**Proceedings of the 9ICEG**
9th International Congress on Environmental Geotechnics
25-28 June, 2023 | Chania, Greece

https://doi.org/10.53243/ICEG2023-337

# The use of green geology for the stabilization and rehabilitation of rock masses

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## ABSTRACT

The consequences of climate change are unquestionable and measures must be taken to prevent and minimize their consequences. It should be noted that the vast majority of problems arise from the mismanagement of human activity, such as in the exploitation of resources or poor territorial management, which can generate problems related to geological hazards.

To deal with the geological hazards that are becoming more and more serious, it is essential to have a team with skills in several areas. The stabilization and rehabilitation of rock masses requires the integration of multiple areas (eg: geology, geotechnics, ecology, economics, etc.) that must be in line with the sustainability policies.

Geology is the basis for all construction and rehabilitation projects and the use of “environmentally friendly” solutions must encompass geotechnics, the use of “green geology” and “green geotechnologies” to achieve a sustainable design. The “green geology” procedures must aim to use increasingly efficient geological study methodologies to foresee instability problems, to increase sustainability and to obtain efficient results allowing economic profitability. It is essential that the increasing use of “green geotechnologies” allows increasing the awareness of society for sustainable practices in geology, but also in other related subjects.

*Keywords: Efficiency, Green Geology, Natural Engineering, Rehabilitation, Stabilization, Sustainability*

## 1 INTRODUCTION

Today, society plays a leading role in the use of the planet's geological resources. According to the Global Risks Report 2022 (WEF, 2022), for the ten most serious risks on a global scale for the next 10 years, the first three correspond to the failure of climate action, extreme weather and loss of biodiversity, and in seventh and eighth places are, respectively, the environmental damage caused by humans and the crisis of natural resources.

Analyzing this report, it is clear that the environmental problem is far from being solved and the big question is how to intervene in a positive way. One important subject is to raise awareness of the environmental issues related with geology. It becomes increasingly important to instill relevant learning bases in the use of geological materials to work based on sustainability. We must increase environmental efficiency and economic profitability as this combination will allow a sustainable approach to the problems.

Considering that geology is the basis for a successful stabilization and rehabilitation, it is essential that the recovery of any site tends towards an autonomous recovery in the long term. This implies that human intervention must be used primarily to build the necessary foundations allowing nature to achieve autonomous recovery in the long term. This procedure saves resources and promotes the evolution of environmental communities.

Concerning stabilization and rehabilitation it is imperative to analyze the geomechanical behavior of the geological material occurring in the study site. Several methodologies can be used, eg: Rock Mass Rating (RMR), Slope Mass Rating (SMR), Q-Slope, GSI and to understand the behavior of the existing soils. After identifying the behavior of the geological material and the associated problems, it is necessary to develop solutions keeping the focus on a “green” approach of geology and geotechnics, in a complementary way with the geotechnologies that have already proved their relevance. For more consistent results, the comparison and cooperation of different subjects are essential, such as geology, ecology, biology, economics, among others.

Finally, a sane analysis and evaluation of the processes from the earliest stages is essential for a good intervention with a focus on efficiency, economic profitability and sustainability.

## 2 GREEN GEOLOGY AND GEOTECHNOLOGIES

### 2.1 Concept

In similarity with the concept of green economy where it is said that, according to the UN Environment Programme (2022), "an inclusive green economy is one that enhances human well-being and builds social equity while reducing environmental risks and scarcity", the *green geology* approach aims at the study of geological resources in a respectful way, supplying the needs of society, without forgetting human and environmental well-being, enhancing itself according to the needs required in a given issue, be it exploration, stabilization or rehabilitation and keeping the focus on efficiency, economic profitability and sustainability.

The use of the expression *green geology* implies the use of traditional and/or more recent geology methods, depending on the case being studied, combined with a sustainable vision. Sustainability is currently the watchword, however in the area of geology it would be important that sustainability presents efficiency, economic profitability and does not waste the planet's resources. Thus, traditional geology takes the form of green geology through the combination of several valid techniques, as well as the combination of geology with other areas (eg: geotechnics, ecology, etc.) that make a particular project sustainable. A sustainable project is one that is based on efficiency, economic profitability and concern for the surrounding environment.

To identify the problems associated with a study site, we have to combine different areas of geology, such as hydrogeology, geomorphology, tectonics, and mineralogy, among others. Knowledge areas depend on the type of site and problems identified, as well as the study necessary to meet the needs of the site.

Thus, a truly sustainable project must be multidisciplinary and have three key points: efficiency (quality of doing something well without wasting time, resources or money), economic profitability (the investment made initially will translate into future gains) and sustainability (use of natural resources and energy so that there is no environmental damage but rather a benefit).

Being sustainable is not about being radical; it is about finding a balance between human activities and the environment. That said, it is noticeable that being sustainable is not so linear, as achieving the perfect combination of the three factors seems practically impossible, so the choices must be balanced.

### 2.2 Green Geology and Geotechnologies as a Resource for Sustainability

Geology is the basis of any stability and rehabilitation study. Traditionally, the first approach to a geological study of a given site is to resort to existing bibliography for a preliminary identification of the geological material and the local topography. Subsequently, a site visit will be required to verify bibliographic data and draw up a detailed site study plan, and it is at this point that we have to consider green geology and geotechnologies.

There are several key points to draw up a strategic plan to identify the problems at the study site, such as: the identification of stability problems or visible hazards, the identification of the local geology and characterization of the geomechanical behavior of the geological materials, so that it is then possible to present the appropriate solutions.

The type of instability (eg: plane and wedge failures, block falls, toppling, among others) and various hazards are directly linked to the local geology and the behavior of the geological material. If, on the one hand, the geology and instabilities or hazards are identifiable to the naked eye, there may also be constraints on the geomechanical behavior of the materials that trigger instability mechanisms. To analyze this type of situation, geomechanical classifications can be used (eg: Rock Mass Rating (RMR), Slope Mass Rating (SMR) and Q-Slope). Laboratory tests (eg: point load test, uniaxial compressive strength test, slake durability, moisture content, porosity, density), defining different parameters of rock (eg: geomechanical classification) or soil (eg: unified soil classification).

Nowadays there are software's that allow, through algorithms, to simulate instability situations and define the failure conditions, which require certain parameters to be input depending on what is to be analyzed, but these procedures can be potentially dangerous when the user does not know how to use and/or interpret.

The use of a green geology in the preliminary study may correspond, for example, to the substitution of soundings by georadar. The georadar allows us to observe in depth without being intrusive and its use is extremely intuitive and in a short time we can draw up various profiles.

For all these reasons, geology can be put to work as green geology by integrating geotechnologies that make them an important resource for sustainability; however, this need to be understood by society, either from the point of view of those who work with green geology, or from the point of view of those who use it.

### 2.3 Geology as seen by Society

As already addressed, one of the most serious risks of the next ten years is the natural resources crisis, and another is the damage caused by humans to the environment. At first, these are risks that are not related to the stabilization and rehabilitation of massifs or exploitation areas, however we can deepen the subject and identify the common points.

As predicted by the World Population Prospects 2022 report of the United Nations Department of Economic and Social Affairs, Population Division (United Nations, 2021), in 2022 the world population reached eight billion people by mid-November and ten billion people are expected to exist by 2059. With this exponential population growth, the need to use various resources also increases, whether technological (eg: mobile phones, computers), locomotion (eg: trains, cars, planes), construction (eg: houses, buildings), among others. To be able to supply these needs, the world depends on geology and the areas directly linked to it. Faced with the increasingly consumption of the planet's resources, it is necessary to make people aware of this excessive consumerism that can lead to a crisis of lack of natural resources.

More and more demonstrations are being seen to demand action to reverse climate, many of them point to the exploitation of natural resources, as society sees areas of geological intervention as the greatest enemy of the planet (eg: use of fossil fuels, mining). In reality the only enemy of the planet is the human being, due to its excessive consumption and its need for evolution.

Thus, it is imperative to act in the educational area in order to instill correct values from an early age and pass on true information to future generations. Take the example of the CEO of BMW, who said that sustainability is to keep the old car instead of buying a new one. In this simple example, the performance of green geology can be introduced, as the mining necessary to obtain the raw materials for the construction of electric cars, computers, mobile phones, among many other things that are used in our daily lives is inevitable. Geologists and engineers must promote appropriate solutions to the rehabilitation of an exploitation area, to recover the site landscape and environment.

Another example is the construction of roads, which is something very recurrent and which has to obey very specific rules. However, we are often confronted with landslides, flows and falling blocks coming from the slopes that border the communication route. With climate change, these instability situations will be more and more recurrent, and on a larger scale, because unexpected bad weather will be more frequent.

## 3 HOW TO USE GEOLOGY AND GEOTECHNOLOGIES IN A SUSTAINABLE WAY

Geology, geotechnics and engineering play a very important role in sustainable solution to everyday problems. The question is how geology and geotechnologies will act towards sustainability. They must be used intelligently and by a work team having the suitable skills to ensure an efficient work.

To stabilise slopes or rehabilitate problem areas, you have to know how to act on site and according to the difficulties. The most important point on the way to sustainability is the efficiency of the work team considering the study on three fundamental bases: efficiency, economic profitability and sustainability. Table 1 identifies different parameters to equate the choices that balance the three main factors: efficiency, economy and sustainability and how the components of society, the stability of the ground mass and the environment react to the descriptive parameters in the short, medium and long term according to the definitions adopted by the Global Risks Report 2022 (short term: 0 to 2 years, medium term: 2 to 5 years and long term: 5 to 10 years).

The educational impact was also considered, since it is essential that in areas such as geology, education and awareness for the stabilization and rehabilitation of massifs. The techniques to be used must be innovative, effective and economical, considering the environmental factor, something that is still not widespread.

***Table 1.*** *Parameterisation of key factors: economic efficiency, sustainability and educational impact*

| | |
|---|---|
| **Efficiency** | Effectiveness<br>Durability<br>Results<br>Monitoring |
| **Economy** | Construction cost<br>Dismantling/demolition/deconstruction cost<br>Cost of rehabilitation<br>Cost of treatment to return the waste to the environment<br>Maintenance cost<br>Competitiveness |
| **Sustainability** | Energy spent on the study and solution work (quantity and type)<br>Recycled materials (type and quantity)<br>Potential for waste recycling<br>Remaining raw material reserves<br>Amount of natural resources/raw material used<br>Disturbance of the environment (pre-intervention and post-intervention)<br>Fire potential |
| **Educational Impact** | Awareness of the work to develop and its contribution to improvements in the stabilization and sustainable rehabilitation<br>Dissemination of the project and of the positive and negative aspects for future learning |

It is highly important that construction costs consider the training of specialized workers in the solution techniques used, knowledge which is gradually acquired with the increase in techniques and solutions with a more sustainable character. When carrying out tests or proposing solutions, the costs in terms of natural resources and raw materials must be considered and valuated.

### 3.1 Balancing Efficiency-Economy-Sustainability: a preliminary case study

A description of the characterization of the Vale da Anta massif through geomechanical classifications, such as RMR, according to Bieniawski (1989) and the Q-Slope according to Bar & Barton (2018), is presented. The aim is to characterize a slope that has intercalated marl and marl limestone and is highly jointed. The layers dip into the rock mass however, there may be falling blocks due to the joints or rock fragmentation. The slope's length is 195 m, and is very heterogeneous, showing marls with a high grade of weathering and also unweathered marly limestone.

The slope was divided into three groups (G1, G2 and G3) according to its structural and geological characteristics. For each of the groups, the two classifications were applied. The results obtained for each classification are shown in Table 2.

***Table 2.*** *RMR, corrected RMR and Q-Slope geomechanical classification values with the β angle (steepest slope angle not requiring reinforcement or support) according to the percentage of failure (PoF=1%) (Silva et al. 2023)*

| Slope Groups | RMR | RMR Classification | RMR (corrected) | RMR_corrected Classification | Q-Slope β |
|---|---|---|---|---|---|
| **G1** | 47 | reasonable | 42 | reasonable | 34 |
| **G2** | 54 | reasonable | 49 | reasonable | 67 |
| **G3** | 65 | good | 60 | reasonable | 67 |

The RMR corrected classification considers the influence of the orientation (strike and dip) of the discontinuities and presents lower values than the RMR, which is also called RMR basic. In the present work, the joint orientation assessment was considered as favorable, so the RMR corrected for the different Slope groups shows a decrease of 5 points comparatively to RMR.

The Q-Slope classification according to Bar & Barton (2018) allowed obtaining the β angle, which corresponds to the limit angle that the slope may present, taking into account a certain set of factors: RQD – rock quality designation, $J_n$ – joint sets number; $J_r$ – joint roughness number; $J_a$ – joint alteration number; $J_{wice}$ – environmental and geological condition number; $SFR_{slope}$ – three strength reduction factors a (physical condition number), b (stress and strength number) and c (major discontinuity number) and O-factor – orientation factor for the $J_r/J_a$ ratio.

The methodologies for obtaining the RMR and Q-Slope classification are different, as well as the results and parameters obtained in each of them, so their use implies an adaptation to the problem under study.

Table 3 shows that the two classifications give information about common parameters, but some of them are very different, as is the case with the RMR, in which one of parameters corresponds to the strength of intact rock material. RMR provides an index of the rock mass quality. On the other hand, with the Q-Slope the value of steepest slope angle (*β*) not requiring reinforcement or support is obtained, which is a very important data to evaluate the stability of the slope. The Q-Slope parameters consider the orientation of the joints and the environmental conditions of the site, which are very relevant for the definition of potential instability situations.

***Table 3.*** *Parameters of RMR and Q-slope classifications*

| | RMR | Q-Slope |
|---|---|---|
| Strength of intact rock material | √ | |
| RQD | √ | √ |
| Joint spacing | √ | √ |
| Joint condition | √ | √ |
| Water flow in joints | √ | |
| Orientation of discontinuites | | √ |
| Environmental conditions | | √ |
| Strength Reduction Factor (SRF) conditions | | √ |

After understanding the parameters and results of these two methodologies, it becomes essential to understand their importance for the immediate assessment of the slope in terms of instability. According to the methodologies presented in Table 1, it appears that the Q-Slope is more suitable for the intended study. However, for a more detailed geomechanical study of geological materials, the ideal would be to use RMR combined with the Q-Slope, given that the results obtained would be more reliable.

Q-Slope corresponds to a rock mass classification that satisfy the three parameters of efficiency, economy, and sustainability. The educational impact in an initial stage would be very small, as this factor will be more imposing in a resolving approach. Through these two classifications, it is not possible to define the safety factor of the slope, however in Silva *et al.*, (2023), the set of tests was carried out and the results were used in the Rocsience software to obtain the factor of safety.

### 3.2 Balancing Efficiency-Economy-Sustainability: presenting solutions

To assess the safety conditions of the rock mass stability, elements and factors such as: roads, buildings, maritime or wind conditions, tourist attractiveness, among others, must be considered. It should be understood which solutions best respond to the safety needs of a given location.
Considering the slope of Figure 1 from Silva, et al. (2023), different solutions are presented in Table 4. The vegetated wall was mentioned in the proposed stabilization solution; however, this is a very infrequent technique in Portugal. With an adaptation in Figure 1 of how the solution should be executed.
The simplest solution would be to use shotcrete on the soft rock, it would be simple, fast and economical, however, the studied slope is located in a coastal zone where the salinity and humidity conditions are quite marked, in addition to the temperature variation that can cause wear and degradation of the concrete. Beyond that, we consider that the worst is the visual impact of the shotcrete.


***Figure 1.*** *Vale da Anta Slope (Silva et al. 2023). Inside the area outlined in red, there is the presence of weathered soft rock*

***Table 4.*** *Slope stabilization solutions adapted from Silva et al. (2023)* requiring intervention and stabilization

| | Marly limestone and marls (variable % of marls)* | Soft rock | Marly limestone (very small % of marl) |
|---|---|---|---|
| **Group 1** | Cleaning fragments and blocks<br>Wire mesh to prevent falling of debris and blocks onto the road and clogging the ditch | Reprofiling/Resloping for the placement of mulch and of living systems to increase the stability of the slope | |
| **Group 2** | Cleaning fragments and blocks | | Eventual cleaning of rock falling blocks |
| **Group 3** | Cleaning fragments and blocks | | Cleaning and maintenance |

*The intercalation of marly limestone and marls in the areas of highly jointed marly limestone, which is located in the northernmost part of the referred slope

The vegetated solution is validated by the presence of vegetation nearby the area where the slope is located, namely in Boa Viagem Mountain, located to the east, and the dunes located to the west (Figure 2).

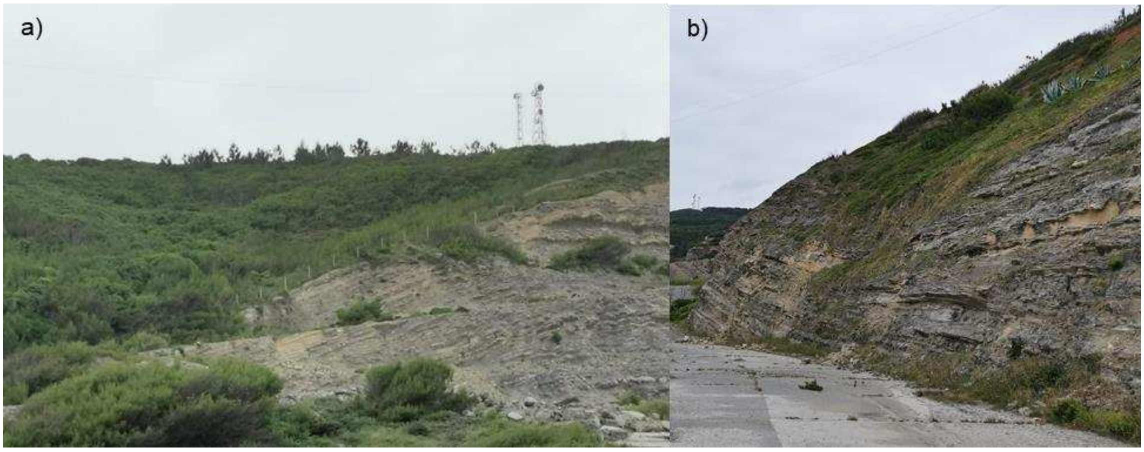


***Figure 2.*** *Adjacent areas of the Anta Valley slope: a) view of the Boa Viagem mountain range, rich and diversified in fauna and flora and b) the zone closest to the coast with the presence of vegetation on a rocky massif consisting of limestone, marly limestone and marls*

For this solution to stabilize the fault zone, with totally defragmented soft rock, it is proposed to reperfill the slope keeping it at an angle between 30º and 35º.The first step is to clean the rock blocks and store them so that they can be incorporated into the stabilization solution, without producing waste. After slope cleaning and adequate reprofiling, mulch should be applied so that the existing soft rock is rebalanced and adapted to the new conditions, so that it can later receive the living systems to be incorporated, and rehabilitation as well as stabilization can be successfully completed.

After rebalancing the area in question, the vegetated should be integrated, where a mixture of soil, manure and endemic flower seeds is covered in a coconut fiber net. This is biodegradable and will help the seed germination, contributing to the stabilization of the site (Figure 3). An adequate drainage system should also be installed to prevent the accumulation of water, to prevent slope failure.

Appropriate vegetation should be chosen so that its roots penetrate deeply into the slope and provide greater stability. However, it must have small vegetation, such as moss, grass and other native species to reduce erosion, otherwise the erosion process can accelerate and cause slope failure. Since if large, non-indigenous species are placed, the instability problem may be aggravated. The water circulates along the slope dip and runs off toward the ditch deadened by vegetation that will integrate the system of this slope.

Some examples of vegetation that can be used on site, according to Sociedade Portuguesa de Botânica (2022) are, for example, *Senecio doronicum subspecies lusitanicus*, which is very characteristic of limestone outcrops and easily grows in areas with soils resulting from decarbonation of limestone. Furthermore *Calendula suffruticosa subspecies lusitanica*, is another example which is easily found in cracks in limestone rocks. These are just a few examples of vegetation that can be incorporated in this case.


***Figure 3.*** *(1) Example of a coconut fiber mesh* (Ecosalix, 2022) *(2) Schematic cross section of the Vale da Anta slope with vegetated cover to promote stabilization of the fault zone*

Comparing the two stabilization options, it is clear that the use of concrete is possible, but local conditions will cause deterioration due to various factors (eg: salinity, humidity, etc.).

The vegetated will be a more advantageous solution in the long term, as it will be exempt from monitoring and only subject to maintenance, as is the case for part of G1 and G2 and the whole of G3. In the vegetated option, there is also the integration of sustainability, with the incorporation of living systems in the stabilizing solution. It is an option with the potential for the educational impact of methodologies that integrate efficiency, economy and sustainability in balance.

## 4 EXPECTED RESULTS

The expected results of the project UI/BD/150842/2021 funded by FCT are the dissemination of methodology and solutions that allow the stabilization and rehabilitation of singular massifs or in the context of abandoned quarry/mine. These solutions must be efficient and profitable economically and above all, sustainable, combining engineering geology with natural engineering practices, sustainable geotechnics, and the restoration of primary geomorphology.

This is a sector on the rise given the increasing burden caused by the impact of climate change and consequently by the high risks associated with slope stability. If the stability of slopes or massifs is not worked on, monitored and well executed, human and animal lives can be put at risk and land use planning can collapse.

Nature is infinitely complex and human beings are not capable of fighting it when it is at its maximum strength, but we can monitor it and move towards more suitable stabilization and rehabilitation procedures.

## 5 CONCLUSION

The geology and behavior of materials are the basis for stabilizing and rehabilitating rock masses, whether they are unique or integrated into a quarry/mine context. The Vale da Anta slope was classified as a reasonable rock mass for groups 1 and 2, and as a good quality rock mass for group 3, with RMR values of 47, 54 and 56, respectively. With the RMR corrected, the rock mass is classified as a rock mass of reasonable quality in all groups with values of 42, 49 and 60 respectively for groups 1, 2 and 3.

Using Q-Slope and defining β (steepest slope angle not requiring reinforcement or support), it was concluded that the maximum limit angle for the slope is 34º in group 1 and 67º in groups 2 and 3, which means that in groups 2 and 3 the maximum limit angle is higher than in group 1.

It is essential for geologists and geological engineers to know how to adapt the working methodologies and solutions to the problems encountered. The main concern must always be to find a balance between the most efficient, economical and sustainable methodologies and solutions. The project to be developed has an educational impact aiming at the disseminating of good practices, of green geology and geotechnologies among future generations.

Finally, the use of green geology, i.e. geology that encourages good practices and respects the rules of sustainability and integration of the environment in the optimization of stabilization and rehabilitation/restoration of massifs, is essential for the future of the planet. It is imperative to adapt the construction works according to environmental needs and not only to the needs of the human being. This is achieved through conscious choices of preliminary works, tests and solutions, aiming at the maximum saving of resources (e.g. mineral resources, water, energy), the greatest possible recycling of materials and the use of ecomaterials (e.g. recycled waterproofing sheets, recycled aggregates, CDW - construction and demolition waste, natural engineering techniques).

The use of vegetation for slope stabilization is an example of an eco-efficient technique. In this case, it will be possible to create a new living system by using a combination of geological resources and living systems, such as plants. The solutions presented are therefore balanced, with regard to efficiency, economy and sustainability.

## 6 ACKNOWLEDGEMENTS

The authors express their gratitude to FCT for the support. The work will continue under project UI/BD/150842/2021 and the project UIDB/00073/2020 funded by the Fundação para a Ciência e Tecnologia (FCT).

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