

Article

Towards the Resilience of Attica Region's Provincial Road 3 in Greece, Due to Slope Failure by Applying Civil Engineering Techniques and a Semi-Quantitative Assessment Approach

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Abstract

Landslide mitigation works, which are used to retrieve the damaged (from the landslide) environment, sometimes lack methodologies to integrate resilience into infrastructure projects economically and sustainably. The necessity of developing resilience in civil engineering technical works is getting more obvious since the outcomes from natural disasters have become more frequent since 2000 and onwards. This article presents the slope failure mitigation measures through a resilience framework, focusing on a case study from a road adjacent to a local stream in Greece. A geological–geotechnical study and mitigation measures were carried out in the context of the restoration of the road surface and the stability of the stream slopes. The purpose of this article is to describe the process of implementing aspects of resilience into the civil engineering technical works and to evaluate the effectiveness of implemented strategies for improving the resilience of infrastructure. It was found that using a semi-quantitative methodology (RES for estimating the slope instability index and resilience matrix for the evaluation of the constructed technical works) can associate designers and subsequently decision makers with valuable tools for facilitating decision-making for more sustainable solutions and contributing to the long-lasting duration of civil engineering projects.

Keywords: engineering resilience; matrix; civil engineering landslide mitigation measures; robustness; adaptability



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1. Introduction

Disasters caused by natural hazards often lead to significant economic and environmental problems in society. Thus, increasing attention is placed on strengthening the “disaster resilience” of communities at site-specific locations, to improve a priori disaster risk reduction and expost recovery.

In this direction, Eurocode 7 (EC7), the (landslide) risk assessment approach, and the factor of safety method are three important geological–geotechnical tools that are used to estimate potential failures and, as a result, take appropriate actions to avoid undesirable consequences regarding the safety of the proposed civil engineering mitigation measures. However, considering the concept of infrastructure resilience, all of them (e.g., Eurocode 7, risk assessment, and the factor of safety method) are associated with some disadvantages, mainly in their practical application, as outlined below [1–4]:

Eurocode 7 (EN 1997), although it attempts to be scientifically based, uses semi-empirical methods in several places that require “mechanical judgment” without clear

instructions. This can lead to different approaches to the same project by different engineers. In addition, EC7 covers basic geotechnical problems (e.g., bearing capacity, subsidence), but does not provide sufficient guidance for: (a) complex soil conditions, (b) dynamic phenomena (earthquakes, liquefaction), and (c) deep stability problems (e.g., large slopes, tunnels). Finally, EC7 does not fully incorporate the geotechnical consequences of earthquakes (e.g., liquefaction, loss of bearing capacity), which are critical in earthquake-prone regions such as Greece.

On the other hand, landslide risk assessment is critical for natural disaster management, but risk-based approaches are only appropriate for events that can be forecasted under usual threats. Furthermore, the factor of safety method, even though it is an important approach for the stability estimation in geological and geotechnical engineering, lacks the capability of considering the uncertainty of geomaterial mass, something that results in making it hard to estimate the reliability of the civil engineering landslide mitigation works [5].

Considering the above, a quantitative resilience assessment approach is necessary for addressing geological and geotechnical issues. The word “resilience” was introduced to the engineering world more than twenty years ago for research in the field of earthquakes [6]. To the author’s knowledge and according to findings from other researchers, research on the resilience of the geotechnical field is lacking [7–10]. Furthermore, a quantitative resilience assessment for geotechnical engineering issues is missing [8]. Thus, to implement the concept of resilience into practical applications in geological and geotechnical engineering, a particular framework is necessary. To this end, this approach can be achieved by presenting characteristic metrics and indicators to understand the resilience of geotechnical assets. Thus, the concept of engineering resilience is going to be presented through the implementation of technical works taking place on a provincial road in the Region of Attica in Greece, where many slope failures and subsidence, historically, have occurred over the last twenty years and pose a threat to the transportation functionality of the broader area.

The case study is focused on Dekeleias Street (named Provincial Road 3, under the jurisdiction of the Region of Attica, very close to the National Motorway from Athens to Thessaloniki, adjacent to the Chelidonous Stream, which is a tributary of the Kifisos River, one of the most significant rivers in the Attica Region), where failures have occurred on the road surface. In the examined area, over the last two decades (e.g., 2005–2022), slope failures, subsidence, and undermining have taken place at the boundaries of the road and the banks of the stream. These failures can be attributed to surface erosion because of inadequate drainage of rainwater and to wider instability of the adjacent slopes due to the erosive action of the stream (Figures 1 and 2).

The idea of facing those failures was based on establishing a solid understanding of what contributes to the under-examination of road disaster resilience and how it can be measured. In the context of roadway rehabilitation, the Directorate of Technical Works (Central Section) of the Regional Authority of Attica conducted geotechnical site investigations as well as stability and rehabilitation studies of the roadway.

As part of the roadway rehabilitation, including investigating the stability of the slopes of the sections of the road in question, topographic survey, geotechnical survey, geotechnical study, study of the stability of the roadway, study of the stabilization and rehabilitation, and traffic study were authorized by the Directorate of Technical Works of the Region of Attica.

In the present study, the hazard of the existing condition of the stream slopes and their adjacent District Road 3 is confirmed using the Rock Engineering System methodology. The specific methodology is presented, and the slope failure parameters that contribute to the instability of the study area are briefly described. Its application led to the calculation

of the slope instability index, which confirms the results obtained from the execution of the geotechnical investigation and study carried out, leading to specific types of technical road support works.

To address the erosive mechanisms, after the appropriate geological and geotechnical study, it was decided that the construction methodology described was the best technical solution to the geotechnical problem of the area examined due to the weak geotechnical profile of the geological formations (e.g., Neogene deposits) situated in the Dekeleias Road. Thus, to prevent soil erosion between the reinforced piles on the outer side of the retaining structure, it was proposed to construct pile walls made of intersecting piles of different diameters and walls on piles anchored with a passive deadman-type anchoring system, given the significant resistance heights achieved [11].

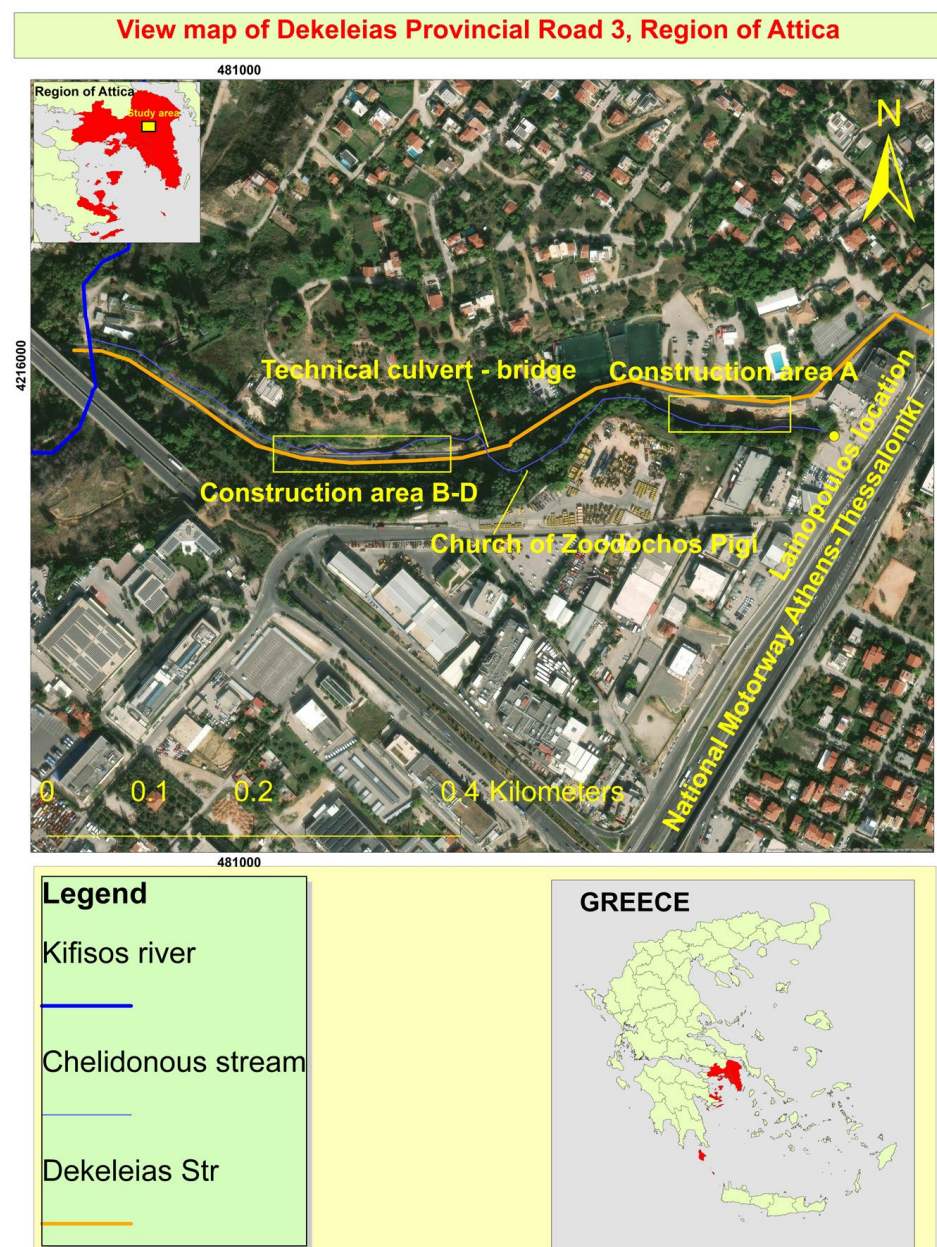


Figure 1. Excerpt from Google Earth (© Google Earth), showing Dekeleias Road (orange line), Chelidonous Stream (thin blue line), Kifisos River (heavy blue line), and the areas under site investigation, design, and construction. This place is located in the northern (Kifissia municipality) part of the Athens capital city of Greece, adjacent to the National Motorway from Athens to Thessaloniki [12].



Figure 2. View from one characteristic slope failure (fall) of the examined road (Author's archive).

Considering Figure 1, the route of Dekeleias Str. is parallel to Chelidonous Stream and at places very close to the street. Under the geomechanical weakness of the geomaterial that constitutes the underground strata (e.g., Neogene deposits), the rainfall episodes that have occurred the previous years, which resulted in the local soil instabilities, the erosion, subsidence and fall part of the examined road, the undermining of the base of the stream slopes, the absence of any civil engineering mitigation measure between the road and the stream and also due to the failure of managing the surface and subsurface water of both the road and the stream, contributed to the slope failure issues.

Based on the above, this paper aims to discuss approaches that improve the understanding of engineering resilience to landslide mitigation measures, as well as to propose tools that aim to estimate disaster resilience.

Thus, the structure of the paper is as follows: firstly, a description of the geology and geomorphology of the area of interest, as well as the presentation of the geological–geotechnical study and construction works, is briefly provided. Secondly, in the Materials and Methods section, the terms of the Driver-Pressure-State-Impact-Response framework that is associated with engineering resilience are presented. In addition, the Rock Engineering System semi-quantitative methodology is described with the intention to prove the pre-existing potential slope failure of the examined road, by estimating the landslide instability index through a matrix. In the Results and Discussion sections, those terms of resilience are integrated with the steps of the design and construction process of the project, and an alternative expression of the above-mentioned matrix is used to apply resilience. Finally, the paper ends with the Conclusions.

2. Geological and Geotechnical Setting of the Study Area

The study area is in the western foothills of the Penteli Mountain, specifically east of the Kifisos River and adjacent to the Chelidonous Stream (Figure 3). The morphological topography of the area is characterized by a gentle, flat terrain with very gentle slopes. The wider area geologically consists of Neogene and Upper Miocene formations. The road section under study runs through the Kifisos Lake formations, according to the geological map of EAGME (e.g., the Greek Geological Research Institute), and more specifically from the geological sheet of Kifissia (1:50,000 scale).

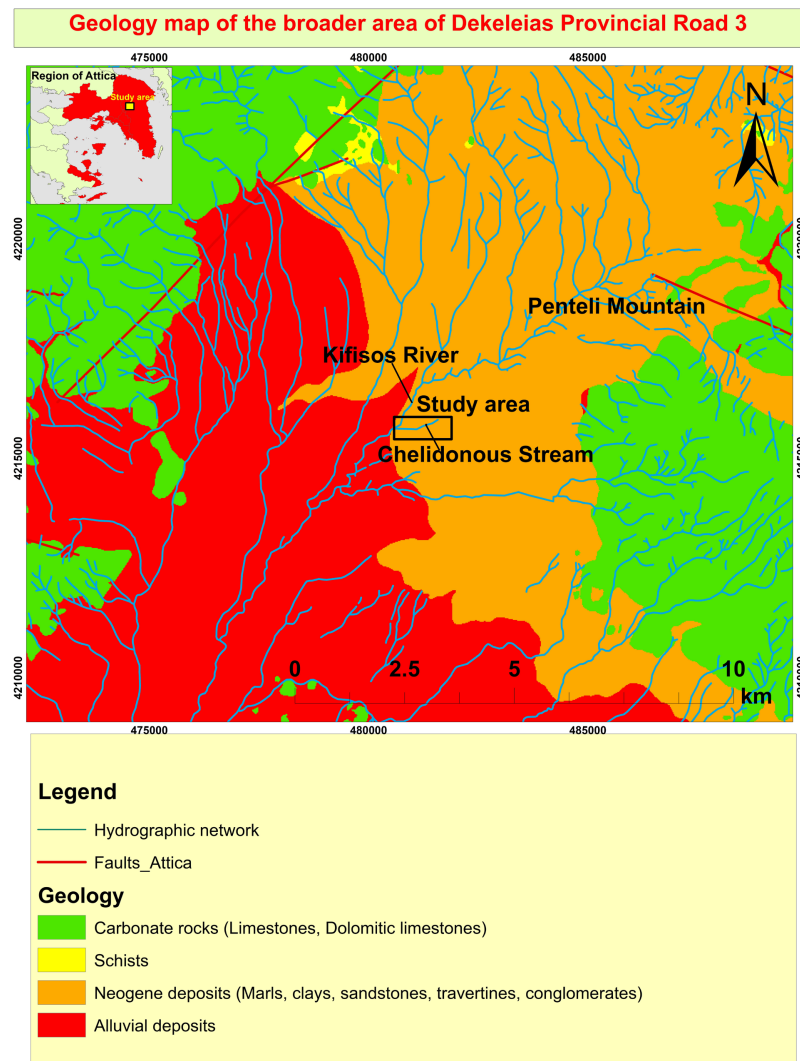


Figure 3. Geological map [modified from the geological sheet of Kifissia (1:50,000 scale)] of the broader area of Dekeleias Provincial Road 3. The examined area is indicated by the black rectangle [13].

To investigate the nature of the formations along the failures of the problematic section of Dekeleias Road, four sample boreholes with a total depth of 65 m were drilled, and field and laboratory tests were carried out. The field work took place in March 2018 (Figure 4a,b).



(a)



(b)

Figure 4. (a) Borehole drilling, (b) part of the borehole findings (sand to clayey geomaterial) is depicted [11].

3. Evaluation of Geotechnical Investigations

Considering the results of the geotechnical investigation, the field and laboratory tests, and all available data, the following sections with uniform geotechnical characteristics were distinguished [11]: (a) modern artificial embankments, (b) alluvial deposits, and (c) lake and pond formations. An aquifer level was detected in all the executed boreholes. In two boreholes, the water level corresponded with the bed of the Chelidonous Stream, which passes a short distance away. In the other two boreholes, the phenomenon of artesianism occurred. Based on the evaluation of the above-mentioned formations, geotechnical measures were proposed for design parameters, range, and characteristic value for each of them, and geotechnical simulations were prepared for the areas under consideration. After evaluating the findings of the geotechnical investigation and considering the geometrical characteristics of the areas in which the geotechnical problems were identified, the study areas were divided into subareas such as A–D (Figure 1). The division of the areas also considered the morphology of the road slopes, the geological and geotechnical conditions, the distance of the road from the Chelidonous Stream, and the failure mechanisms evaluated per area.

4. Geotechnical Study—Description of the Constructed Technical Works

The proposed solution is an example of targeted resilience strengthening investment and action. To address the erosive mechanisms, it was proposed to construct pile walls made of intersecting piles of different diameters and walls on piles anchored with a passive deadman-type anchoring system, due to the significant resistance heights obtained [11]. To avoid soil erosion between the reinforced piles on the outer side of the retaining project, unreinforced piles are provided between them that reach a depth greater than that of the existing stream bed [14]. Area A was examined separately from the other three areas, B, C, and D, as it is located at a great distance from them and was divided into subareas A1, A2, and A3 to consider the variations in the morphological characteristics of the road slopes and failure mechanisms. Analyses of the internal failure or excessive deformation of the structure (STR) and failure or excessive deformation in the ground (GEO type limit states according to EN 1997-1) were carried out on critical control cross-sections covering the most adverse conditions per study area. The results showed that the lower limits of the safety factors defined by the relevant regulations are covered [11]. The selected solutions are summarized as follows.

4.1. Area A

In Area A, the main contributing factor to the failure mechanism is estimated to be, based on the failure morphology, the flow of the stream as the stream bed approaches the roadway slope (Figure 1). Area A was divided into three subareas (A1, A2, A3). Subarea A1 starts after the turn from the Athens Lamia Highway (Lainopoulos location) and extends 8.50 m to the west. To address the erosion mechanisms in subarea A1, it was decided to construct a pile wall with interlocking piles 1.00 m, with the reinforced piles having an axial spacing of 1.7 m. Subarea A2 starts from the end of area A1 and extends 32.90 m to the west. In this area, significant undermining has occurred on the existing road, with the crown of the existing steep slopes bound within the road zone. To address the erosion mechanisms, anchor walls 3.0 m and 5.5 m high were constructed, found on interlocking piles of 1.00 m diameter at 1.7 m intervals. In this section, the retaining elements (piles, retaining walls) needed to be anchored. Subarea A3 starts from the end of area A2 and extends 5.10 m towards the west. To address the erosive mechanisms in area A3, it was decided to construct a pile wall with intersecting 1.00 m piles, with the reinforced piles having an axial spacing of 1.7 m (Figure 5a,b).



Figure 5. Views from Area A construction: (a) cutter bar machine, (b) pile walls made of intersecting piles (Author's archive).

4.2. Areas B, C, D

The main factor causing the failure mechanism in areas B to D is the flow of the Chelidonous Stream, which causes erosion at the foot of the road slopes (Figure 1). The erosion of the foot and the gradual change in slope gradient to steeper gradients cause generalized slope stability problems affecting the existing Dekeleias Road in the form of soil movement and subsidence of the roadway on the stream side. It should be noted that in areas where the stream, due to its natural flow, is near the Dekeleias Road, such as in areas B and D, the foot of the road slope is also the boundary of the streambed, and as a result, the instability problems were more pronounced. In area C, the stream moved away, and the erosion problems appeared milder [11].

A significant contribution to the occurrence of failures was also made by surface stormwater runoff, which was uncontrolled through the natural slope of the road due to the absence of a drainage system. In addition, the underground aquifer, which in some places took the form of artesianization, had an adverse effect on the overall stability of the slopes. Based on the above, area B was divided into two (2) subareas, B1 and B2, and area D was divided into five (5) subareas, D1 to D5, to consider the variations in the morphological characteristics of the road slopes and the failure mechanisms.

Area C was treated as an area with uniform morphological and geotechnical characteristics. Subarea B1 started after the technical culvert, which was constructed after the church Zoodochos Pigi, to drain the stream water under Dekeleias Street from upstream to downstream and extends for 10.10 m to the west. The failures on the roadway in this area were due to the erosion of the slopes caused by the flow of water exiting the culvert, as well as the failure to manage the surface runoff of stormwater. Rainwater collected on the upstream side of the road through the culvert flowed uncontrolled through the culvert into the bed of the natural stream, causing erosion of the existing adjacent slopes. In addition, the uncontrolled surface flow of rainwater on the road caused localized undermining of the road. (Figure 2). To address the erosive mechanisms in subarea B1, a pile wall was constructed with interlocking 1.20 m piles, with the reinforced piles having an axial spacing of 2.0 m. Subarea B2 started from the end of area B1 and extended 24.20 m to the west. In this area, the main contributors to the failure mechanism were estimated to be stream flow and groundwater, while surface water flow appeared to have little or no contribution based on the morphology of failures. As a result, localized soil instabilities and subsidence

occurred in Area B2, affecting the existing Dekeleias Road, but on a smaller scale than the adjacent Area B1. To address the erosive mechanisms in subarea B2, a pile wall with 1.00 m piles was constructed at an axial spacing of 1.7 m.

Area C started from the end of area B2 and extended 28.20 m to the west. In area C, it was estimated that the road slopes were in a state of limit equilibrium. The main factor contributing to their destabilization mechanism was estimated to be the erosive action of the stream. The local soil instabilities and subsidence that occurred immediately were small in scale due to the removal of the natural flow of the stream from the road slope, but works were needed to contain the erosive mechanisms to protect the road from future larger-scale failures. To address the erosive mechanisms in Area C, it was decided to construct a pile wall with 1.00 m piles at an axial spacing of 2.3 m.

Area D is divided into five (5) subareas, D1 to D5, as mentioned above, starting from the end of Area C and extending approximately 87.00 m in length to the west, numbered sequentially.

In subareas D1 to D5, the main contributing factor to the failure mechanism was estimated to be the flow of the stream as the stream bed approached the road slope. As a result of this action, localized soil instabilities and subsidence occur in areas D1 and D5 in the lower portion of the roadway slope, affecting the existing Dekeleias Road. Similarly, in areas D2, D3, and D4, local soil instabilities and subsidence occurred, which affected not only the lower part of the slope but also the upper part of the slope in contact with the existing Dekeleias Road. To address the erosive mechanisms in areas D1 to D5, interlocking piles 1.00 m and 1.20 m were constructed with reinforced piles having axial spacings of 1.7 m and 2.0 m, respectively. In subareas D2, D3, and D4, retaining walls of 1.5 m to 3.0 m high founded on the interlocking piles are also planned. It should be noted that in all areas and subareas, the project was decided upon, and then the diameter of the piles and their axial spacing were calculated.

The accuracy of the geotechnical data was confirmed by the following actions [14]:

- Validation of the pre-existing available information (e.g., bibliography) via the execution of ground investigation (e.g., four boreholes of 15 m depth, carrying out sampling, drilling, and field testing, as well as carrying out laboratory tests).
- According to the provisions of EN1997-1, the geotechnical study, followed the process of selecting characteristic geotechnical values from field and/or laboratory testing to determine representative design parameters (and as a result to confirm the accuracy of geotechnical data), which was: (1) determining the means and standard deviations of the parameter values, and (2) selecting the characteristic value as a conservative estimate of the value that affects the probability of occurrence of boundary conditions based on all relevant, supplemental information.
- Based on the above, according to EN1997-1, the requirements that are necessary for the supporting of the retaining works [e.g., all types of walls and supporting systems (without or with anchors, etc.) on the structural elements of which forces (earth thrusts, hydrostatic and dynamic forces) are applied and relate to conventional, gravity and/or flexible footing walls], should be tested for the following failure limit states:
 - a. Inspection of loss of total stability (GEO).
 - b. Inspection of the failure of a structural element (STR).
 - c. Combined failure of soil and soil element. Proficiency check (GEO), regarding the depth of embedment of flexible walls, anchorage forces, etc.
 - d. Inspection of hydraulic lift failure (UPL).
 - e. Check wall movement and in serviceability conditions (SLS).
 - f. For conventional walls—gravity walls, the limiting states of surface foundations should be considered, which are: (a) failure due to exceeding the bearing

resistance (capacity) of the soil, (b) failure due to slide at the base of the wall and (c) failure due to overturning of the wall.

The geotechnical study was completed in January 2019, whereas the stabilization work started in September 2020 and was completed in September 2023. In Figure 6a–g, characteristic views from the construction phase of areas B to D are depicted.



Figure 6. (a–g) Different successive steps of pile wall construction of Areas B to D (Author’s archive). In Figure (e), a view from the drainage system (for lowering the potential pore water pressures and accomplishing adaptation to possible disruption from heavy rainfall episodes) is depicted. Figure (g) is associated with the accomplishment—end of the technical works in September 2023 in the examined segment of the road (Author’s archive).

The above-mentioned mitigation measures (piles, drainage systems, retaining walls) have been implemented in similar geotechnical environments in the Region of Attica (unpublished technical reports) and internationally [15].

In the following section, the above-described construction phase will be integrated into an engineering resilience framework.

5. Materials and Methods

The term “resilience” originated from the Latin word “resiliere” [5], while Holling [16] expressed that resilience is the measure of the persistence of systems and of their ability to absorb change and disturbance.

Regarding disasters, the term was first discussed among national governments in 2005 with the adoption of the Hyogo Framework for Action to ensure that reducing risks to disasters and building resilience to disasters became priorities for governments. Disaster resilience has been described as a process, an outcome, or both, and as a term that can embrace inputs from engineering and the physical, social, and economic sciences [17].

In the field of civil engineering projects, resilience is the ability of a system to withstand disruptions and continue to function by rapidly recovering from and adapting to the disruptions [18]. The necessity of integrating resilience into infrastructure is getting more urgent nowadays since the frequency of natural hazards increases [7]. In the following, the concept of resilience will be developed through the description of the process of the design and implementation of the civil engineering works of the selected case study.

5.1. Engineering Resilience

The meaning of resilience in civil engineering projects is associated with the preparedness and response of a system against catastrophic events. Preparedness is basically related to the ability to proactively mitigate the effects of disastrous events by providing adequate resources and designing strategies before the disruption [7].

The term “response” includes the meanings of “absorption” and “recovery”, where they both are expected after the event of disruption [19,20]. Absorption is the immediate response of an infrastructure system in which the system withstands the disruption, and recovery is the organizational efforts to rapidly repair the damaged system and the consequential effects propagated to other systems [7]. The above-mentioned terminology can be depicted through a graphical curve that illustrates how an engineering system’s performance changes over time, considering a disruptive episode [21].

To be more specific, absorption of shocks is reflected by the degradation of system functionality in the event of disruption. The recovery efforts can be initiated immediately after the disruption; however, the system functionality can be unchanged for a certain period until adequate resources are collected, and response strategies are organized (this is the assessment stage). Finally, it is expected that the system’s functionality will recover to an acceptable level for normal operation.

An alternative scheme of the resilience framework in the transportation network, such as in our case study, can be provided by diagrams that depict the metrics of the reduced level of service and the time required to restore that service [22].

Bruneau et al. [23] further described the meaning of resilience by defining four properties: robustness, rapidity, resourcefulness, and redundancy. Robustness is the ability of technical works to resist the impact of hazard events, such as landslides, floods, etc. Rapidity is associated with how quickly the infrastructure recovers after an event, which depends on the available resources and the damage level [9]. Resourcefulness is the capacity to identify problems, establish priorities, and mobilize resources (i.e., monetary, physical, technological, and informational resources). During the assessment stage t_a to t_r , resource-

fulness can contribute to lessening the time of assessment. Furthermore, resourcefulness can contribute to developing mitigation measures for disaster prevention and contribute to the recovery process [7]. For example, sufficient monetary and informational resources reduce the time in identifying damages or vulnerability of the system. Redundancy indicates the extent to which existing elements or systems are substitutable.

Redundancy and resourcefulness are the means to improve the resilience of an infrastructure. For example, the resilience of a road network (as it is for the examined case study) can be improved by ensuring that alternative routes can be used [24], during the restoration of deteriorated components [9].

The same researcher [23] further categorized resilience within the engineering discipline into different dimensions, such as technical, organizational, environmental [7], social, and economic. The technical dimension includes all the technological issues related to the construction [25]; the organization dimension includes all the management activities and response to emergencies [25]; the environmental dimension is associated with the influence of the constructed technical works on the surrounding environment (slopes, stream, fauna and flora) and the increased carbon dioxide emissions due to the prolonged time travel after the slope failures and the subsequent closure of the road; the social dimension considers the impacts of failure of infrastructure system to social groups; and the economic dimension refers to economic losses, both direct and indirect, because of the occurrence of the disaster, as well as the subsequent rehabilitation [25]. Based on the above, a resilient system should be characterized by the following [8]: reduced failure probabilities, reduced consequences from failures, and reduced time to recovery.

5.2. DPSIR Framework

The DPSIR (Driver-Pressure-State-Impact-Response) framework has been used as a resilience assessment framework implemented for geotechnical infrastructure.

“Drivers” and “pressures” describe the hazard scenarios applied to a civil engineering project. For example, slopes and bridge foundations (as in the examined case study) are crucial factors in transportation networks. Therefore, the drivers affect the users’ travel behavior and business logistics [7].

As a result, the driving forces result in pressures, which can be identified as the effect of climate change or funding constraints.

“States” include the robustness, rapidity, resourcefulness, and redundancy of the examined infrastructure [7]. The states indicate the metrics that represent the resilience of a civil engineering project. An example of this will be presented in the following section by quantifying the resilience through a matrix table and an index.

The technical, economic, organizational, environmental, and social effects can be described by the impacts [26]. Lastly, disaster management and decision-making are associated with the term ‘response’ [7], which will be described by mentioning the series of civil engineering construction and bureaucratic procedure steps that are needed for the restoration of the damaged road segment.

The above-mentioned terms will be integrated into the description of Provincial Road 3’s restoration.

5.3. A Semi-Quantitative Methodology [Rock Engineering System (RES)]

To quantify the response of the geotechnical environment in terms of its limit states as well as to confirm the hazard of the geological–geotechnical condition of the slopes of the study area before the restoration technical works, the Rock Engineering System (RES) methodology was used [27].

RES was developed in the early 1990s as a semi-quantitative technique to approach increasingly complex problems in rock mechanics [27]. Semi-quantitative coding is important, particularly when mechanisms cannot be quantified and there is a need to assess their importance. The matrix concept has its roots in the 1970s, when it was used to assess the cause-and-effect relationship between existing (environmental/physical) factors and human activities. Since then, it has been modified and applied to rock stability problems, landslide hazard and risk analysis, and rock engineering [13]. The basic idea of RES is first to define the scope of the geological–geotechnical problem, and then to construct a table (e.g., interaction matrix), in which the most important parameters related to the specific problem, as well as their interactions, will be contained.

The method proposes an appropriate coding of the matrix so that it can be determined how important each parameter is to the system. Furthermore, RES is characterized by parameters that belong to the cause-and-effect domains. Cause is the effect of the parameter on the system, while effect is the system's effect on the parameter. This method is used to quantify qualitative or subjective observations concerning a geotechnical engineering problem. Especially on most natural slopes, the analysis is complicated by a lack of data, geological complexity, scale of instability phenomena, and many interaction parameters. To address this complexity in a structured manner, an in-depth method based on the RES methodology has been adopted [27].

The basic principle of the matrix is to place the main parameters of a system along a diagonal and study the interactions of these parameters outside the main diagonal (Figure 7). For example, if we consider an interaction matrix that is based on two main parameters, then a 2×2 matrix is created where in the main diagonal, the first main parameter (e.g., A) is placed on the top left and the second corresponding main parameter (e.g., B) is placed on the bottom right. The interactions in the matrix correspond, on the one hand, to the effect of A on B (the top right section) and, on the other hand, to the effect of B on A (the bottom left section).

Therefore, in a 2×2 matrix, there are two main diagonal terms and two non-main diagonal terms. In a 3×3 matrix, there are three main diagonal terms and six non-main diagonal terms. In a 12×12 matrix, there are twelve main diagonal terms and one hundred and thirty-two non-main diagonal terms. In this way, all parameters can be considered, and there is no risk of ignoring the interaction of one parameter or another [27].

Another advantage of using this semi-quantitative methodology is that it allows for the use of appropriate case-by-case parameters, which can be more easily quantified than those that require time and economic costs. Additionally, the use of RES aims to determine whether there is a possibility of failure in areas where both natural and artificial slopes are present, built from a combination of rocks, soils, semi-rocks, or alternations of rocks and soils, such as schist formations [28]. In addition, this table is constructed based on calibrated parameters directly related to the landslide under consideration, which help to understand the mechanisms of interaction between them and thus contribute significantly to the effort of slope failure prediction, through the determination of an instability index. By coding the individual landslide parameters (elements) of the interaction matrix and summing the values in each row and each column for each parameter, cause (Cause) and effect (Effect) coordinates are generated, indicating the degree of interaction intensity for each parameter in the matrix. The sum of the coding values in each row and each column for each parameter generates the coordinates of the cause and of the effect.

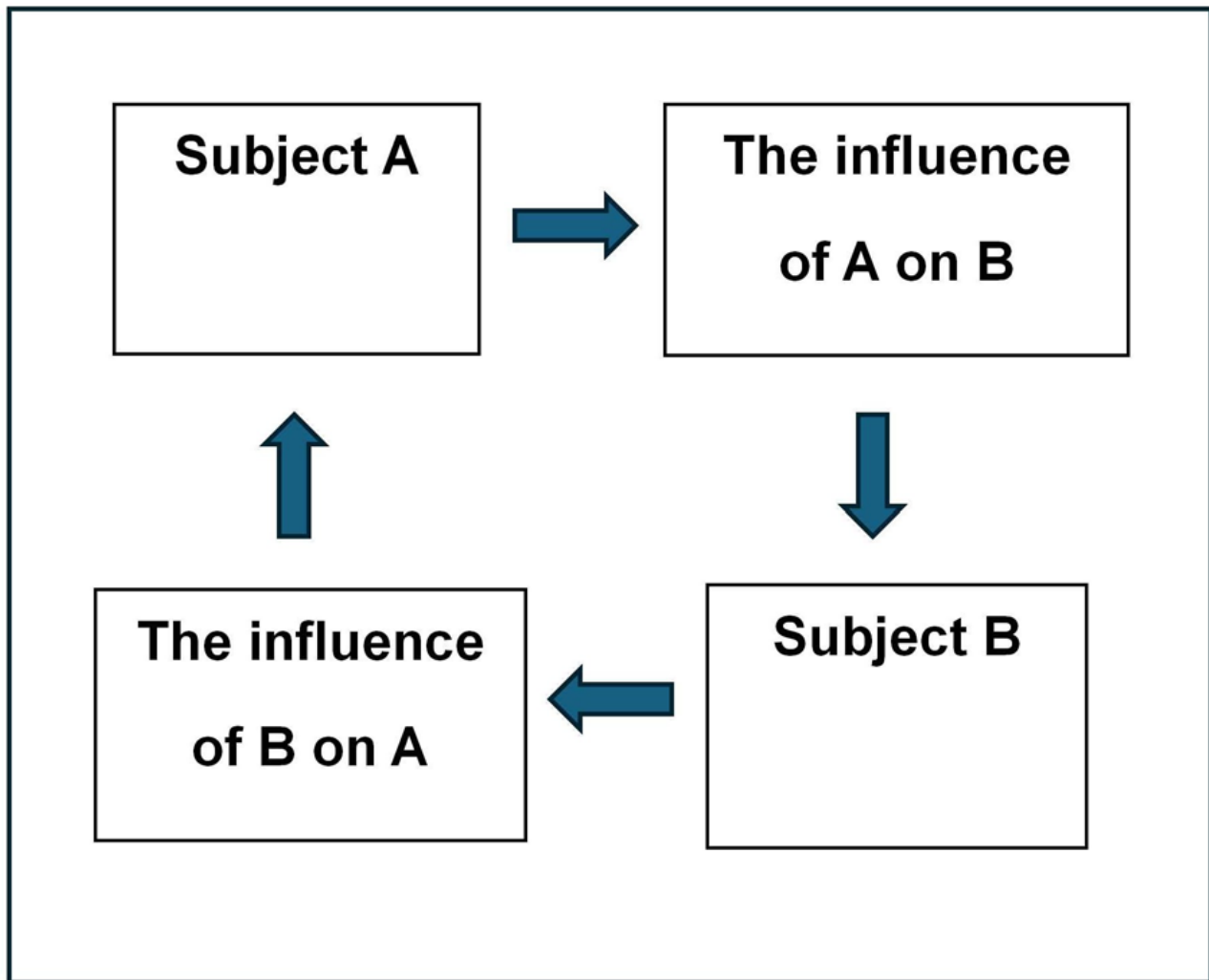


Figure 7. Basic idea of RES [27].

Figure 8 shows that the line through the parameter P_i represents the influence of that parameter on all other parameters in the system. Conversely, the column through the P_i parameter represents the influence of all other parameters on the P_i parameter.

The next step after constructing the model is to encode the outside of the main interaction diagonally to express its meaning, while also allowing for the mathematical manipulation of the matrix. There are five main methods to achieve this encoding:

- the binary (on–off or 1–0): either the mechanism is on and receives the value one (1), or the mechanism is off and receives the value zero (0),
- the semi-quantitative [(a range of possible interactivity from zero (0) to four (4) is adopted, corresponding to: (i) “none” (coded 0—most stable conditions → no interaction), (ii) “weak” interaction (coded 1), (iii) “medium” (coded 2), → moderate interaction, (iv) “strong” (coded 3) → strong interaction, (v) “critical” interactions (coded 4—most favorable condition for slope failure)],
- linear correlation,
- partial differential equation, and
- numerical analysis of the mechanism.

By far the most widely used coding is (b). The former does not lead to differentiation of parameters between them, while (c), (d), and (e) are rarely used. With (b), a greater degree of sensitivity is provided, and a calibration from zero (0) to four (4) can be determined by

one or more individuals associated with the project under consideration, preferably after a decision by a group of many individuals—experts [27].

It should be highlighted that the selected parameters are not encoded with values in the main diagonal, assuming that the parameter in question does not affect itself but is only affected through the rest of the parameters.

The degree of influence of each parameter on the system (in the case of a slope failure), which is translated by finding the weighting factor, is identified by the cause (Cause or C)—effect (Effect or E) diagram. The sum of C and E values is converted into a percentage that plays the role of the weighting factor, i.e., expressing the percentage of participation of each parameter in the failure of a slope and is normalized by dividing it by the maximum of the calibration, which is the value (4) “four” [29].

For the construction of the above-mentioned RES matrix, a number of particular landslide parameters are needed. In such a case, many research studies co-evaluate the following findings and provide observations on how to select the landslide parameters [30]:

- The quality and quantity of data available.
- The functionality of the parameter. This characteristic derives from the “affinity” of the parameter with the occurrence of failures.
- The spatial continuity of each parameter. This criterion is particularly important since it attempts to clarify the effect of each parameter on the occurrence of failures on the area scale. In addition, the local geological–geomechanical characteristics of a region play an important role in the choice of parameters. If a potential parameter (for example, seismic hazard or rainfall) that was to be considered is constant across the region of interest, it is appropriate not to consider it as a critical factor for zoning.
- The spatial heterogeneity of the parameter. A reliable spatial capture of any parameter requires, in addition to its spatial continuity, the required degree of heterogeneity. The correct modelling of physical parameters relies heavily on the collection of data, whose numerical values must cover the widest possible range within which each parameter ranges. If this is not achieved, then the resulting error is also transferred to the final result of the analysis.
- The measurability of each parameter, i.e., the possibility of assigning numerical values (indirectly or directly) to each parameter.
- The qualitative texture of the effect of the parameter, i.e., the ‘substantial’ effect of each parameter
- The qualitative texture of the parameter effect, i.e., the ‘substantial’ effect of each parameter on the occurrence of failures.
- The results of an independent parameter should not be double-counted in the final result.
- A parameter should represent the entire area of interest,
- The selected independent parameter should have a specific degree of preference with the dependent variable (presence or absence of slope failures).

Thus, after the selection and rating of the parameters, the construction of the matrix, the coding, and the analysis of the binary interactions between the selected parameters, what follows is the calculation of the weighting coefficient of each parameter, and finally the estimation of the instability index by using the following equation: $I_i = \sum a_i \times P_{ij}$, where i refers to parameters (from 1 to 10), j refers to the examined slope and a_i is the weighting coefficient of each parameter given by the formula: $a_i = 1/4 * [(C + E)/(\sum C + \sum E)]\%$, scaled to the maximum rating of P_{ij} (maximum value = 4). P_{ij} is the rating value assigned to the different categories of each parameter’s separation, which also fits better to the conditions related to the parameter in question regarding the examined slope failure.

The instability index is an expression of the inherent potential instability of the slope, where the maximum value of the index is 100 and refers to the most unfavorable condi-

tions. In the following section, the above-mentioned steps are analytically presented and discussed.

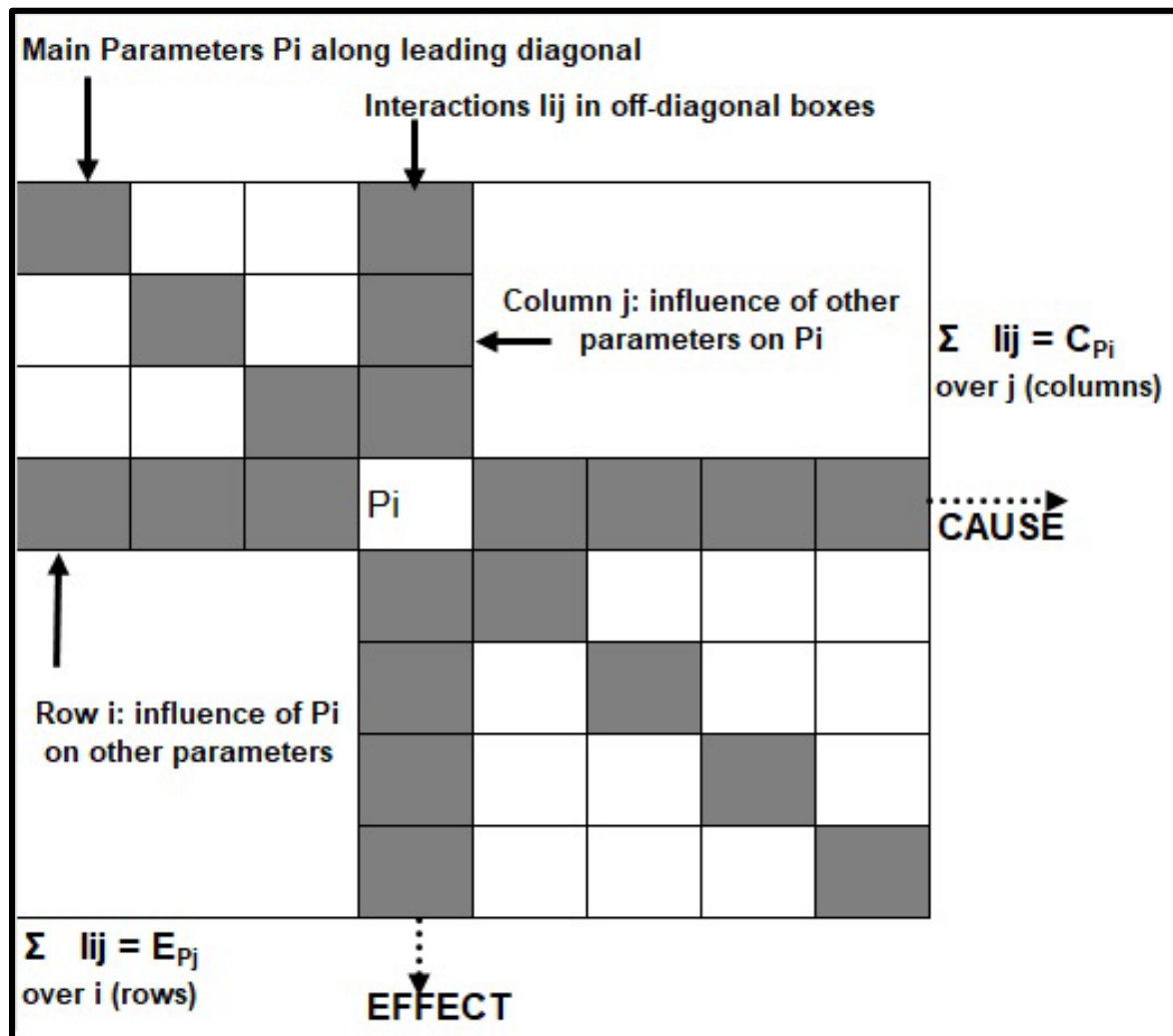


Figure 8. Interaction matrix. The working principle is explained in references [27,28].

5.3.1. Selection and Rating of Landslide Parameters

At the site considered, the RES methodology was implemented, and ten landslide parameters associated with the specific failure were selected [13,30,31]. The selection of the appropriate parameters was based on valuable knowledge from the literature, the overall experience gained from the study of landslide phenomena in Greek territory, and additionally from case studies from all over the world, as well as their affinity with landslide occurrence in the examined area. Based on the above, the selection of the specific parameters was made with a view to obtaining the most useful and reliable representation of the geological, geotechnical, hydrogeological, and environmental conditions relevant to the site-specific conditions and purpose of the project [11,14].

The rating for each selected parameter for the construction of the RES matrix was considered to be appropriate based on the investigations made mainly by Koukis and Ziourkas for the whole Greek territory during the period 1949–1991 [32]. Also, the categorization of some parameters was based on literature references from Greek researchers [29,33,34].

Ten parameters were selected as independent controlling factors for the landslide occurrence, and each factor was classified into five (5) classes. These factors, which were utilized for the RES methodology, were [30]:

1. Human activity (distance from roads): The use of the human activity parameter in the interaction matrix is implemented through the term “distance from the roads”, which indicates that the shorter the distance of the slope from a linear axis appears, the more likely it is that the slope in question will fail. The man-made and natural slopes of linear axes (e.g., local roads, national roads, motorways, railway line slopes) are more susceptible to landslides, due to the disturbance of the natural balance by digging trenches and constructing embankments, with the consequence that nature “reacts” to this failing. In the area under consideration, the distance of slopes from Provincial Road 3 (Dekeleias Road) is less than 50 m.
2. Tectonic regime: The presence of a fault zone in geological formations due to the action of tectonic forces, regardless of whether it is active or inactive, most often affects the geological structure, causing differentiation of the lithostratigraphic structure. Therefore, tectonic evolution on the one hand causes changes in the geometric elements of natural slopes (height, slope); on the other hand, it affects the secondary structure of a geological formation as well as the quality of discontinuities in combination with the processes of ongoing erosion. In the area under consideration, the tectonic regime is weak, i.e., it is associated with the near absence of significant tectonic events.
3. Slope inclination: The slope gradient is an important parameter in considering the initiation of a landslide, and in most landslide studies, it is considered the main initiating factor or triggering parameter. The progressive increase in the slope gradient of a slope can cause an increase in shear stress and, in limiting cases, fracture and movement of the masses. The change in slope gradient may be due to both the process of evolution of the earth’s relief, which is constantly changing and subject to alteration, and to human intervention. At the studied site, due to the steep depositional slope ($>45^\circ$), the parameter was calibrated with a value of 4.
4. Slope orientation: Slope orientation is influenced by solar radiation, wind, and precipitation and thus strongly influences hydrological processes through evapotranspiration. It influences processes (formation of a weathering mantle), the moisture content of the soil, vegetation, and root growth, and consequently leads to a reduction in soil strength. Based on the above, the parameter was given a value of 4 ($0\text{--}45^\circ$, $135\text{--}225^\circ$).
5. Lithology: From investigations carried out in the Greek territory, it is proven that the lithological composition and the strong variation in the lithostratigraphic structure, which results in a sequence of formations with completely different geotechnical characteristics, have a significant influence on the occurrence of landslides. At the location under consideration for the Neogene and Quaternary formations, a value of 3 is taken for this parameter.
6. Hydrogeological conditions: The presence of water is most often decisive for the final behavior (failure or not) of the geological materials on which a technical project is based. The presence of water is most often decisive for the final behavior (failure or not) of the geological materials on which a technical project is based, and this is because the action of water affects the slope in three ways:
 - contributes to the formation of loose surface geological materials, which cover the slopes in the form of the decomposed mantle,
 - causes high pore pressure in soil formations and rock mass fractures, thus increasing the weight of geological materials while contributing to the lubrication of the discontinuities, resulting in friction reduction,
 - helps to move loose materials downstream, increasing the loads in the deposition area and making it easier for erosion and weathering to occur, without any more soil mantle to cause possible failures.

In the study area, because the formations involved are alluvial deposits over a Neogene basement, the parameter “hydrogeological conditions” was calibrated with a value of 2.

7. **Rainfall (Precipitation):** Rainfall is one of the most important external factors that contributes to the occurrence of landslides and mainly triggers movement. It has been observed that during periods of increased rainfall, the frequency of landslides is high since it causes a change in pore water and increased hydrostatic pressures. In addition, weathering processes (chemical and mechanical) are triggered, along with erosion caused on a slope by surface water. In the study area, the phenomenon of failures is dynamic, and the main reason for this is the intense and prolonged rainfall that has taken place there over time (especially during the period October 2018–February 2019). For the case study, the average annual rainfall from the measuring adjacent meteorological station in Tatoi is 450 mm. Due to the above, the parameter was calibrated with a value of 1.
8. **Vegetation:** The vegetation covering an area is one of the most important external factors associated with slope stability since it is very sensitive to changes that can occur due to human activities. Plant roots tend to hold the soil together and therefore help to reduce settling and delay the instability of a slope. Consequently, the loss of vegetation cover not only alters the hydrological conditions of a slope but also causes an increase in pore water pressure resulting in a significant increase in the vulnerability of the soil to erosive processes, altering the physical and chemical properties of the soil, as well as the removal of the soil cover, leading to an increase in the likelihood of slides and soil flows. These events are accelerated during the wet season that follows. Considering the standard criteria used by the Greek Ministry of Rural Development to evaluate different sites and field observations, the category “moderate vegetation” characterizes the examined area with a score of 2.
9. **Distance from streams:** Research has shown a close spatial relationship between the occurrence of landslides and the presence of streams. One of the causes of potential changes in the geometry of a stream slope is the erosion that the stream contributes to removing the support of the adjacent slope. This removal is one of the most common factors in causing landslides. The rate of lateral erosion of a stream is related to its depth, the erodibility of its geologic material, and the velocity of its flow. However, the proximity of the slopes to the stream beds also contributes to the degradation of the geomechanical characteristics of the geological materials that make up the slopes. It has been found that as the distance from streams increases, the frequency of landslides generally decreases. In the study area, the distance of the slope from the stream is almost negligible (less than 50 m) and is therefore rated with a maximum value of 4 (critical interaction).
10. **Distance from tectonic features:** The parameter “distance from tectonic features” is particularly critical in the construction and interpretation of the interaction register, and this is because it is directly related to the tectonic evolution that shapes the secondary structure of a geological formation and the quality of the rock mass discontinuities. It is generally known that the presence of a fault zone due to the action of tectonic forces from a geomechanically point of view: (a) drastically reduces the cohesion of the rock in a zone along the fault and (b) affects the hydrogeological regime of the wider area either by increasing the permeability in the aforementioned zone and creating a selective groundwater drainage axis or by decreasing the permeability, which leads to an influence on the geomechanically behavior of the formations affected by the aforementioned fault elements. The study area is located approximately 3–4 km east of the nearest active fault [6]. Therefore, it does not directly affect the study area (rating: 0). The rating and interpretation of the selected parameters (Table 1) were

carried out based on the technical–geological data of the slopes of the study area, considering data from research on landslides in Greece [13,30,31]. In Table 1, the selected parameters are presented, along with their ratings that represent the local geological and geotechnical conditions of the study area.

Table 1. The selected parameters and their rating.

Parameters	Rating	Parameters	Rating
1. Distance from roads		6. Hydrogeological conditions	
Distant (>200 m)	0	No geomechanical action of water	0
Moderately distant (151–200 m)	1	Fractured formations characterized by almost zero to low permeability (Flysch, schists)	1
Immediate (101–150 m)	2	Alluvial deposits, carbonate formations of low to moderate permeability	2
Less immediate (51–100 m)	3	Debris of moderate permeability	3
Close (0–50 m)	4	Medium to high permeability Carbonate formations	4
2. Tectonic regime		7. Precipitation	
Weak: associated with the near absence of significant tectonic events	0	<400 mm	0
Medium: associated with the presence of scaling, fissuring and splitting	1	400–600 mm	1
Strong: associated with the presence of folds, cracks and discontinuities.	2	600–1000 mm	2
Very strong: linked with the presence of fragmented zones	3	>1400 mm	3
Intense: represents up thrusts and over thrusts	4	1000–1400 mm	4
3. Slope's inclination		8. Vegetation	
0–5°	0	No vegetation (Urban area)	0
6–15°	1	Zero vegetation	1
16–30°	2	Moderate vegetation	2
31–45°	3	Agricultural cultivation	3
>45°	4	Intensive farming	4
4. Slope's orientation (aspect)		9. Distance from streams	
225–275°	0	Distant (>200 m)	0
45–90°	1	Moderately distant (151–200 m)	1
90–135°, 275–315°	2	Nearby (101–150 m)	2
315–0°	3	Very close (51–100 m)	3
0–45°, 135–225°	4	Direct (0–50 m)	4
5. Lithology		10. Distance from tectonic elements	
Volcanic rocks	0	Distant (>200 m)	0
Cherts, schists, limestone, marbles	1	Moderately distant (151–200 m)	1
Metamorphic rocks	2	Nearby (101–150 m)	2
Old disturbed landslide geological materials/Neogene	3	Very close (51–100 m)	3
Flysch	4	Direct (0–50 m)	4

5.3.2. Construction of the RES Matrix—Calculation of the Landslide Instability Index

According to the methodology analyzed in Section 5.3, the construction of the RES matrix, the estimation of weighted coefficients, and the calculation of the instability index are presented (Table 2). Regarding the way the matrix has been constructed, a characteristic indicative interaction among the selected landslide parameters in Table 2 is described (by assigning the appropriate coding value) in detail below. For example, the tectonic regime of the case study area has a critical influence on lithology, as represented by the value 4.

On the contrary, concerning the influence of lithology on tectonic regime, there is a weak interaction (rating equal to 1). For a better understanding of the interactions between the selected parameters, the reader is advised to read the following references [13,28,30].

Table 2. Modified Rock Engineering System (RES) approach of the examined Dekeleias Road.

Interaction Matrix												
P1	0	2	1	0	3	0	2	4	0	12	(Cause—C)	
0	P2	4	4	4	4	0	0	4	4	24		
4	0	P3	2	0	2	0	1	2	0	11		
4	0	2	P4	0	1	0	4	2	1	14		
4	1	4	1	P5	4	0	4	2	0	20		
4	1	2	1	2	P6	0	3	2	1	16		
4	0	3	0	2	4	P7	4	2	0	19		
0	0	2	0	2	1	0	P8	2	0	7		
4	0	2	0	1	4	0	2	P9	1	14		
0	1	3	1	2	4	0	0	3	P10	14		
24	3	24	10	13	27	0	20	23	7	ΣC	151	
(Effect—E)										ΣE	151	
Parameters C		E	C + E		[(C + E)/Σ(C + E)] * 100%			Maximum rating		Weighted coefficient (ai)		
P1	12	24	36		11.92			4		2.98		
P2	24	3	27		8.94			4		2.24		
P3	11	24	35		11.59			4		2.90		
P4	14	10	24		7.95			4		1.99		
P5	20	13	33		10.93			4		2.73		
P6	16	27	43		14.24			4		3.56		
P7	19	0	19		6.29			4		1.57		
P8	7	20	27		8.94			4		2.24		
P9	14	23	37		12.25			4		3.06		
P10	14	7	21		6.95			4		1.74		
Σ (C + E)			302									
Calculation of Instability Index												
Parameters		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Instability Index
E.O.3 Dekeleias road 3		4	0	4	4	3	2	1	2	4	0	65.07
Maximum rating		4	4	4	4	4	4	4	4	4	4	
[(C + E)/Σ (C + E)] * 100%		11.92	8.94	11.59	7.95	10.93	14.24	6.29	8.94	12.25	6.95	100.00
Weighted coefficient (ai)		2.98	2.24	2.90	1.99	2.73	3.56	1.57	2.24	3.06	1.74	

Based on the geological and geotechnical data of the specific study area, the existing information was decoded (quantified), and through the RES methodology, the instability index was calculated and found to be equal to $I = 65.07$. The instability index in this study is related to the categorization of landslide susceptibility proposed by Brabb [24], specifically, to the average of the percentage of the area under failure to the total area of interest through lithological or geological units (Table 3). Internationally, there is no accepted classification system for spatial and spatio-temporal maps of landslide events. A common standard would be extremely valuable for comparing maps and categorizing landslide areas at all latitudes and longitudes of the Earth, as is the case, for example, with the categorization of seismic areas [35]. A simple categorization of landslide susceptibility is the average of the percentage of the area at failure to the total area of interest, through lithological or geological units, such as the one proposed by Brabb et al. (1972) [36] with the term “Relative Susceptibility Numbers (RSN). This categorization has been used as the basis for the present study and is as follows (Table 3):

Table 3. Classification for relative landslide susceptibility proposed by Brabb et al. [36]—Correlation with instability index.

% Failed Area	0–1	2–8	9–25	26–42	43–53	54–70	100
Relative Susceptibility	I	II	III	IV	V	VI	L
	Negligible	Low	Middle	High	Very high	Extremely high	Landslide

The purpose of using the above table is to assist the specialist (designer, researcher) after finding the instability index through RES, to place the area under consideration in one of the above categories of landslide susceptibility. The interest is focused especially on the last two categories “Very high relative susceptibility (54–70%)” and “Landslide (100%)”, which indicate that if the instability index of an area under consideration is within the zone of either one or the other category, then the area under study is at risk of failure, and, as the percentage of the failure area increases, the closer it is to the landslide event.

Regarding the validation of the estimated landslide instability index, through the RES approach, the appropriate steps were the following:

1. There were many technical site visits during the 2015–2018 period, executed by the Directorate of Technical Works of the Region of Attica, where the in situ landslide susceptibility was confirmed due to falls, subsidence, and erosion of the area between the road and its adjacent stream,
2. the implementation of a landslide susceptibility map for the entire Region of Attica, the creation of which was accomplished via a research project briefly entitled “DIAS” [13]. Specifically, the calculated landslide instability index for the study area achieved a consistent coincidence with the zone of “Very high slope susceptibility” of the following map (Figure 9). The readers are kindly requested to read how this landslide susceptibility map was generated [13]. Furthermore, the practical evaluation of the RES methodology in case studies of different geological formations, areas—sites and geotechnical–geological conditions that have taken place during the last thirty-five years internationally [27–31,33,37–40], verifies its usefulness as a time-saving and economical tool for the calculation of the instability index.

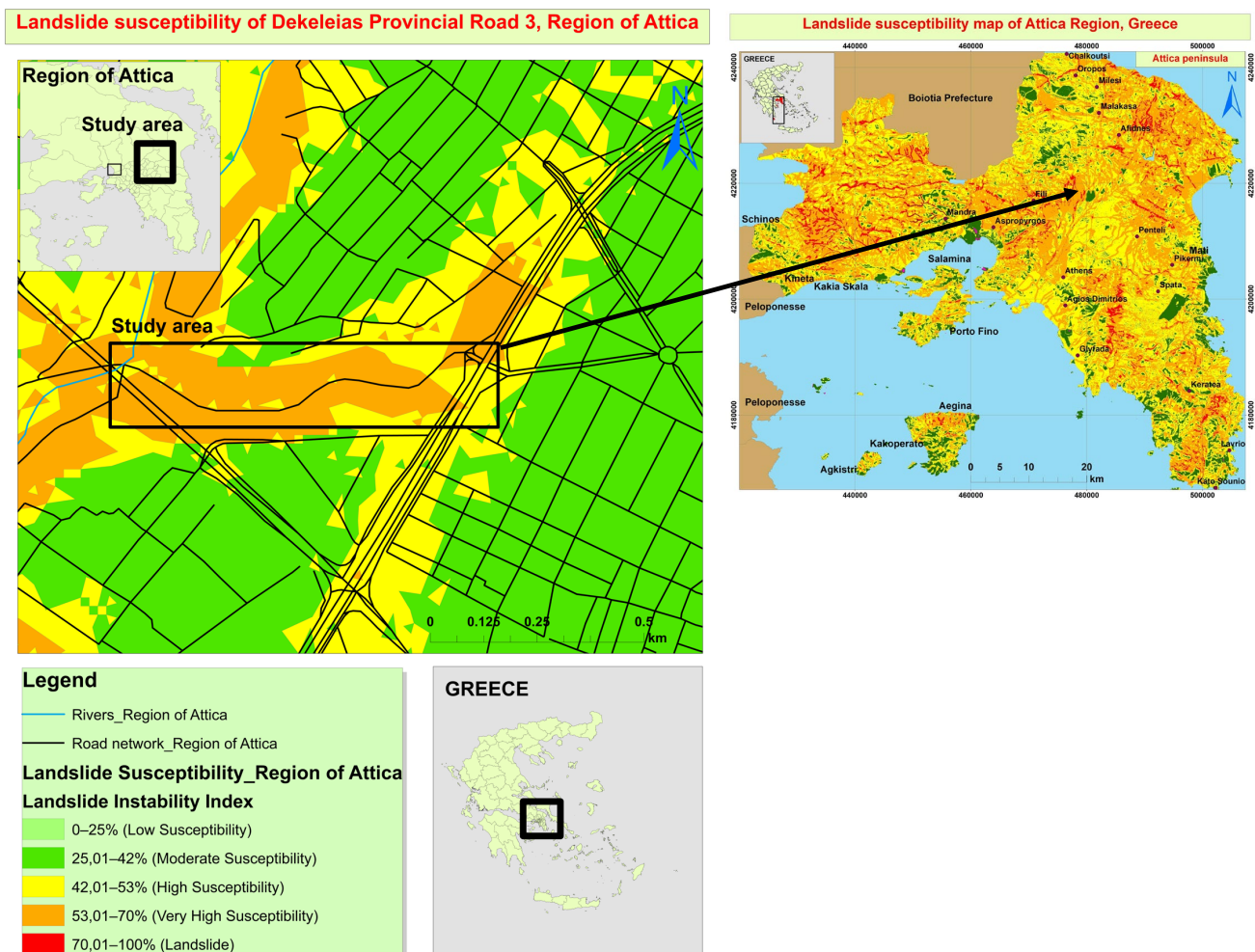


Figure 9. On the left, the landslide susceptibility (scale: 1:4000) of the examined area is presented, where Dekeleias Provincial Road 3 (particularly the landslide susceptibility within the rectangular shape) is entirely in the very high susceptibility area (orange color). On the right, the landslide susceptibility map for the whole Region of Attica is depicted [13].

6. Results

In Section 5.1, a comprehensive introduction to resilience was provided. This section will apply the concepts of engineering resilience through the description of a geotechnical project (e.g., case study of Provincial Road 3): from the identification of the initial problem and the site investigation to the design, financing, and implementation of the technical works.

The main challenges that were encountered during the implementation of the proposed civil engineering measures, and the way they were addressed, are as follows:

1. The roadway traffic for approximately three years was interrupted due to the limited space available during the construction works. Thus, an alternative pass was provided by the authorities for that period.
2. The philosophy of the project was that all the construction work was performed from the existing roadway, thereby altering traffic flow with traffic control, and no work was performed from the stream bed.
3. During the construction phase of areas B to D, at the end of area B of the road and specifically at the height of the Church of Zoodochos Pigi, further erosion of the roadway slope was created (21.80 m), which manifested itself in the form of a collapse of part of the existing retaining wall and with a sliding volume of soil. The new erosion of the roadway slope was due to the heavy rainfall of recent years, which

had been dynamic and had progressed in time until the time of the construction technical works. To restore the traffic on the road and to limit the future extension of the phenomenon, it was considered imperative to modify the original design to include additional works to support the above-described 21.80 m section. As a result, this led to additional geotechnical studies and an extra budget being afforded. The study provided the independence of the road from the natural processes of the stream bed (erosion) through the construction of a 20–22 m span bridge. The foundation of each of the two abutments was built on a series of piles (e.g., five piles in diameter of 150 mm, about 15 m deep each per abutment). The bridge accommodated both traffic branches (i.e., a width of 8–10 m) and required, in continuation of the eastern abutment, the construction of another part of interlocking piles.

4. The installation of drainage system wells was implemented to reduce the destabilizing forces developed due to the sudden occurrence of heavy moisture on the surrounding slopes during the construction stage of the B to D area.
5. The period of the COVID-19 pandemic initiated just at the beginning of the construction stage, and for three (3) months, no construction works could be performed due to lockdown (e.g., traffic curfew from the Greek Government). This situation was a problem, as it had never manifested before; thus, nothing could be done but wait for the lifting of the prohibition.

To begin with, the disruption of the engineering infrastructure of the study area comes from the impact of climate change, such as sudden extreme climate events (e.g., often heavy rainfall episodes). The inspections that were conducted after the heavy rainfall confirmed that Dekeleias Provincial Road 3, adjacent to the local Chelidonous Stream (e.g., system), deteriorated with time and its performance progressively went below the acceptable level of its life span (e.g., safe traffic circulation) due to the appearance of the manifested soil instabilities, subsidence, and undermining erosion. As a result, those failures resulted in the disruption of the road's functionality, which made the authorities close the road for a long period of time to implement the necessary adaptive actions for the restoration of its functionality. The closure of the road partially affected the local traffic and the access to social needs such as emergency services or medical care. In this direction, the Directorate of Technical Works of the Region of Attica decided in 2016 to address the problem by using engineering analyses (e.g., detailed geological–geotechnical studies) along with the subsequent construction works, which consisted of pile walls made of intersecting piles of different diameters, not to mention the improvement of the existing drainage system. Those mitigation measures were the necessary steps in order for the system to recover from the disruption caused by the above-mentioned failures.

To be more specific, over the last twenty years, part (e.g., with a length of about 300 m and especially in the section very close to the Kifisos River, which is the most important river in the Region of Attica) of Provincial Road 3 faced problems of both slope failures and subsidence, because of the severe bad weather phenomena, the resulting erosion, and its proximity to the adjacent stream of Chelidonous. Thus, due to:

- The phenomenon of the erosion of the slopes of the examined road on the side of the Chelidonous Stream was dynamic and had caused, owing to heavy rains on October and December of 2018, new significant problems in the roadway and its slope (conditions of undermining of the road) compared to the time of the announcement of the study (three years ago),
- The failure to manage the stormwater from the road and the stream, a failure of the existing retaining wall, and the parallel exposure of the public utility networks had already occurred. In addition, the above phenomena were exacerbated by the absence of drainage of stormwater from the road.

- The consequence of the previous finding was the unsafe passage of vehicles and pedestrians due to increased danger and the continuously deteriorating existing condition of the roadway and the parts of the slopes supporting it.

Provincial Road 3 had poor resilience. Therefore, a need for mitigation measures to enhance the resilience of the road was necessary, and geotechnical engineering needed to play a significant role in this response [22]. The Directorate of Technical Works (Central Section) of the Region of Attica decided in 2016 to definitively address the problem by awarding a topographic survey and geological–geotechnical research and study to a specialized consulting firm after an open tender. The study was carried out during the two-year period 2018–2019, which proposed specific technical works to remove the existing risk. After a significant period had elapsed during which the urgency of the issue had to be clarified and the source of funding sought, the Directorate of Technical Works of the Regional Authority of Attica launched an open tender, where the final bidder was awarded the implementation of the technical works proposed by the geotechnical study. Construction work started in March 2020 (start of the COVID-19 pandemic) and was completed in spring 2023. To translate the above actions into the engineering resilience concept, the following steps were executed:

According to the terminology described in Section 5.1 (Engineering Resilience), the existing infrastructure of the examined road before the reconstruction of the provincial road was weak (inadequate robustness and technical dimension) and lacked the geotechnical and geological characteristics that could resist erosion and undermining of the road due to heavy rainfall and an inadequate drainage system. As a result, the concept of rapidity was raised, meaning how quickly the infrastructure recovers after an event. Thus, judging by the damage level and the available resources, the rapidity of the reconstruction process was moderate (organization dimension), taking into consideration the identification of the emerging geotechnical problems, the difficulties of establishing priorities and mobilizing monetary resources (Resourcefulness stage), not to mention the constraints in terms of budget priorities. To this end, some extra problems were raised, such as those mentioned before (e.g., challenges due to the period of the COVID-19 pandemic and the additional unexpected erosion of the roadway slope at the construction area B–D).

As far as redundancy is concerned, which indicates the extent to which existing elements or systems are substitutable, during the reconstruction of areas A to D, an alternative transportation route was used, based on a traffic engineering study (social dimension), resulting in the closure of the examined segment of Provincial Road 3 for approximately three years. Lastly, speaking about the economic dimension (direct economic losses because of the above-mentioned phenomena), the total amount of the reconstruction stage was equal to the amount of EUR 2 million, approximately, without including in this amount the indirect costs from the closure of the particular segment of Provincial Road 3. However, no economic impacts of the road closure and construction delays have been quantified, nor has any cost–benefit analysis been conducted.

Referring to the DPSIR (Driver-Pressure-State-Impact-Response) framework, slopes and bridge foundation (e.g., drivers) were important factors in the transportation network of the examined area, since they affected the users' travel behavior and business logistics [7] and consequently resulted in pressures, which can be identified as the effect of climate change or funding constraints. The robustness, rapidity, resourcefulness, and redundancy of the examined infrastructure are associated with the term “states”, which indicates metrics that represent the resilience of a civil engineering project. The technical, economic, environmental, and social effects can be described by the impacts. Last, disaster management and decision-making are associated with the term of response [7], which is described by mentioning the series of civil engineering construction steps that are needed for the restoration of the damaged area.

6.1. Quantitative Framework to Evaluate Resilience

To evaluate the effectiveness of the above-described mitigation measures for improving the resilience of the geological–geotechnical environment of the examined case study, a (resilience) matrix approach [from a different perspective than the previously described (RES)] has been developed, which includes both quantitative and qualitative data under the context of the resilience process. It is about decision-making for resilience improvement, which depends on experiential knowledge [41].

Even though there are advanced numerical methods such as Coupled Eulerian–Lagrangian (CEL), Material Point Method (MPM), and Smoothed Particle Hydrodynamics (SPH) that can capture the dynamic behavior of landslides or the detailed mechanisms during the post-failure stage [42], RES methodology has been implemented from a different perspective (than the first case), by evaluating the parameters (that constitute resilience such as adaptability, recovery, social impact, etc.) after the restoration works using the resilience matrix.

For the construction of this matrix, it is important to consider not only the engineering resilience of a civil engineering project in the existence of a disruptive event (e.g., flood, landslide, etc.) but also the cascading impacts of it, such as what impact it has on the people (social), the surrounding environment, and the economy [26].

To this direction, the resilience matrix (RM) is consisted of an 8×8 matrix (Table 4), where, as already mentioned before, the basic principle of the matrix is to place the most important parameters of any system (e.g., technical, environmental, social and economic) and the steps of a disruptive event (preparation, absorption, recover, adaptation) [43] along a principal diagonal and to study the interactions of the selected parameters outside the principal diagonal, through a cause–effect diagram.

Table 4. Resilience matrix template.

Technical							
	Environmental						
		Social					
			Economic				
				Preparation			
					Absorption		
						Recover	
							Adaptation

Technical resilience aims to minimize the probability of failure in case of a severe meteorological or earthquake event [26]. On the other hand, social, environmental, or economic resilience can be the (derivative) impacts (e.g., positive or negative, overestimated or underestimated, respectively) of technical resilience [26].

To perform a resilience assessment and understand an adverse event (e.g., the consequences of a heavy rain on to a road functionality), the following steps should be taken [43]: (i) definition of the system boundary (e.g., road adjacent to a stream) and threats (e.g., natural disaster: slope failures, subsidence and undermining of the stream slopes), (ii) identification of critical functions such as the transportation system functionality, (iii) selection of indicators (meaning that each cell of the matrix acts as a value of how well the system behaves) implementing expert judgement on a relative numerical scale from 0 (being the least resilient or having the highest impact), 1 (low), 2 (medium), 3 (high) to 4 (very high

resilient), (iv) assessment of the overall resilience of the system by aggregating the cells scores across the matrix.

6.2. How Is the Resilience Matrix Table Working?

Taking into consideration that the most critical function is the proper operation of Provincial Road 3, the technical–absorption cell is assigned a rating according to the ability of the system to withstand any new heavy rainfall episode in such a way that will be able to resist from potential failures similar to those that resulted in the road devastation before the civil engineering mitigation measures took place. To succeed in accomplishing that in the case study of Provincial Road 3, building codes, construction procedures [8], numerical models and engineering analyses took place, during the working out of the geotechnical study of the examined area, taking into consideration different alternative scenarios regarding the occurrence of extreme weather events. Considering the interaction of technical–adaptation, the appearance of subsurface drainage during the construction works in areas B to D resulted in the construction of a drainage system well with the intention to regulate the groundwater.

Another example is the interaction between economics and recovery. In this, a rating is assigned based on the assumption that the size of the potential slope failure would adjust the time of the repair works needed for the restoration of the road. In case of a new road closure due to a new failure, the citizens' perception of the surrounding examined area is estimated to be positive, because minor new technical mitigation works will be required. In this direction, the interaction between economic preparation will lead to less budget than the one needed for the restoration of the road.

Considering the environmental impact on one side was deteriorated due to the increased carbon dioxide emissions because of the prolonged time travel after the disruption, but on the other side, slope failures, subsidence, and undermining were restored, and the environmental view of the examined area was restored too. Studying the interaction of environmental–social aspect of resilience, it can be said that in high frequency but lower impact events as a storm, the society needs to be able to function to the fullest extent possible, whereas in lower frequency but higher impact events such as disastrous landslide, the services for response and survival will be very important to allow to return to socio-economic functionality [22].

Regarding the technical–preparation cell, the ability to proactively mitigate the effects of the disruptive events by constructing subdrainage systems confirms the capability of appreciating the scale of the rescue task and devising strategies before disruption.

Finally, studying the relationship between social factors and preparation, public safety, and quality of life is connected to how well-prepared society is, because the absence of preparation in the face of a natural hazard is associated with the lack of understanding and information on the effects of a disruptive event. On the other hand, speaking about the relationship between social and absorption, one could say that the restoration of the road can improve the daily life of the people who cross by that segment of the examined Provincial Road 3. As far as the relation between social and adaptation is concerned, it can be highlighted that the closure of Provincial Road 3 due to the civil engineering restoration works partially affected the local traffic and, as a result, the access to social needs such as emergency services or medical care [8]. Thus, the above-mentioned remarks are quantified in the following Table 5, which mentions the ratings for each cell of the resilience matrix, estimated by the author of this manuscript, considering the road functionality, as well as the improved geotechnical conditions of the examined study area, after the mitigation works. The rating for each interaction has been assigned in an analogous way to the one estimated for the landslide instability index in Section 5.3.2.

Table 5. Resilience matrix after the restoration of Provincial Road 3.

Resilience Matrix								
Technical	4	0	0	4	4	4	4	20
0	Environmental	0	0	0	4	4	4	12
0	0	Social	0	0	0	2	4	6
4	4	0	Economic	0	0	0	0	8
4	0	4	4	Preparation	0	4	4	20
4	0	4	0	4	Absorption	4	4	20
0	0	3	1	3	3	Recover	3	13
1	1	2	1	3	3	3	Adaption	14
13	9	13	6	14	14	21	23	
(Effect—E)								
Parameters			C	E	C+E	$\frac{[(C + E)/\Sigma (C + E)]}{* 100\%}$	Maximum rating	Weighted coefficient (a _i)
P1—Technical			20	13	33	14.60	4	3.65
P2—Environmental			12	9	21	9.29	4	2.32
P3—Social			6	13	19	8.41	4	2.10
P4—Economic			8	6	14	6.19	4	1.55
P5—Preparation			20	14	34	15.04	4	3.76
P6—Absorption			20	14	34	15.04	4	3.76
P7—Recover			13	21	34	15.04	4	3.76
P8—Adaption			14	23	37	16.37	4	4.09
$\Sigma (C+E)$				226				

To an analogous calculation as the one estimated for the landslide instability index (Section 5.3.2), the resilience index for the road segment of Provincial Road 3 is calculated as follows:

Calculation of Resilience Index									
Parameters	P1	P2	P3	P4	P5	P6	P7	P8	Resilience Index
Dekeleias Road 3	4	4	2	1	1	3	1	3	60.73
Maximum rating	4	4	4	4	4	4	4	4	
$[(C + E)/\Sigma (C + E)] * 100\%$	14.60	9.29	8.41	6.19	15.04	15.04	15.04	16.37	100.00
Weighted coefficient (a_i)	3.65	2.32	2.10	1.55	3.76	3.76	3.76	4.09	

For the validation of the Resilience Index, the Building Resilience Index (BRI) which is an innovation of the International Finance Corporation (IFC), a member of the World Bank Group, will be used, making some appropriate adjustments to take into consideration the in situ geodata from the examined study area, as well as the internationally accepted standards and codes about civil engineering technical works [44].

The Building Resilience Index (<https://resilienceindex.org>, accessed on 10 August 2025) is a resilience assessment approach, and its objective is to provide a simple tool for engineers to identify and address risks for infrastructure projects. BRI offers a relative rating of resilience from higher to lower and to motivate experts to reduce physical risk, rather than an absolute rating against some standard of performance. It is understood that even the highest levels are not 100% resilient but retain certain residual risks. BRI can be of use and benefit to multiple stakeholders such as: (a) Construction Developers, (b) Banks, (c) Insurance Companies, and (d) Governments and Local Authorities. The latter may: (a) create codes and standards for more resilient construction practices, and (b) reduce

repetitive costs of post-disaster recovery and reconstruction. BRI is organized around the four major hazard categories that buildings experience: wind (air motion), water (liquid motion), fire (rapid oxidation), and geoseismic (ground motion). In our case study, BRI has been adjusted, and it will be used for the geoseismic hazard category only.

6.3. Methodology

Hazard applicability considers empirical best practices at a realistic level at the project location, based on a variety of datasets accessible to IFC, including those elaborated by the institution and those from reliable third parties. BRI rating levels are based on metrics related to the risk reduction measures of the building when faced with a hazard.

BRI is a relative index; in other words, infrastructure having higher indices will generally be more resilient than those with lower indices. However, there may be certain conditions when this does not apply. It should not be viewed as an absolute measure against an external performance standard. The overall BRI rating is based on the ‘weakest link’ principle. That means that the risk of all applicable local hazards must be reduced to achieve overall resilience. The levels of different hazards are not mathematically combined to extract overall resilience. The infrastructure’s resilience cannot be higher than the weakest level. To improve its overall rating, a project will need to improve its ‘weakest link’ measures.

The application uses various data sets accessible to IFC, including those developed by reliable third parties and those developed by the institution itself. For the necessity of the case study, the assessment framework includes only the hazards of geoseismic risks, as follows (Table 6):

Table 6. Summary of geoseismic hazards (modified BRI).

Hazard Category	Hazard Type (Subtype)	Description	Affected by	
			Climate	Location
GEOLOGICAL HAZARDS Land motion	Earthquake	Earthquakes occur near geological fault lines	No	Yes
	Landslides	Landslides can be caused by earthquakes, extreme precipitation typically in weak to medium geomechanically soil to rock slopes	Partly	Yes
	Subsidence	Subsidence can be triggered by a range of human or natural factors including extraction of groundwater and underground resources, earthquakes, and erosion which causes solid or fluid mobilization underground	Partly	Yes

BRI uses the rating scale as shown in the following Table 7. Rating refers to the risk-reduction measures that the infrastructure incorporates and is not predictive of the infrastructure behavior during a natural disaster or climate change event. These ratings are part of the outputs of the application, which are explained in the following sections.

According to the ‘weakest link’ principle, the infrastructure rating is determined by the lowest score achieved per hazard indicator. For example, if three out of the four hazard indicator categories achieve a rating of A, but in the fourth category the rating is B, then the overall building rating will be B. An infrastructure that achieved a rating above NR on all the available hazard indicators—categories can obtain a “+” next to the rating, such as A+, by implementing at least three operational continuity measures.

In the current case study, the hazard that will be analyzed is the geoseismic one, which consists of earthquakes, landslides, and subsidence. As geoseismic forces can be very

powerful, the location of the infrastructure is a major risk factor, particularly for landslide hazards. They can also be interrelated to other hazards, meaning that landslides can be triggered by earthquakes or heavy rain.

Table 7. BRI rating level descriptions.

Level	Probable Maximum Loss	Definition
NR	>50%	The project fails to incorporate most recommended resilience measures of BRI at a basic level.
B	~30–50%	The project incorporates recommended resilience measures of BRI at a basic level.
A	~10–30%	The project incorporates recommended resilience measures of BRI at a strong level.
AA	~5–15%	The project incorporates all recommended resilience measures of BRI at a global best practices level.
+	~5–15%	The rating followed by ‘+’ indicates that the project meets all requirements of the identified BRI rating, plus a minimum number of recommended operational continuity measures.

For the evaluation of the BRI, the best practice standards for geoseismic hazards are considered those from:

- NASA Global Landslide Catalog (GLC)
- United States Geological Survey
- European Soil Data Centre (ESDAC)
- Norwegian Geotechnical Institute
- United Nations Office for Disaster Risk Reduction

The following risk reduction measures/hazard indicators list is in BRI and forms the basis for the BRI geoseismic rating (Table 8). Measures marked ‘Y’ apply if the project is in a location with that hazard type. Projects that do not obtain an AA, A, or B rating are rated NR.

Defining in depth the above-mentioned hazard indicators for the estimation of BRI of a project, such as the case study of Provincial Road 3, it can be said that [44]:

- GS01. 1 km Distance from Earthquake Fault or Seismically Designed/Built (B Rating)

In areas prone to natural hazards (earthquakes or landslides), if the infrastructure does not include the seismic measures required for AA or A rating, it must be located more than 1 km away from an earthquake fault or designed/built to a site-specific seismic study. In the examined area, the nearest active fault is about 4 km from the infrastructure project.

- GS02. Foundation Seismically Designed for Site-Specific Soil Conditions (A Rating)

The ground conditions are of great importance in the stability of the infrastructure. Ground deformation can damage foundations. The foundations of any infrastructure must be designed to withstand seismic forces near fault lines. If the infrastructure site is composed of filled rock or soil, it cannot be rated AA or A, unless either the foundation extends below the filled section into hard rock. In the case study, piles with intersecting piles constitute the reinforced geotechnical profile of the underground of the project.

- GS03. Foundation Piling Adequately Secured in Rock Below Subsiding Soils (AA Rating)

Table 8. List of risk reduction measures for geoseismic hazards (modified BRI).

Geoseismic Hazard Type/Risk Reduction Measure—Hazard Indicators	Description	Required for AA Rating	Required for A Rating	Required for B Rating	Subsidence	Landslide	Earthquake
GS01 1 km Distance from Earthquake Fault or Seismically Designed/Built	The infrastructure is either located at least 1 km away from an earthquake fault line or it is designed/built specific to the site's seismic properties.			Y		Y	Y
GS02 Foundation Seismically Designed for Site-specific Soil Conditions	The infrastructure is either not located on filled rock and soil, which has high risk of ground fluidizing (liquefaction) during an earthquake, or it is designed/built specific to the site's seismic properties.		Y			Y	Y
GS03 Foundation piling adequately secured in rock below subsiding soils	If the infrastructure is designed/built on a subsiding soil, the foundation pilings are adequately secured in the underlying non-subsiding rock.	Y			Y		
GS05 Slope of Neighboring Area <30 degrees	The neighboring area of the infrastructure either has a slope less than 30 degrees to avoid higher risk of landslide, or the infrastructure is designed/built according to a slope hazard analysis.	Y				Y	
GS13 Defensive Structures for Landslides	Defensive structures for landslides (e.g., retaining barriers, wire mesh, check dam, stabilizing material, drainage to reduce soil saturation, and vegetation) are incorporated on the infrastructure site.	Y				Y	

Subsidence can damage technical works partially or entirely over time or suddenly. Each site will have its own soil type, which will need to be addressed through analysis of the site-specific geological–geotechnical conditions. Each site has been exposed to its geological progression over time, which will impact the soil/rock build-up and structure. If the site has subsiding soil conditions, the foundations of the infrastructure must be designed and built to withstand subsidence. The foundation pilings of the project must be adequately secured in the underlying non-subsiding rock for a building to have an AA rating. The above conditions are satisfied in the study of Provincial Road 3.

- GS05. Slope of Neighboring Area < 30 degrees (AA Rating)

Landslides can be caused, among other causes, by earthquakes and extreme precipitation, and there is an increased risk of slope failures in areas with a steep slope gradient. Therefore, the surrounding area of a site should have a slope of less than 30° , otherwise a slope hazard analysis must be performed to assess the risks and risk reduction to the landslide hazard. Those conditions are satisfied in the study of Provincial Road 3.

- GS13. Defensive Structures for Landslides (AA Rating)

Defensive structures for landslides are to be incorporated within the infrastructure premises to protect them from slope failures and subsidence. These should be properly designed and inspected by a geotechnical engineer, taking into account the in situ geological–geotechnical conditions. Examples of defensive mitigation structures, such as piles and drainage systems, are the technical measures that have been implemented in the restoration of Provincial Road 3.

Taking into consideration the ‘weakest link’ principle, the BLI rating for the examined infrastructure is determined by the lowest score achieved per hazard indicator, which is category B. That means the project incorporates some recommended resilience measures of BRI. To this extent, the expected outcome coincides with the Resilience Index (e.g., RI = 60.73,) which came out from the RES approach, as analytically described before.

In the following Figure 10, the performance of the calculated resilience index, associated with the performance of Provincial Road 3 (before the disastrous event, during the period of the design phase and the construction stage and after the restoration of the road) is depicted.

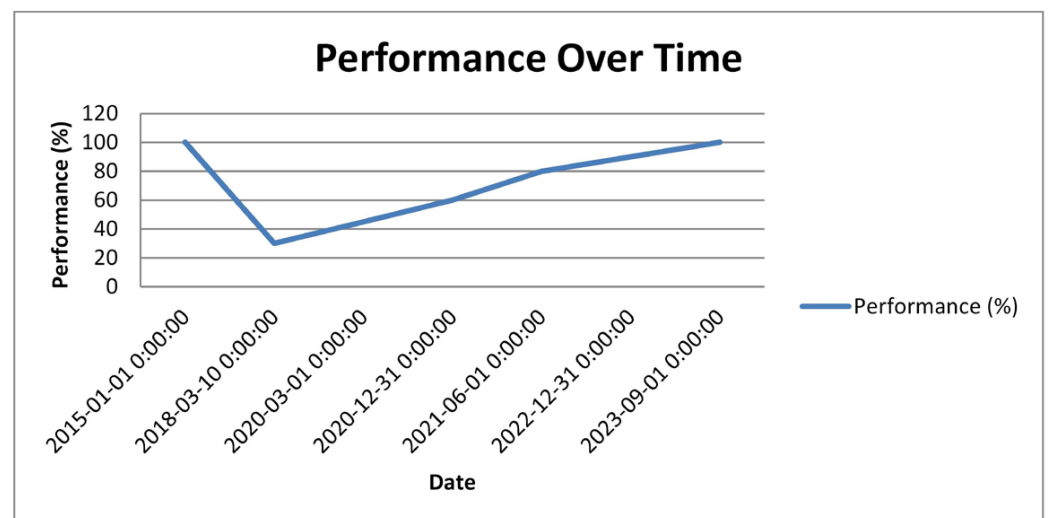


Figure 10. The performance of the resilience index of the examined segment of Provincial Road 3 from the beginning of the significant failure (2015), through the study (2018), the reconstruction–restoration works (2020–2022) until the end of the restoration technical works (2023).

7. Discussion

As mentioned before, the selected parameters for the construction of the RES matrix were based on the cause–effect interaction. The same philosophy has been followed for the implementation of the DPSIR framework, regarding Provincial Road 3 (e.g., the cause–effect relationships of hazard to the geotechnical behavior of the mitigation technical works of the case study [8]). Thus, the “drivers” (e.g., driving forces), in our case study are the slopes and the bridge foundation, which are important components in transportation networks because they provide mobility for passengers and goods to the destination

point [8]. “Pressures”, such as serious subsidence to the examined case study road, can take place due to the loadings from heavy and large commercial vehicles. Another type of pressure could be an incident of an earthquake or the episode of heavy rainfall resulting in floods, where hydraulic inputs and outputs to soil and drainage system are directly important to geotechnical failures [8]. Furthermore, a pressure could be a wildfire as the one which took place in the summer of 2021 in an area (e.g., Varimpobi) very close to the case study (during the construction stage of areas B to D) and it almost reached the outer limits of the construction site with the danger of burning the vegetation which is located adjacent to the examined road and the slopes of the Chelidonous Stream.

Regarding the “states”, they are correlated to robustness, rapidity, redundancy, and resourcefulness. Robustness in our case study is associated with the estimation of bearing capacity and instability index.

Rapidity concerning time is correlated to how fast bureaucratic procedures (e.g., agreement for the beginning of the project, searching for extra budget, delay of permissions from different organizations of utility networks due to COVID-19 restrictions) were completed to fulfill the civil engineering mitigation works in the examined area.

Redundancy is related to the supplementary study, which is needed due to the unexpected rainfall episodes that took place during the reconstruction works. Finally, resourcefulness is the cost required for the restoration of the road.

As far as “impacts” are concerned, these are the effects of the damaged geotechnical components (change in traffic volumes and times due to the closure of the examined segment of the road), construction costs for mitigation and repair. In the case study, the closure of the examined segment of the road for about three years resulted in the loss of functionality and eventually affected the surrounding community [8].

Finally, “responses” are associated with the mitigation measures that took place (construction of piles and walls, improvement of the existing drainage surface system of the road), which are analytically described in Section 5.1. According to the previously mentioned, the resilience matrix (RM) allows the use of both qualitative and quantitative data in the resilience scoring process. In addition, RM is adaptive enough to be used as a tool, considering any level of data availability, but detailed enough to support decision-making [45,46]. Thus, improving the resilience of geotechnical engineering structures and preventing them from large-scale collapse to small-scale damage in unexpected conditions is of great importance to the safety of the infrastructure, the citizens, and the society in general [1]. As a result, the present study can contribute to the implementation of EU Directives by fostering a culture of preparedness and proactive risk management [47].

Limitations and Future Challenges

Concerning landslides, the major obstacle in their study is the identification of all parameters that contribute to the occurrence of the phenomenon, and especially the determination of the relationships between them, which according to Hudson [27] is solved by the RES methodology. Consequently, careful completion of the cause–effect matrix makes the best use of the expert’s judgement, and finally the resulting weighted coefficients express the maximum possible objectivity, which can be revealed by existing experience. However, it can be argued that, using RES, there is a degree of subjectivity when an expert evaluates the interaction between the selected parameters, either to be for landslides or engineering resilience judgement. This statement can be refuted since many, in parallel, experienced experts can evaluate the above-mentioned interactions in order to minimize the subjectivity of the parameter values and, as a result, the degree of uncertainty.

Regarding the concept of engineering resilience and taking into consideration its future challenge framework, resilience demands informed decisions based on risk assessments

that rely on the best technology, data, and management. Based on that, disasters cannot be entirely prevented, but with proper understanding and adequate action, we can be better prepared, reduce losses, and recover better if an event does happen. For this reason, the management of resilience requires appropriate risk information, quantitative risk modelling, and advanced data analysis trained in machine learning or Big Data analysis. Thus, the implementation of a landslide risk assessment would develop the engineering resilience approach, since the identification of areas susceptible to slope failures would facilitate policies to restrict further development in those areas. As a result, proper land-use zoning would prevent urban development in areas that are prone to failure, protecting people from potential landslides and resulting in engineering resilience. How can the above-mentioned be executed? By building codes and standards, by using early warning systems, which will both enhance resilience, and finally by educating the people about the risks connected to natural hazards.

Regarding the monitoring of assessing the continued resilience of the road infrastructure after the construction works, a maintenance plan has already been implemented (increase of maintenance frequency), consisting of two visits per month for the in situ inspection of the road service capability [e.g., monitoring the behavior of the structure about the original reference conditions (deformations, displacements, and direct environmental impact)]. Furthermore, a monitoring system consisting of LIDAR, drones, and satellite images connected to the digital data center of the Region of Attica is about to be implemented shortly.

8. Conclusions

One way to reduce the impacts of disasters on the nation and its communities is to invest in enhancing resilience. Enhanced resilience allows better planning to reduce disaster losses, rather than waiting for an event to occur and paying for it afterward [17].

In order to practically implement resilience thinking in geotechnical engineering, a framework that can quantitatively measure the resilience of geotechnical infrastructure is needed [7]. In this direction, in the present study, the resilience of the Attica region's Provincial Road 3 in Greece due to adjacent stream erosion and subsequent slope failure was presented by explaining the geological engineering study that was undertaken and depicting the steps of the civil engineering stabilization works that were implemented. Furthermore, in the context of this study, the hazard of the existing condition of the slopes of the Chelidonous Stream and of Provincial Road 3 of the Attica Region before the failure was confirmed, using the Rock Engineering System methodology for soil and soft rock slopes.

Furthermore, a tool for semi-quantitative assessment of the examined segment of the road resilience after the end of the rehabilitation measures was analyzed, highlighting, in parallel, the metrics and indicators needed for the estimation of resilience from a quantitative point of view. This case study emphasizes the need to maintain the early focus on resilience through design and construction. It was found that using a semi-quantitative methodology (RES for estimating the slope instability index and resilience matrix for the evaluation of the constructed technical works) can associate designers and subsequently decision makers with valuable tools for facilitating decision-making for more sustainable solutions and contributing to the long lasting duration of civil engineering projects despite the appearance of extreme weather conditions or earthquake events or even the (mega) wildfires whose frequency is getting more and more alarming.

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