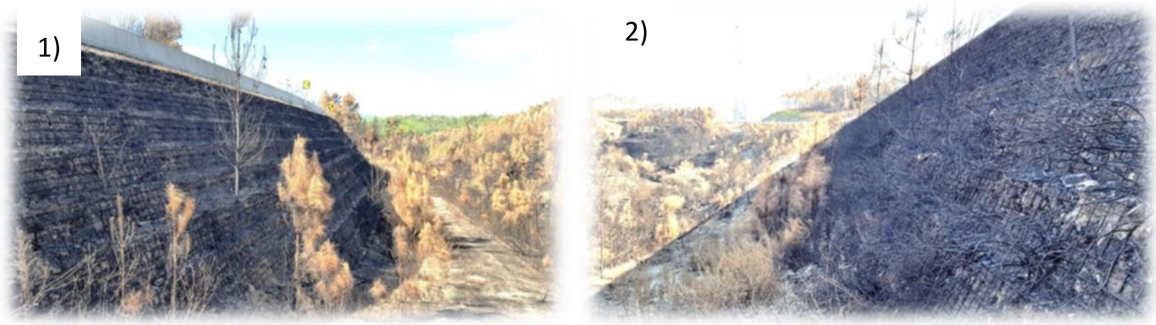


Figure 1: Photos 1) and 2) – Embankment and reinforced walls damaged by fire - 2016

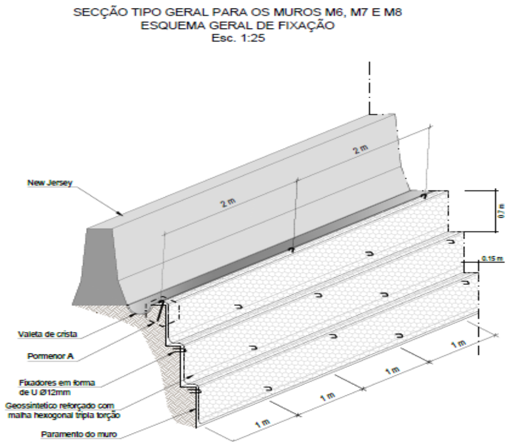
A detailed visual inspection was carried out and it was found that:

- the fire had not structurally affected the reinforced embankments, either compromised global stability;
- as consequence of these observations, a reinforce the surface protection and the reforestation of the wall was the solution for the rehabilitation of the walls.

3.21.2. Brief Summary of the Solution

The rehabilitation of reinforced landfills focused on the superficial protection of the walls, to protect the surface erosion and promote the growth of the vegetation cover. Main activities:

- cleaning of the burnt vegetation;
- mooring the electro welded mesh panels with anti-corrosion wire;
- application of geosynthetic with integrated triple torsion wire mesh;
- application of hydroseeding.



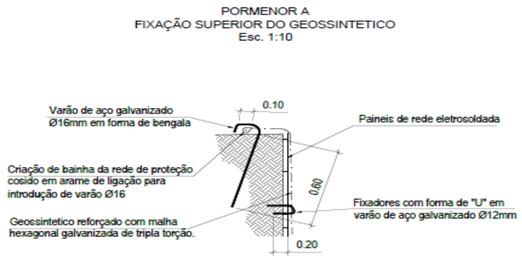


Figure 2 – Construction Phase 2017: Photos: 1) and 2) anchoring the electro welded mesh panels with anti-corrosion wire; 3) installation of geosynthetics with integrated triple torsion wire mesh.

Figure 3 – Construction Phase 2017: Photos: 4) and 5) Hydroseeding works

3.21.3. Lessons Learned

The following lessons were learned by the project team:

- The reinforcement of embankment slopes with reinforced geogrids is a solution that allows the construction of almost vertical embankments, of medium to high height, with space constraints. it is a solution with an appropriate landscape setting.
- After almost 4 years the solution is still performing as expected.
- The solution was cost–effective and the reinforced soil walls proved to be an effective and resilient solution, resisting adverse situations, such as fires.

3.22. CASE STUDY 22 - GABION WALL

Authors – Mário Quinta-Ferreira, University of Coimbra; Fernando Valério, TPF; Alexandra Ferreira, Ascendi

Location – Lisbon, Portugal

3.22.1. Brief Summary of the Problem

During the annual visual inspection, in 2017, deformation of the gabions was observed from Pk 0+300 to 0+400, including the deterioration of the marls inside the baskets of the gabion wall, with greater expression at the base. The analysis of the pathologies and the observations of the wall material, showed that some of the limestone and marlstone blocks appeared to be crushed. Topographic targets in the gabion wall were installed, and between 2017 and 2019 were frequently monitored and observed.

Figura 1: localization and longitudinal view of the gabion wall

3.22.2. Brief summary of the solution

In 2020 the recorded deformations of the topographic targets were analysed, for horizontal and vertical displacements. The pathologies compromise the global stability of the gabion wall. A new procedure was developed proposing a solution for structural reinforcement - providing the injection of a viscous cement inside the baskets, seeking to fill the gaps left by the degraded limestone and marlstone blocks. The procedure also aimed to increase the number of contact points between the rock blocks inside the gabions, particularly in places where the blocks suffered degradation. The application of this new methodology, also allow the contact stress between rock blocks to be reduced, mitigating both their rupture and the deformations of the baskets, increasing the safety of the wall.

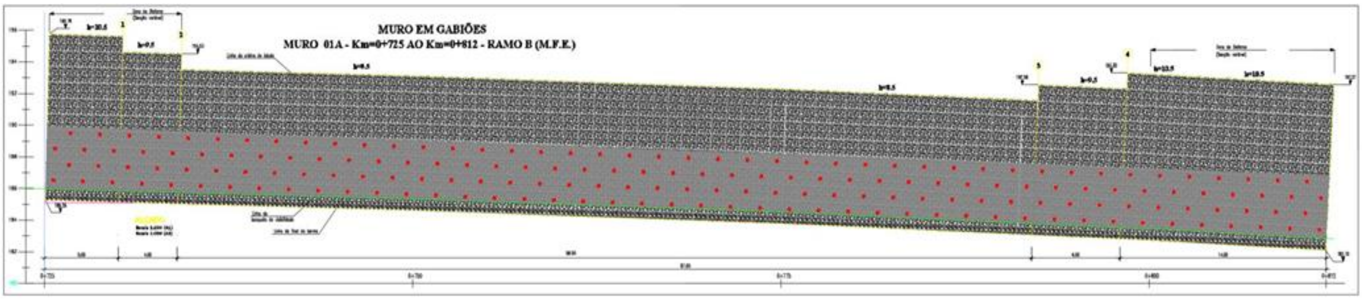


Figure 2: Longitudinal view of the gabion wall with the localization of the injection points

Construction phasing:

- Creation of an outer barrier on the front and side of the wall, through the projection of 5 cm of concrete reinforced with fibers along the entire length of the wall, and up to about 4 m above the base of the wall.
- Drilling for installation of injection spots
- Gravity Injection of the cement until reflux at the mouth of the tube
- Drilling and installation of the geodrains.

Figure 3: Construction Phase: Photos: 1) projection of 5 cm of reinforced concrete; 2) Gravity Injection of the cement, 3) Drilling for installation the geodrains and 4) Final view after the reinforcement of the gabion wall.

3.22.3. Lessons learned

The developed rehabilitation and reinforcement solution made it possible to maintain traffic on the A16 motorway during the work. The solution was cost–effective and turned the wall more resilient and less vulnerable to the weathering processes.

A monitoring and evaluation plan was also recommended, in order to evaluate its behaviour and validate the implemented solution, namely the construction procedure and the materials used, aiming at validating the methodology to be used in future interventions.

The implementation of the Annual Maintenance Plan achieves the resilience of the geotechnical infrastructure.

3.23. Case Study 23 - Large Embankment Construction Using Soil-Cement

Authors: Eduardo Fernandes (ELSAMEX)/ Monteiro Bernardo (IEP)

Location – Marão, Portugal

3.23.1. Brief Summary of the Problem

For the construction of the A4 motorway, there was a need for embankments with a very significant height. After analysing the situation, it was found that the execution of "traditional" embankments would occupy a very large area, requiring large land acquisition and the need for a large volume of material. Coincidently, the excavation of the Marão tunnel would lead to a volume of materials that would need to be disposed of if they could not be reused.

3.23.2. Brief Summary of the Solution

The solution of the soil-cement walls/embankments made it possible to build the A4, reducing the amount of land acquisition and the opportunity to reuse the volume of excavated materials from the tunnel and minimizing the disposal of materials. While the soil-cement mixtures technology has been recurrent in the pavement stabilization, its use in the construction of high-height landfills can be considered as innovative.

In general, the solution involved the construction of embankments with side slopes of 1:1 (V: H), built with layers of a mixture of soil-cement. Every 15 m in height, a 3 m wide bench was constructed. For the stabilization of the embankments, the addition of cement into the mixture with the soil was implemented using cement rates around 4%. The remainder of construction involved the use of standard earthmoving equipment. A typical section of the embankment is shown below.

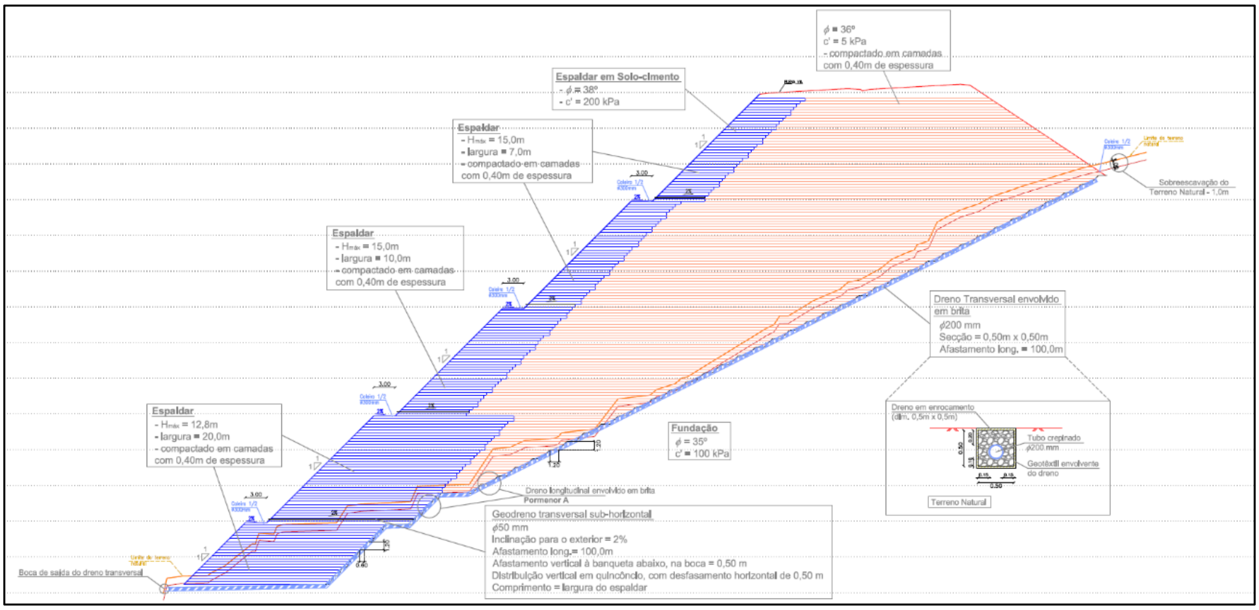


Figure 14 Typical Section of Embankment

Construction Phase Photos (Clockwise from top left) – a) Placement of water, b) Addition of cement, c) Operation of mixer, d) Close up of mixer

An overview of the embankments carried out, after the completion of the works, highlighting their good landscape integration. First image the M24 soil-cement embankment and second image, the M40 and the M41A.

Figure 3: Final view

3.23.3. Lessons Learned

The following lessons were learned by the project team:

- The soil-cement mixture was cost-effective, saving approximately €2 million, and could be constructed in the prescribed manner. It was constructed on time and within budget.
- After 7 years of monitoring the stabilization and reinforcement solution implemented, it is said to be effective. There have been no signs of instability nor surface erosion issues. Instrumentation has shown that there are no deformations as well.

3.24. Case Study 24 - Ground Treatment Solutions using Jet Grouting

Authors: Alexandre Pinto, Lisbon University; Rui Tomázio, JET-SJ

Location – Alfeizeirão (Lisbon), Portugal

3.24.1. Brief Summary of the Problem

The Motorway A8, connecting Lisbon to Leiria in Portugal, lost its global stability at km 92+600, close to Alfeizerão. The platform was built about 8 years before with part over excavation and part over embankment. The lower part of the platform was stabilized with a 9m high gabions wall to protect some small buildings. The embankment was built over clayey soils, with cohesion and resistance increasing with depth. After the land slide, it was possible to confirm by the analysis of the deformations and cracks that a circular slip surface was formed, passing under the gabions wall foundation. The movement intersected a mass of soil approximately 60m wide and 18m high, and included 3 lanes of the motorway platform (Figure 1).

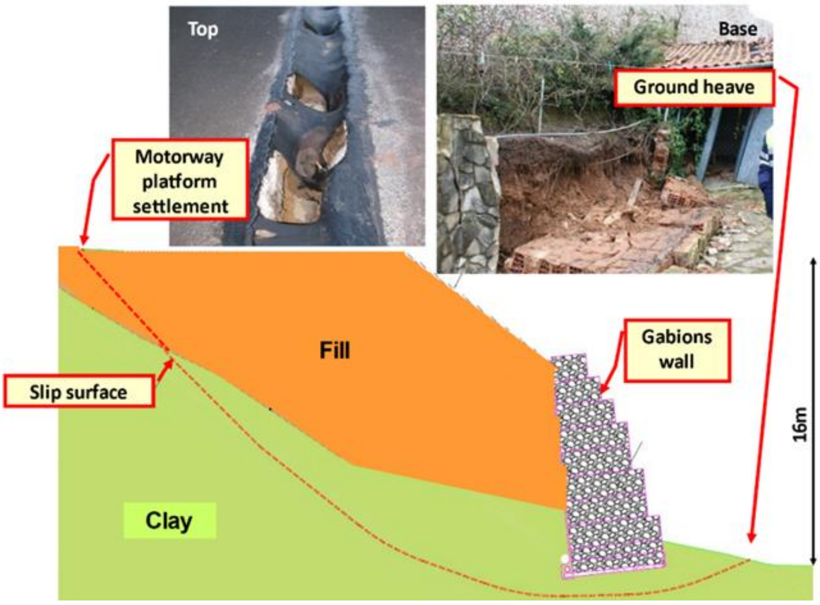


Figure 15: Problem geometry and cross section

3.24.2. Brief Summary of the Solution

The stabilization solution had to reduce the impact on the motorway traffic, as well as the schedule for the stabilization works. A solution based on jet grouting and steel tubular micropiles was adopted, performed using small and versatile equipment. The adopted solution included the execution of a jet grouting vertical wall, columns ∅1,2m spaced 1,0m, stiffened by buttresses, spaced 3m. Each buttress was formed by 3x∅1,2m inclined jet grouting columns and one micropile. The vertical column located at the buttress alignment was also reinforced with one micropile. Over the jet grouting wall, an upper reinforced concrete wall was built to allow the partial demolishment of the gabion wall, as well as the excavation of the existent fill, to decrease the unstable gravity loads. Behind the upper wall, a lightweight aggregate (LWA) backfill over a lower sandy backfill layer was installed to also allow the reduction of the unstable loads, as well as to improve both the wall and motorway platform drainage (Figure 2).

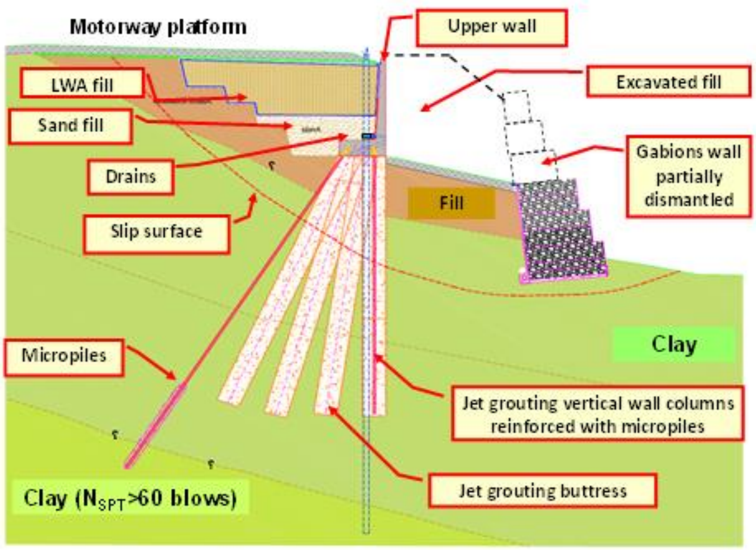


Figure 16: Cross section of the adopted stabilization

3.24.3. Lessons Learned

The following lessons were learned by the project team:

- The gabions wall solution when built at slopes should be designed considering the slope stability analysis.
- The jet grouting was a cost-effective solution, allowing the construction of the stability solution on time and within the initial budget.
- The use of small and versatile equipment minimized the impact on the motorway traffic.

3.25. CASE STUDY 25 - CAVIBAG TECHNIQUE TO MITIGATE UNDERGROUND VOIDS

Authors – Frederic Clément (Cerema Bordeaux)

Location – Bordeaux, France

3.25.1. Brief Summary of the Problem

Karstification of limestone creates large voids and cavities that can appear under roads. This happens in many regions in France. The treatment of cavities is well known, and many techniques exist to prevent collapses. However, sometimes the cavities are very large and involve an underground river. In that case, filling the cavity represent huge volumes to fill (sometimes unknown at the moment of starting the work) and can have a big impact on the water and the environment.

When cavities are under the infrastructure, the best solution consists of reinforcing the structure cost-effectively and without having environmental impact. To meet these criteria, CAVIBAG Technic has been developed, inspired by similar techniques (grout-bag, etc.) by the Cerema Bordeaux.

3.25.2. Brief Summary of the Solution

The main idea of CAVIBAG solution is to fill in the voids right under the road and not more. For that, a specific bag has been developed with a geotube from LowBonar (Figure 17 (a)), composed with 2 polyester geosynthetics, one outside very strong and one inside impervious. Cerema Bordeaux developed the concept and tested it for the first time on a national road in France to treat “La Fuie” cavity.

Figure 17 : the CAVIBAG process, developed by Cerema (Courtesy Cerema)

Boreholes are laid out over and around the cavities. Then the geotube is attached to the same drilling machine (Figure 17(a)) and advanced into borehole. Once in the cavity, the geotube is filled with cement or micro-concrete (Figure 17(b) and (c)). Material is not excessively wasted with this technique as it is with direct injection of the cavities.

The cement or micro-concrete hardens and creates a sort of pile exactly right on the road. This project has been developed by the French administration (Cerema) in the frame of a research project on cavities called Precas. Bonar Company, provided fruitful help for this development. Part of the costs have been supported by the stakeholder (French administration called DIR-A and DIR-CO) affected by the cavities under their roads (Figure 18).

3.25.3. Lessons Learned

Figure 18 : inspection of LA FUIE cavity, RN.141, France (Courtesy Cerema)

The CAVIBAG Technic is an available technique, cheap and affordable, that can easily be used in other situations and in all countries. The materials and equipment for installation are traditional and the technique can be adapted everywhere, even with different types of filling material.

3.26. Case Study 26 - Mixed-soil with liquid lime solution injection to repair swelling-shrinkage cracks

Authors – Olivier Martin & Corinne Cambefort, Cerema Toulouse

Location – Rural Roads, Haute-Garonne, France

3.26.1. Brief Summary of the Problem

Rural roads are more and more affected by cracks due to summer drought in France. These roads are often low volume roads, crossing forests and topping very clayey soils. The cracks are very typical of swelling-shrinkage phenomena: they are parallel to the lane and near the road shoulder. They may be very deep, around 1 to 2 meters depth and several centimetres wide (Figure 1). In France, they are caused by the need of water of trees and plants near the road, particularly in clayey soils (A3-A4 in French classification for earthworks). This phenomenon is aggravated by more drastic climate, i.e. hydric variations during the year.

Figure 19: Example of damages in the south of France.

The cracks appear suddenly and are dangerous for users, especially two wheels drivers. Along these cracks, infiltration of rainwater may occur, which causes loss of bearing capacity. When the road is repaved, cracks re-appear the following year, indicating the phenomenon is not properly resolved. The usual techniques for repairing the structure are not adapted to that kind of natural hazard. Many techniques are tested but with poor results as geogrids, new pavement structure, etc. The global substitution of the clayey soil is also a very expansive technique that would create a lo of disposal.

3.26.2. Brief Summary of the Solution

Due to the continued cracking on county roads, it was decided to test the possibility of liquid lime solution (in French « lait de chaux » that can be translate as lime milk) injected in vertical wells. Lime treatment is known to reduce the swelling-shrinkage potential of a clayey soil.

This technique had already been implemented in the 2000s and is mentioned in the Practical Guide to Current Maintenance of SETRA 1996 at a depth of 0,50 to 0,70 meters.

The solution is to adapt this technique to dry soils, so it was decided to test the injection of liquid lime solution in vertical wells, including mixing lime and soil with an auger in the wells. A specific tool has been developed for that process (Figure 2).

Figure 20: A specific tool has been adapted to incorporate lime into the soil with a vertical borehole

The lime incorporated into the soil like an inclusion or an injection in a vertical borehole will naturally diffuse in the matrix of the soil. The lime operates by slow diffusion in the clayey soil. The column of lime-treated soil can also reinforce the structure like micro-piles or rigid inclusions.

After a first test with a hollow auger from a drilling company was not conclusive (no satisfying mixture between soil and lime milk), it was decided that Haute-Garonne's county would make a tool for drilling. This tool can pass through clayed soils and inject lime milk and mix soil and lime milk at the same time. After several more or less conclusive tests, we now have a tool that can drill and destructure soils over 1.50 m to 2.0 m depth. An injection test with lime's milk of using an earlier version of the tool and a peristaltic pump of the brand WATSON MARLOW Type 521 (0.25kW-220V) lent by LHOIST seems to have given satisfaction but has to be improved after some failures. The first idea was to realise staggered holes 10 to 15 cm in diameter, 50 to 70 cm depth and spaced at about 1 meter intervals, as done in the past.

3.26.3. Lessons Learned

At present: a new and stronger tool has been manufactured and the drilling tests have been satisfactory. Cerema Toulouse is now waiting for the supply of a pump in order to carry out lime well tests and waits new earthworks in Haute-Garonne to finalize the procedure.

3.27. Case Study 27 - Column Supported Embankment for the Harlem River Drive Bridge Replacement

Authors – Arsanious Guirguis (Hardesty & Hanover, LLC)

Location – New York City, New York, United States

3.27.1. Brief Summary of the Problem

As part of the Harlem River Drive bridge replacement, the existing cellular bridge approaches were to be replaced with embankment fill. A soft compressible stratum comprised of organic cohesive soil underlies the entire project site. The stratum is encountered at a depth of approximately 9 feet below the existing grade and is up to 20 feet thick in some areas. The original bridge approach spans consisted of pile-supported cellular structures. To minimize future maintenance costs and accommodate the complex staging required to build the proposed bridge, the original cellular approach structures were proposed to be replaced with embankment fill. However, replacing the cellular approach with embankment fill would induce settlement due to consolidation of the soft compressible layer. Inducing settlement would create harmful effects to adjacent facilities particularly to the underlying utilities by 1) differential settlement causing deformation of the utilities 2) overstressing utilities from the overburden soil pressure.

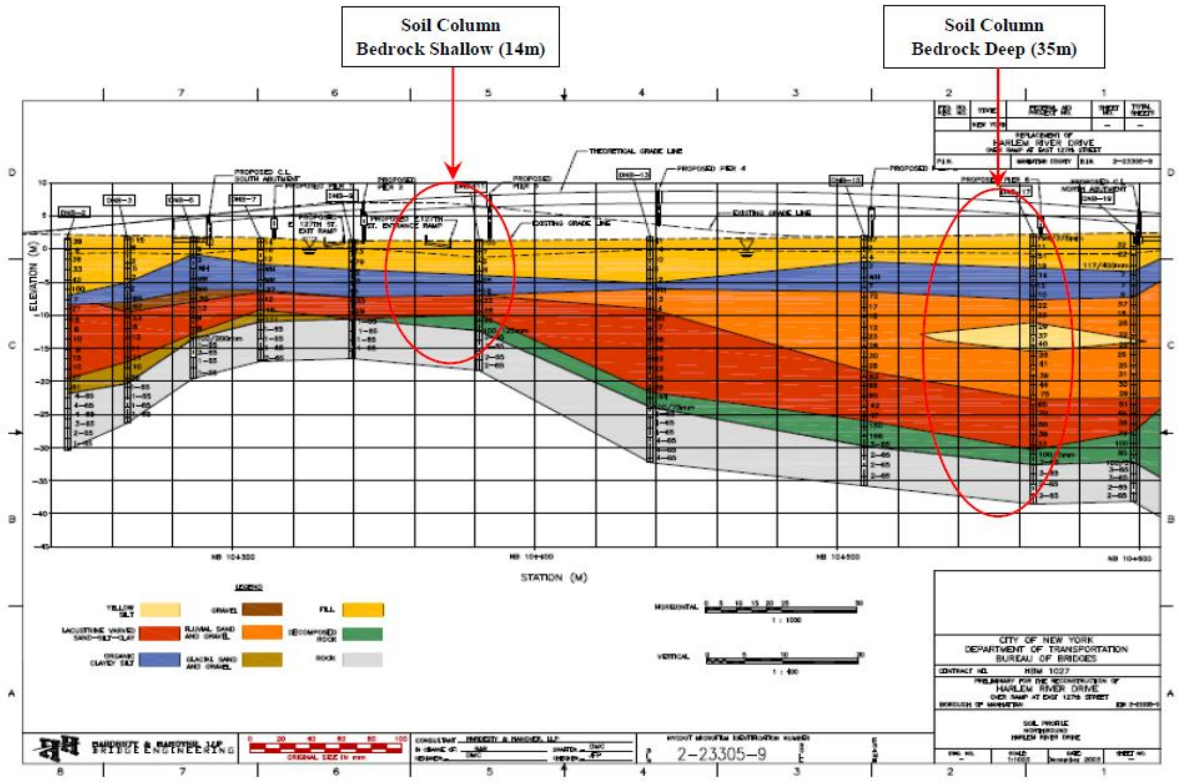


Figure 1: Soil Profile

3.27.2. Brief Summary of the Solution

To avoid undesirable settlement and overstressing the underlying utilities, a column supported embankment (CSE) system was proposed. The design concept of a CSE involves constructing a pattern of unreinforced cement-grouted **columns** that transfer the overburden pressure produced by embankment loads to a firm bearing stratum. A load transfer platform consisting of well-graded fill with multiple layers of geosynthetic reinforcement is constructed immediately above the tops of the columns.

Controlled modulus columns (CMC) for the column supported embankment system was selected as the method to install the cement-grouted columns for this project. CMC's utilize reverse flight augers which displace the soil laterally. This installation technique virtually creates no vibration, radially densifies the surrounding soil and eliminates spoil. Once the firm bearing stratum is reached the auger is extracted and simultaneously grouted. The cement-grouted columns were 12.5 inches in diameter and approximately ranged from 50 ft to 75 ft in depth.

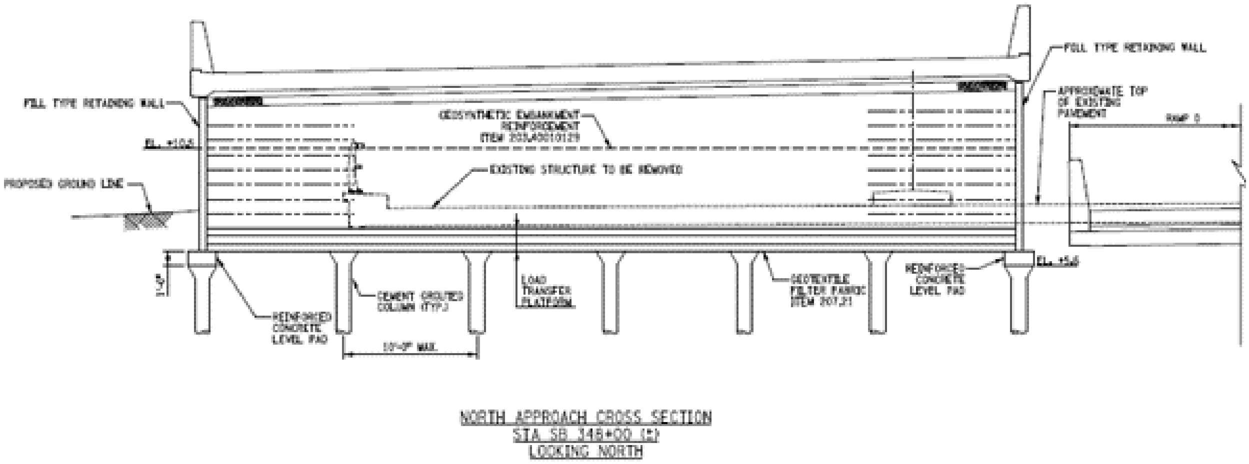


Figure 2: Typical Section

3.27.3. Lessons Learned

The following lessons were learned by the project team:

Field instrumentation program was implemented to monitor the CSE's performance during embankment fill placement, and the results indicated the CSE performed properly and effectively transferred the embankment loads to the firm bearing stratum underlying the soft compressible stratum.

The CSE alternative was the most cost-effective, approximately $800,000 less than the next cheapest alternative

The CSE alternative can be performed with minimal impact to traffic.

The design team would specify a different grout/concrete mix that was compatible with CMC installation methods.

The design team would also perform a more thorough preconstruction utility location program to better identify locations of the underlying utilities.

3.28. Case Study 28 - Use of King Sheet Pile Walls

Author – Paul Nowak, Atkins Ltd

Location – Buckinghamshire, UK

3.28.1. Brief Summary of the Problem

The M25 Widening dbfo project involved the widening of the existing M25 motorway from dual 3 lane to dual 4 lane over a 32 kilometre section between junctions 16 and 23 north west of London. all solutions for widening of cuttings and embankments had to be effected within the existing motorway boundary as the client, highways England did not want to engage in further land purchase. where possible earthworks solutions were adopted to reduce the carbon footprint of the project. the M25 is one of the busiest motorways in the UK and construction had to be carried out using the hard shoulder and lane 1 only to maintain 3 lane traffic flow in both directions. in many locations, however, space did not permit the construction of conventional earthworks solutions. The scheme design inherited by the design and build team at tender stage included some 13 kilometres of bored pile walls. It was decided during the tender design process that sheet pile walls afforded a more cost and programme solution at these locations.

3.28.2. Brief Summary of the Solution

During early stage of design, the designer considered that minimum pile section should be decided by driving rather than design. Further consideration by the contractor realised that further savings could be made to cost and programme by adopting and King Sheet Pile solution where intermediate piles were of similar section but shorter length. As the widening scheme progressed development of sheet pile sections allowed further reduction of the intermediate pile section some 24 kilometres of sheet pile wall were eventually installed using the king sheet pile method and realising a saving of 30% of the steel compared with full section walls.

A schematic diagram of the concept is illustrated in Figure 1 below.

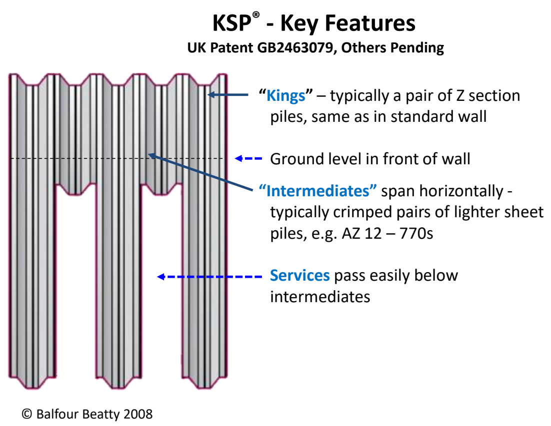


Figure 1: Key Features of the King Sheet Pile Wall

Figure 2: Completed King Sheet Pile Wall

3.28.3. Lessons Learned

The following lessons were taken from the project:

- The king sheet pile solution provided the same design performance as a full section wall

- The method accounted for considerable saving in steel over a full section wall
- The Method accounted for considerable programme certainty and programme savings against other structural solutions on a contract with tight construction programme
- The solution has been used extensively since the original contract particularly on motorway widening and highway improvement schemes.

3.29. Case Study 29 – Technology of construction of anti-landslide structures in cramped conditions

Authors – Matsiy S.I. (KSAU Department of Building Materials and Structures), Podtelkov R.V. (KSAU Department of Building Materials and Structures)

Location – Sochi, Russia

3.29.1. Brief summary of the problem

In 2009, construction began on a two-level transport interchange at the intersection of Donskoy and Vinogradnaya Streets in Sochi. One of the exits of the projected road is an extension in an embankment of the existing Vinogradnaya Street, which is located in the upper part of the landslide-prone slope (Fig. 1). On the lower side of the slope is a five-story residential building, as well as a retaining wall that serves to protect the house from the upper slope. The wall is gravitational, made of separate concrete elements on a cement-sand mortar and is not designed to withstand significant loads. However, the construction of an additional exit leads to an increase in the load on the slope due to the weight of the embankment and the additional transport load.

Fig. 1. General view of the plot along Vinogradnaya Street. The exit axis runs along the slope.

The situation is complicated by the presence of several utilities crossing Vinogradnaya Street (and exit) and having a security zone. The exact location and depth of the communication linesare unknown. To protect the embankment of the highway and the residential building located farther down the slope, the project provided for the construction of a retaining wall on a pile foundation of two rows of bored piles. The main problem was the preparation of the working area on the slope. On the upper side, the slope is bounded by an existing road, along which there is a continuous flow of traffic. When performing work on a section in cross-section, it is necessary to block and dismantle one of the traffic lanes. This option is technically possible, but the customer refused it due to the lack of detours on this section. According to the second option, it is proposed to perform a working platform in the embankment. When performing work on the construction of a pile structure, the heavy weight of the drilling equipment and the embankment itself can lead to the collapse of the existing wall on the residential building. Therefore, this option is only possible when additional considerations are implemented.

3.29.2. Brief summary of the solution

To solve this geotechnical problem, an additional retaining structure was developed, consisting of a reinforced concrete wall reinforced with three tiers of Titanium-type anchor piles (Fig. 2). Two tiers of anchor piles are inclined to the horizon at an angle of 30° and work mainly for tension, the third tier, which is necessary to ensure the rigidity of the structure, is located vertically and works for compression.

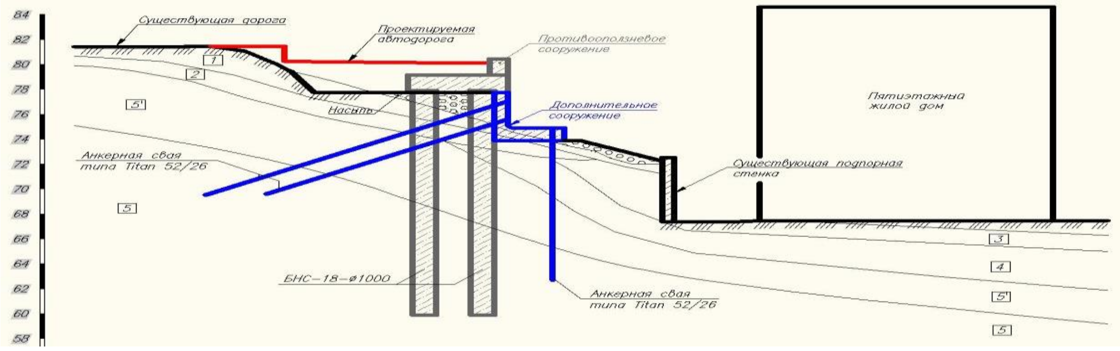


Fig. 2. Design solution of a landslide structure for a road and a residential building

The technology of the device has some features related to the fact that additional forces can not be transferred to the existing wall. After preparing a small working area, the light drilling machine performs vertical and lower inclined anchors. Then the construction of the w/w wall and the filling of the soil with compaction is carried out. Only after that, the upper tier of inclined anchors is carried out through the provided holes in a "self-lifting" way. As the concrete gains strength, the anchors are stretched to a working load of 20 tons and immediately put into operation. This design has a number of significant advantages:

1) The work can be carried out without blocking the traffic lane on Vinogradnaya Street, where the traffic flow is very intense.

2) For the construction of the structure, a light anchor technique is required, which does not create an additional slope load. To perform the work, a very small working area is required, and if you have the appropriate equipment, you can do without a working area at all and carry out work directly on the slope.

3) The ability to perceive loads from heavy construction equipment during construction.

4) After performing construction and installation work on the main structure, it is included in its work as an additional attachment at the top of the piles, and the facing panel.

3.29.3. Lessons learned

1) The technology of the device of an anti-landslide structure in the cramped conditions of residential development in Sochi during the construction of a transport interchange is proposed. The technology involves the use of an additional structure that ensures the safe construction of the main structure, and then is included in the operation of the latter for the entire period of operation.

2) Calculations in the Plaxis program confirmed the effectiveness of the proposed structures. The use of an additional structure allows you to reduce the slope deformations to almost zero during the construction period: the deformation of the existing retaining wall is 10 mm. Without additional reinforcement of the slope, the deformations of the existing wall are 97 cm, which means its collapse and probably serious deformations of the residential building.

3) It provides for monitoring of existing and under construction structures, which allows you to conduct operational observations of stresses and deformations in structures and the body of a

landslide, to make timely adjustments to design decisions, both during construction and during the operation of structures.

3.30. Case Study 30 – Slope Protection Using Modular Pyramid-Shaped Steel-Framed Retaining Elements

Author – Enrico Mittiga, Anas SpA – Gruppo FS Italiane

Location – Fortezza-San Candido international railway (Alto Adige-Sudtirol - Northern Italy)

3.30.1. Brief Summary of the Problem

When road and railway embankments are damaged by running water (during flooding, heavy rainfall, erosion around culverts, etc.) the matter is how fast it is possible to carry on reconstruction works: the road/railway axis is, in some cases, a vital link that cannot be out of service if not for few hours.

Road/railway managers are therefore forced to use technical solutions that, in spite of a short execution time, cannot guarantee to maintain their own performance over time. This means that new and more accurate works must be eventually planned at a certain point of the life of the infrastructure, with more costs and road/railway disruption.

The matter is, therefore, to use technologies and materials that can combine a fast and relatively cheap installation phase with unquestioned durability.

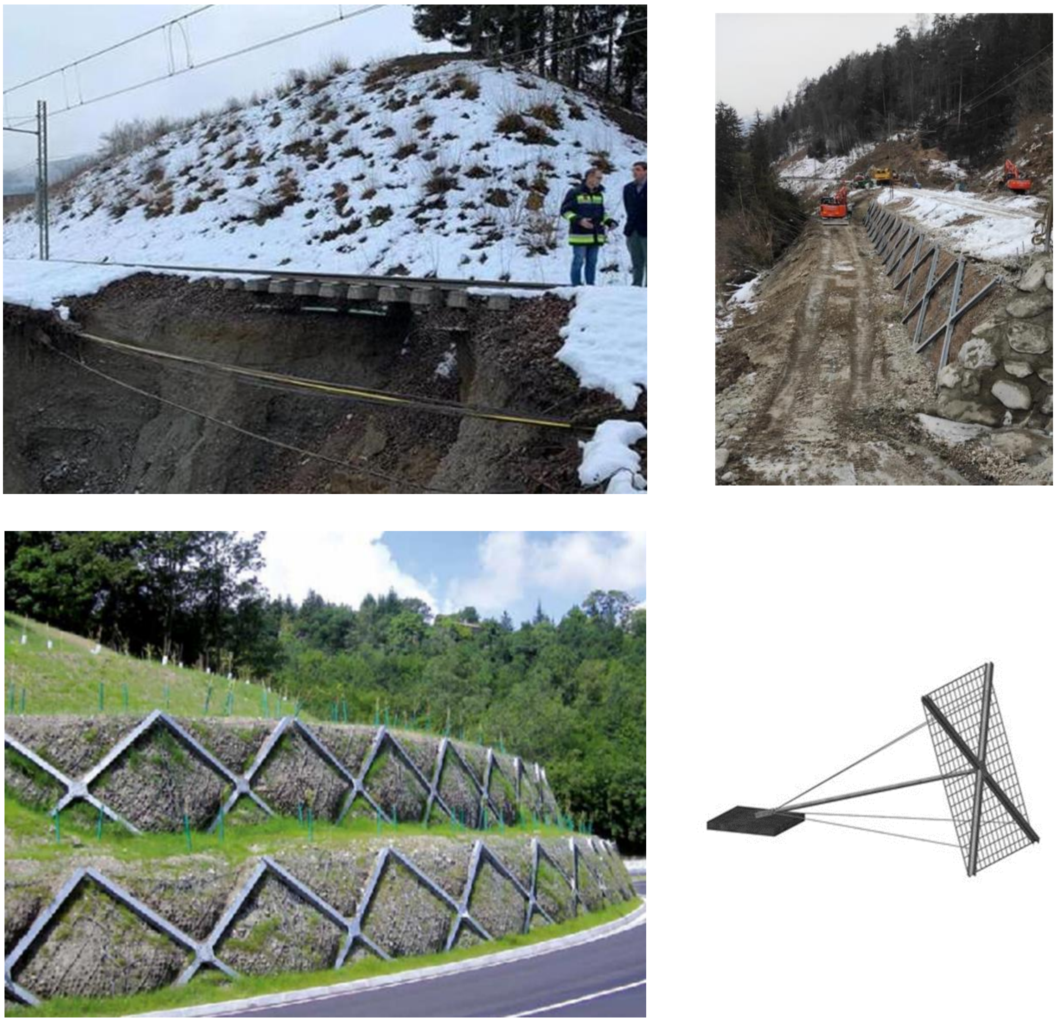
In the case described, railway embankment of Fortezza-San Candido international link between Italy and Austria was in many points completely washed out by flooding after heavy rain in November 2020.

The forced closure led to many inconveniences. The network manager was therefore obligated to seek fast solutions to reopen the line as soon as possible.

3.30.2. Brief Summary of the Solution

The solution consisted of the application of modular pyramid-shaped steel-framed retaining elements, that are a registered trademark under the name of Erdox(™). The main characteristics of the elements are:

- The Erdox(™) element is a pyramid-shaped and flexible steel construction, with a reasonably small net weight. A simple bolt on the base slab or on the anchor achieves the anchorage at the end of the pyramid-shaped construction. The system is extremely adaptable and flexible.
- Two steel beams forming an X on the face compose the Erdox(™) element; steel ropes connect the edges of the X with the anchor slab; the centre of the X is connected to the anchor slab by a tubular steel rod. On the face of the element, a geosynthetic and/or a welded mesh assure the retention of the soil. The anchor slab can be act as a counterweight (considering the weight of the soil acting on it) or can be connected to an anchor or a micropile.
- There is no need to remove the damaged embankment totally: the pyramid-shaped elements can be arranged to adapt perfectly to the voids. This cuts restoration times dramatically.
- Very fast put-in-place phase and no need to wait for concrete elements curing before filling the lacking parts of embankment.



From top left clockwise: railway embankment damaged, the railway during works, the pyramid-shaped element, a similar work as it is finished.

3.30.3. Lessons Learned

The following lessons were learned by the project team:

- The technique resolved the problem very quickly and in a very effective way: railway was reopened to full traffic after just three months since interruption and almost forty-five days of actual works only (November 2020-February 2021).
- Medium-term behaviour of similar structures is reported as very good, completely in line with not damaged parts of embankments. There is no remarkable change in stiffness between a regular embankment and the contiguous part reinforced with pyramid-shaped elements.
- Considering the stringent constraints related to time of interruption of the railway and the loss of money in the meanwhile, this solution can be considered definitely cost-effective.

3.31. Case Study 31 - Reinstatement of the failed segmental retaining wall (SRW)

Authors – Lee Jaehoon, Dongil Engineering Consultants Co., Ltd.

Country – South Korea

3.31.1. Brief summary of the problem

A mechanically stabilized earth wall (block type) collapsed in September 2013 in Seoul, Korea due to (a) poor backfill material behind the wall (i.e. silt, fine sand with clay, hence lower friction resistance between soil and geogrid whereas higher earth pressures were developed thus resulting in internal sliding failure or pull out failure), (b) pore water pressures built up at the back of the wall due to the heavy rainfall for several consecutive days while the insufficient drainage system (at behind the wall) was incapable of releasing the water pressures.

3.31.2. Brief summary of the solution

As there were buildings at the above and below the SRW, the failure zone had to be confined to the status quo, and thus as a solution concrete retaining wall with shelf (relieving platform) was adopted to reduce earth pressure, hence achieving increase of overall stability and cost reduction.

3.31.3. Lesson learned

(a) Importance of proper backfill materials and adequate drainage system behind the SRW shall never be overlooked nor underestimated.

(b) Proper action (even temporary measure) must be taken in an urgent manner right after the initial symptoms (bulging or cracks, etc.) being detected (or recognized), which may otherwise cause catastrophe, i.e. total failure of SRW.

Photo 1. Failure of SRW

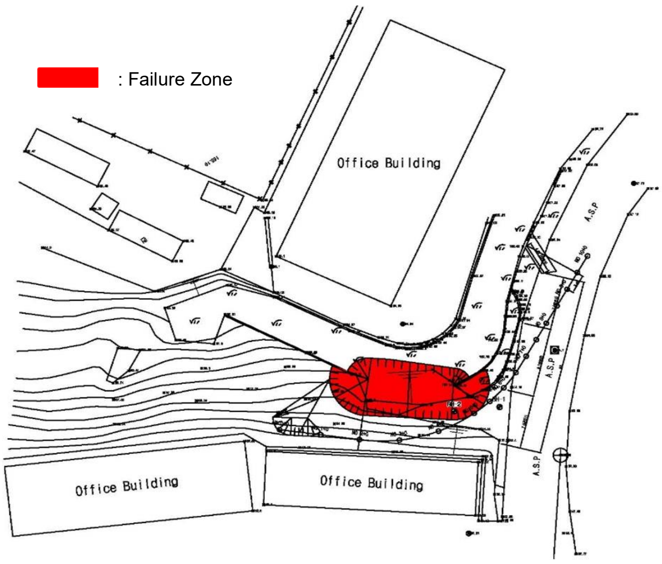


Figure 1. Site Plan

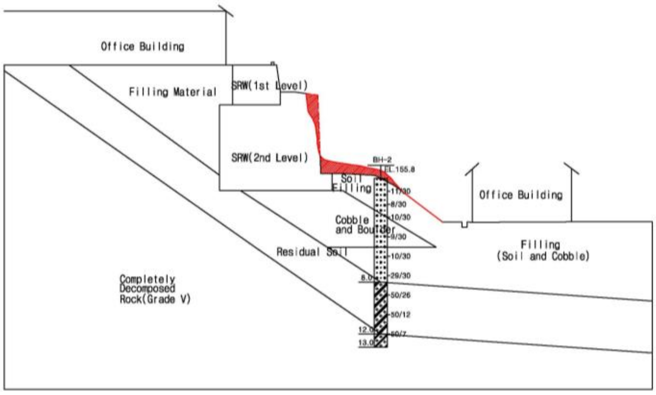


Figure 2. Typical Section (Failure Mode, Geometry, Geological Formation)

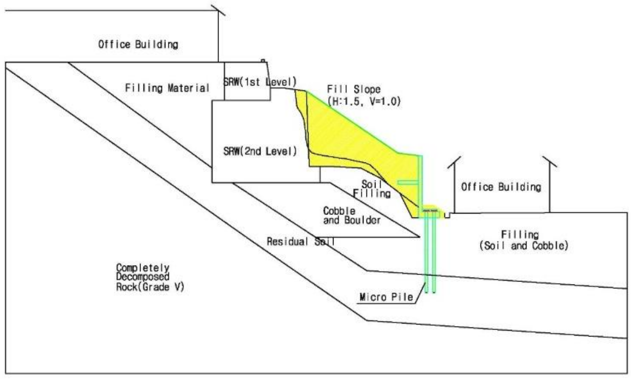


Figure 3. Typical Section (Reinstatement Solution)

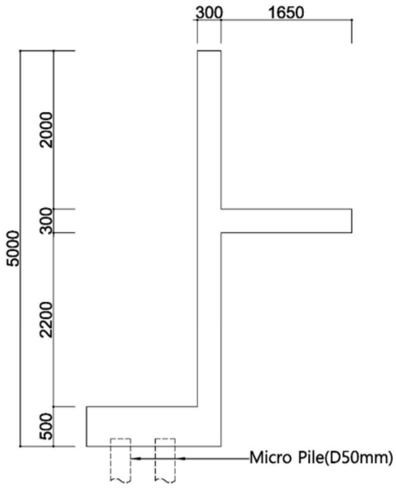


Figure 4. Retaining Wall Detail

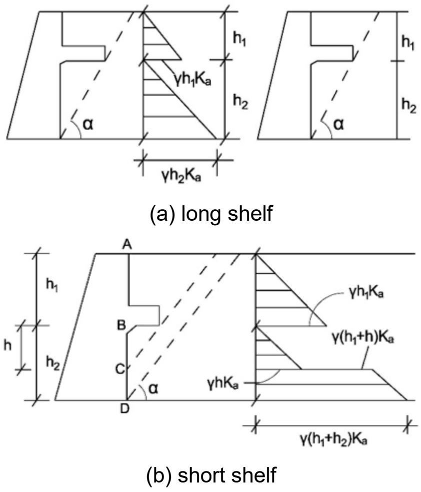


Figure 5. Earth pressure envelope by shelf length (Liu & Lin, 2008)

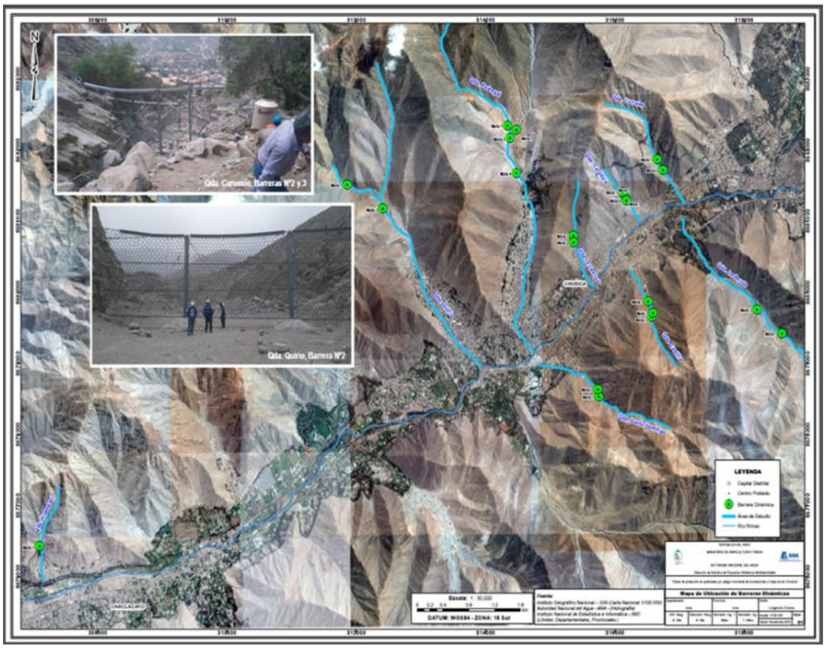
3.32. Case Study 32 – Control of debris flows with steel mesh

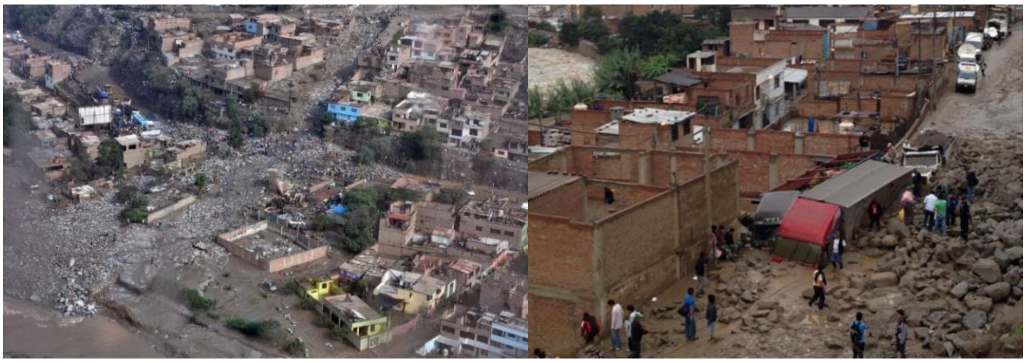
Authors – Sergio MarK L., Geobrugg

Location – Chosica, Perú

3.32.1. Brief Summary of the Problem

The town of Chosica borders the Central Road and is located 45 km west of Lima in Peru. The project was based on the need to increase the level of security in the town of Chosica. This town was constantly affected by debris flows that descended from the surrounding ravines in rainfall seasons (December to May). These flows produced significant damage to the infrastructure and took many lives of the inhabitants of the sector. To reduce the risk level and increase the safety of the residents of Chosica, the authorities proposed to intervene with mitigation systems.





Consequences of a debris flow in Chosica - Year 2015

After severe damage caused by debris flows in 2015, the National Water Authority (ANA) and the Ministry of Agrarian Development and Irrigation (MINAGRI) promoted and carried out the project to install a series of dynamic barriers with the purpose of protecting Chosica against this recurring phenomenon.

3.32.2. Brief Summary of the Solution

As a mitigation measure, 22 UX and VX type barriers were designed to control the debris flows. The design considered a protection measure in some ravines aiming to contain the direct flood. In other streams, these barriers were implemented as a stabilization solution. With the goal of stabilizing these ravines, multilevel systems were implemented. This type of intervention aims to diminish the global slope, reducing the energy levels of the future events.

The project was awarded to Tecnología de Materiales, SA, who used Geobrugg to supply the systems and Desnivel Perú SAC to install the systems. The cost of the project in terms of supplying the material and the installation of the 22 flexible barriers against debris flow reached an estimated value of US $6.0 million. This value is negligible compare to the estimated US $54.2 million calculated considering economic losses due to the direct and indirect consequences of the debris and water flow events that took place in March 2015.

UX barrier instalation – Carosio Ravine (2016)

3.32.3. Lessons Learned

The following lessons were learned by the project team:

- The 22 flexible barriers were installed within 75 days, considering that the material must be manufactured in Switzerland and imported to Perú by an air charter.
- The biggest challenge of the project was the time constraints. The reason for this was that the barriers had to be installed and fully operational before the rainfall season, which is when the activation of the ravines starts. The deadline not only made the installation process complex, but also the manufacturing, logistic and import from Switzerland to Perú.
- Another project challenge was that there were no access roads to the ravines surrounding Chosica. To solve this, various transport means such as helicopter, mules and cattle, zip line systems, and manual loading were implemented, making the construction much less efficient.
- The implementation of the 22 flexible barriers (as a protection and stabilization system) in the 9 streams located in the surroundings of Chosica town, increased the degree of security and protection.
- After almost 5 years the solution is still performing as expected.

3.33. CASE 33 - STABILIZATION WORK TO CONTROL LANDSLIDES IN URBAN AREAS

Author – Waldo Aliaga, Geobrugg

Location – La Paz, Bolivia

3.33.1. Brief Summary of the Problem

On April 30, 2019, there was a major landslide west of the city of La Paz, Bolivia. The landslide affected 88 families and left 68 homes damaged. Losses of more than US $7.9 million are estimated.

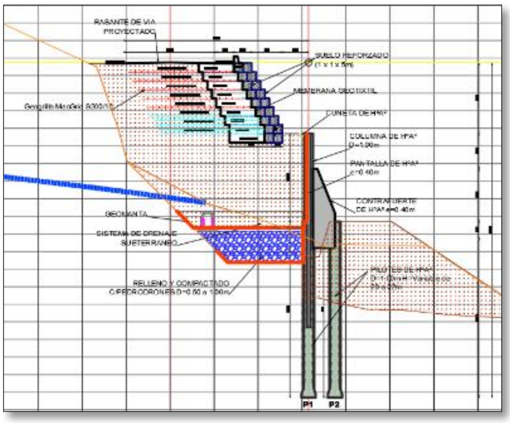
Area-Before and after landslide

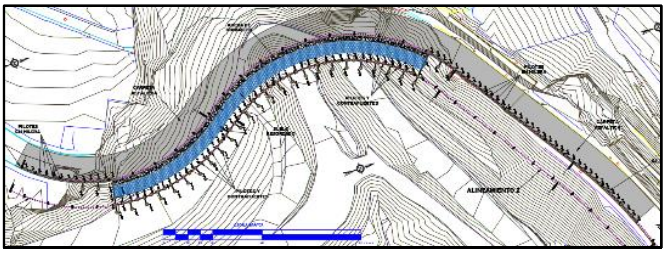
Although construction was not allowed since 1960 because the whole area was filled with garbage, many families built their houses in the area since 1990. In addition, the presence of groundwater combined with the leachates generated by the garbage and the clandestine connection of sanitary and river sewerage, produced the landslide of a large soil mass.

3.33.2. Brief Summary of the Solution

The project aims to stabilize the whole area and rebuild the access road to the "Trillizo" viaduct, linking the west and east sides of the city. After the earth works, removing all loose material and build four embankments, improving the slope geometry, the project includes a row piloting system with buttresses, on which a reinforced soil embankment is built, to reach levels close to the existing landslide escarpment.

The works were delayed by the COVID-19 pandemic, we hope to conclude the works at the end of 2021, until then we will get evidence of the proposed solution.





Photos 2020 – Earth works

3.33.3. Lessons Learned

The following lessons were learned by the project team:

- The implementation of a mixed containment wall, stilt system, reinforced earth and an underground drainage system, will allow the stability of the slopes that support the road platforms and housing; as well as reducing river erosion that deepens the riverbed, generating landslides in the Kantutani preservation area. This kind of structure, with some adjustments, could be the typical solution for other areas in the city with similar risks.
- Due to the emergency, the cost of the project was high, more than US $6.8 million, we need to optimize the design and modify them for different types of foundation soils and geotechnical conditions.
- According to the economic analysis, the solution is cost-effective and resilient to natural disasters.

3.34. Case Study 34 - Rehabilitation of Tunnel

Authors – Sergio MarK L., Geobrugg

Location – Mendoza, Argentina

3.34.1. Brief Summary of the Problem

Tunnel 1 is a 245 meters long passage located at the kilometer 32 of Provincial Route 82 in Mendoza-Argentina province. This is one of the oldest connecting tunnels in the high mountains' region width of 7.20 meters and sidewalks of 0.70 meters on both sides.

After 20 years, the vehicles returned to circulate along this traditional mountain road that formerly served as a connection between the city of Mendoza and the border crossing point with Chile.

Photo1 - the mounth of the tunnel

Photo 2 overview the gallery of the tunnel begore the works

In the year 2000 the transit had to be interrupted due to rockfall events inside the tunnel. Concerning this issue, a temporary road was set up which allowed the circulation from Mendoza city to the town of Cacheuta. However, due to the topography of the place, neither the road nor the shoulders had the minimum design requirements established for a provincial route in a mountainous area. According to the National Directorate of Roads, a re-functionalization of this tunnel had to take place in order to established a safe and agile vehicular traffic.

3.34.2. Brief Summary of the Solution

This rehabilitation Project was under the jurisdiction of the Provincial Directorate of Roads of Mendoza and financed by the Inter-American Development Bank (IDB). After a detailed engineering study inside the tunnel, an 8-centimeter-thick fortification with shotcrete and steel fibers was installed. A geohazard study also took place in the south-east portal. This portal had severe problems regarding rockfall and slope instability which compromise the road safety. Because of this, a series of rockfall barriers, a debris flow barrier, a slope stabilization system and a drape system were installed. The restitution of the pavement, a new lighting system inside the tunnel and painting were minor tasks that complete the entire project.

To attend the geohazards problems, Swiss technology systems were installed in the south-east portal. These systems are listed below:

Solution	Description	Dimensions
Rockfall protection barriers	**RXE-500**	**H4 L30,8 m**
	RXE-500	**H4 L24,3 m**
	RXE-500	**H4 L42,3 m**
Debris flow protection barrier	**VX060L**	**H4 L13,5 m**
Slope stabilization and drape protection	**QuaroX® Plus**	**972 m²**
	Tecco® G65/3	**774 m²**
	DeltaX® G80/2	**847 m²**

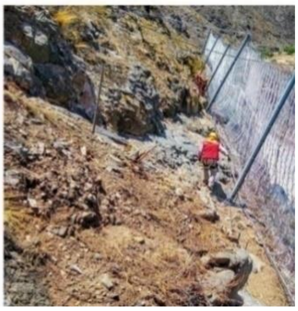


Photo 3 and 4 – works – debris flow protection barrier

3.34.3. Lessons Learned

The design stage of the project concerning the entrance portal protection, began the first months of 2019. This stage involved mainly rockfall models to assess the risk generated by this phenomenon. Once the project was awarded, deadline of 6 months was established. This lapse of time also had to contemplated, the manufacture and import of the systems from Chile.

The main difficulties were found in the protection systems against rock falls installation. This is a high-risk task and the local personnel of the awarded company had limited experience to carry out the technical requirements of the manufacturer (Geobrugg).

Regarding this concern, Geobrugg Andina in Chile designated a trained staff that made a permanent supervision and assistance on site. Through an exhaustive transfer of knowledge, they trained the local personnel during the assembly and the installation process according to international standards and good practices in the matter.

Photo 5 - overview the gallery of the tunnel after the works

Photo 6 – general overview I

The project gives the tourist corridor a higher level of agility and safety including the mitigation of the risk that rock falls represent to the more than 15,000 daily users of the route. The total amount of the Tunnel 1 Rehabilitation project was USD 1.2 million. The natural risk protection systems at the entrance portal reached an estimated value of USD 0.3 million.

3.35. CASE 35 - SLOPE STABILIZATION AGAINST SEISMIC EVENTS

Authors – Sergio MarK L., Geobrugg

Location – Niebla, Chile

3.35.1. Brief Summary of the Problem

The route T350 is located in "Los Rios" region and connect Valdivia city with Niebla town, in January 2013 a considerable landslide occurred affecting the transit and isolating Niebla.

Investigations determined the collapse of the slope was produced by many fragmented rockfalls from the top. This was a consequence of unusual high temperatures that changed the soil proprieties in the sector.

Landslide, 2013

The Public Road Ministry (MOP) made an investigation about the landslide consequences and the possible solutions like a slope stabilization, superficial drainage and erosion control with high interest in the slope revegetation.

In collaboration with Geobrugg, they propose as a solution the TECCO® GREEN system. This system consist in a high tensile steel mesh that allows the tension transmission to the system anchors, it also has an anti-erosion membrane to achieve a fast slope revegetation.

3.35.2. Brief Summary of the Solution

From the design perspective, Valdivia is a seismic active zone were the highest earthquake registered in human history took place. To determine the safety factor and guarantee a long term slope stabilization, scientist made a pseudo static analysis and geophysical studies to determined wave velocities profile.

With these investigations results, they determined that a TECCO SYSTEM with 6m long and Ø32mm anchors was the best solution.

From the construction perspective, the main difficulties were the partial road interruptions. This was the main issue because this road is the most direct connection between the cities. As a high wingspan slope project, they worked with climber's mountain specialists to maximize security and work protection.

3.35.3. Lessons Learned

As a governmental Project, the main objective was providing a benefit to the community, the slope stabilization brought positive consequences and guaranteed the connection between cities. Also, the Niebla's fishing terminal which was affected by the landslide, was complete renewed and is being protected by slope stabilization until today.

After the engineering and tender process, the execution lapse of time was 5 month considering earth movement, 6m long anchor drill and mesh installation.

The cost of the project was approximated USD 0,980 million dollars.This emergency work investment was made by the "Los Rios" regional government.

Slope stabilization in 2013, 2014, 2018 and 2021

3.36. Case study 36 - Soil Improvement of Organic Soil in the Substructure of A Road or Railway Line with the Cut-Mixing-Injection- Method

Autors – Monika Schad, Hochschule Biberach, University of Applied Sciences

Country - Germany

3.36.1. Brief summary of the problem

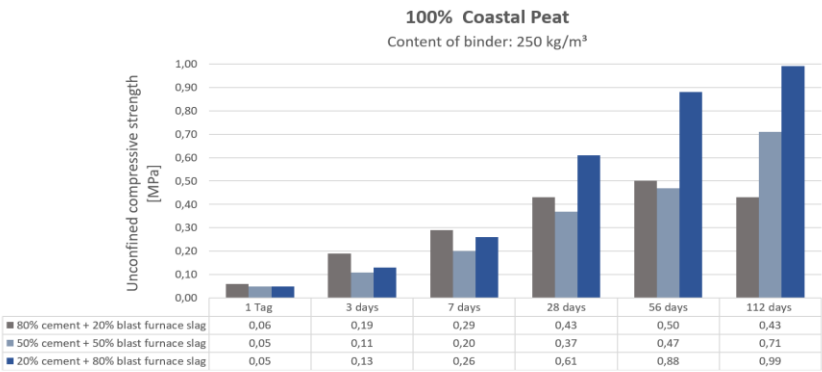
The construction of earthworks and earth structures is often required in areas of soil that is typically considered unsuitable. These unsuitable soils often consist of peat and other soils high in organic content. Removal and disposal of these soils can be costly and time-consuming. Researchers in Germany identified a potential solution to reuse, rather than remove and dispose of, these “unsuitable” soils. The study took place at two sites, a coastal area in northern Germany and a high moor peat from southern Germany.

3.36.2. Brief summary of the solution

The laboratory tests are based on the boundary conditions of the FMI-Method (Cut-Mixing-Injection Method). Unconfined compressive strength tests were carried out to verify the degree of improvement. The current railway guidelines allow a maximum peat content of 30 % by volume in the stabilised soil mixture. In the studies of the university the peat content in the mixture was increased from 30% to 100%. In order to show the influence of the binder and humic acids, the results of the stabilised pure peat (100% peat) are presented in this case study. Different binders were used, consisting of cement and residual material from industry. In the second step, comparative investigations were carried out on a high moor peat from southern Germany.

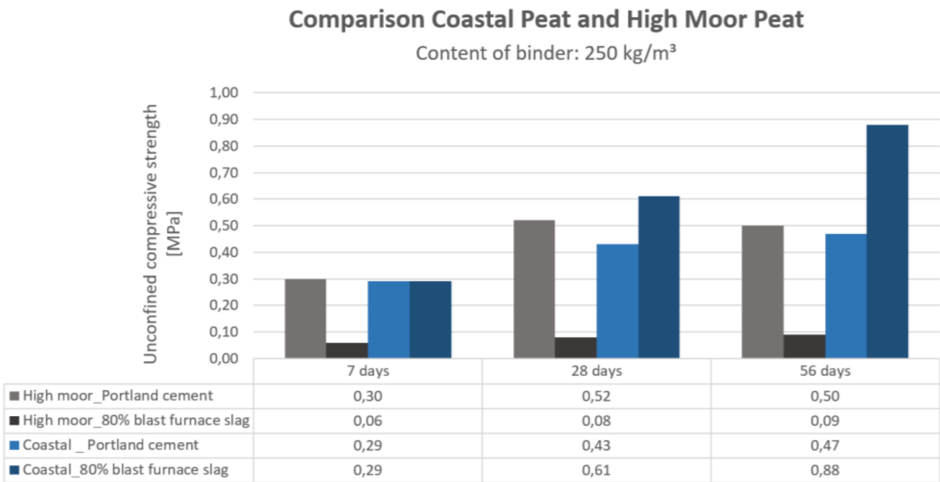
Pictures: The FMI (cut-mixing-injection) machine - Sidla & Schönberger Germany

The results from the stabilization tests of 100% peat show that different types of cement, i.e. different mixtures with cement and blast furnace slag, show differences in the results. A high content of blast furnace slag gave the best result in the coastal peat but a very low compressive strength in the high moor peat. Using Portland cement, the results showed comparable medium strength in both cases.



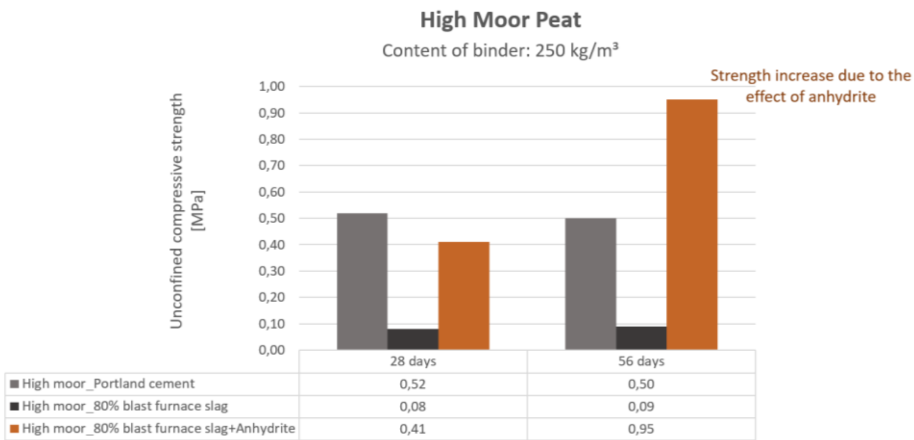
	1 Tag	3 days	7 days	28 days	56 days	112 days
80% cement + 20% blast furnace slag	0,06	0,19	0,29	0,43	0,50	0,43
50% cement + 50% blast furnace slag	0,05	0,11	0,20	0,37	0,47	0,71
20% cement + 80% blast furnace slag	0,05	0,13	0,26	0,61	0,88	0,99

The graph shows that increasing the proportion of blast furnace slag in the binder leads to significantly higher long-term compressive strength in the stabilized coastal peat.



	7 days	28 days	56 days
High moor_Portland cement	0,30	0,52	0,50
High moor_80% blast furnace slag	0,06	0,08	0,09
Coastal _ Portland cement	0,29	0,43	0,47
Coastal_80% blast furnace slag	0,29	0,61	0,88

The graph shows that the high moor peat has no development of strength when a high content of blast furnace slag was used as a binder. Using Portland cement, the results show comparable medium strengths.



	28 days	56 days
High moor_Portland cement	0,52	0,50
High moor_80% blast furnace slag	0,08	0,09
High moor_80% blast furnace slag+Anhydrite	0,41	0,95

A significant increase in long-term strength is achieved by adding anhydrite (20% of the cement mass) as an accelerator for the blast furnace slag. The decisive increase in strength takes place during the secondary reaction of the blast furnace slag between 28 and 56 days.

3.36.3. Lessons Learned

The effectiveness of binder type and dosage on the stabilization of peat is very site specific due to differences in humic acids composition. Black humic acids in organic matter have a strong chemical affinity to calcium and can lead to a stop in the binder reaction (Chen et al., 2005).

Using Portland cement, a comparable compressive strength was achieved, irrespective of the humic acids of the investigated peats. Using a binder with a high content of blast furnace slag, the black humid acids result in no strength development. This behaviour can be positively influenced by the addition of anhydrite (calcium sulphate). By adding anhydrite, a sufficient amount of calcium is available for the secondary binder reaction despite the humic acid content.

4. CONCLUSIONS

While the problems related to earthworks have been around for centuries, it is clear from this compilation of thirty-six "pearls" that globally we continue to innovate to develop better solutions to these problems and ultimately provide a more resilient infrastructure. Today, we strive not just for more cost-effective solutions but also solutions that are more environmentally friendly and sustainable, as well as provide socioeconomic benefits. This report highlighted several case studies involving the reuse of materials, whether it be reuse of existing poor soils reducing the amount of disposal or the repurposing of end-of-life tires or glass into backfill materials.

The report also highlighted solutions involving green technology, using various forms of vegetation to solve slope stability issues, that not only solve the geotechnical problem but also improve the environment on and around the slope as well as reduce the carbon footprint of the construction activity. There are also many case studies involving simple techniques, simple equipment, and simple materials, such as a Geosynthetic Reinforce Soil (GRS) bridge abutment, which uses stones and geotextiles placed by unskilled labor instead of concrete and rebar.

On the other end of the spectrum, there are case studies featuring cutting edge technology that improves compaction techniques and testing, as well as data collection to help with designing the solution to the earthworks problem.

Through all of these case studies, we learned that the keys to resilience include:

- Structural robustness to withstand man-made and natural hazards
- Recoverability and the ability to recover quickly from an event
- Inspection, monitoring, and maintenance plan,

And the solutions to be developed in the design phase should consider:

- cost-beneffit;
- reinforcement of the drainage system;
- sustainability - use the most appropriate material, use local material, recycle material and low energy and less carbone emissions;
- adaptation to the ecosystem.

These solutions can be applied to a wide range of scenarios all over the world, including Low and Middle Income Countries (LMICs). The adaptability of these solutions will depend largely on the stakeholders' willingness to take on risk, speed needed for the solution, and incentives to be innovative. It should be noted that resiliency can be easily increased without a significant increase in cost.

However, the biggest benefit of these case studies likely will not just be the solution itself as presented but the potential for these solutions to spark ideas for new innovative solutions that may be even more cost effective and environmentally friendly within the LMIC looking to solve an earthworks problem.

5. RECOMMENDATIONS FOR PIARC

5.1. Recommendation A: Repeat Compilation of Innovations and 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.

5.2. Recommendation B: 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.

5.3. Recommendation C: Water Management of Earth Structures

Water is the single most damaging element to earthworks. Obviously, flooding events cause major damage to earth structures, including culverts, through direct impact, erosion, debris, and landslides. However, water also cause 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.

World Road Association (PIARC)

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