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RESTORATION OF DAMAGE TO A PROVINCIAL ROAD IN THE REGION OF ATTICA (GREECE) AFTER A DISASTROUS WEATHER EVENT

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Abstract

This paper describes soil instabilities and rockfalls that occurred during the heavy rainfall of September 2023, named "Daniel," in a total length of 4.8 km of the Provincial Road Old Epidaurus-Galata belonging to the Region of Attica in Greece. The Department of Technical Works of the Piraeus & Islands Regional Unit (Attica, Greece) oversaw the restoration of the damage manifested in the above-mentioned area. On the rocky slopes of the road, instability phenomena were activated during the occurrence of intense rainfall in September 2023.

In the present study, the geological and geotechnical characteristics of the instabilities problems which activated after the extreme weather phenomena are briefly described and proposals and immediate measures to address them are presented.

Furthermore, two well-known assessment methodologies were implemented, which confirm the hazard and risk respectively in selected part of the area under consideration. Since this section of the Provincial Road had been closed after the occurrence of "Daniel" and because this road is connected with tourist resorts as well as many towns and villages in the Piraeus & Islands Regional Unit, the immediate and secure restoration of the described damage and removal of risk were of major importance for the Regional Authority of Attica.

Key words

Rockfalls, Old Epidaurus – Galata Provincial Road, Daniel rainfall, mitigation measures, hazard estimation

1 Introduction

On 5-7 September of 2023, a very heavy rainfall (maximum daily rainfall recorded: 754 mm), named as "Daniel" manifested in many areas of Greece, resulting in tremendous damages to infrastructure and losses of people lives. One of those areas that suffered from this devastating event was part (e.g. 4.8 km) of the Provincial Road Old Epidaurus - Galata belonging to the municipality of Troizinia-Methana of the Region of Attica (e.g., the biggest regional government authority in Greece). The Provincial Road Old Epidaurus - Galata junction, which is a main transit route to Galata, Troizina, Kalloni, etc (Figure 1), closed for restoration works (EDAFOS S.A, Region of Attica, 2024).

For the section from ch. 4+370 to ch. 9+170, with a total length of 4,8 km, the geological and geotechnical conditions are presented and evaluated, in order to record and determine problems of soil instabilities and rockfalls that occurred on 5-7 September of 2023.

Rockfalls and soil instabilities of small and large scale occurred in the studied section of the road, which were mainly related to but not limited to the occurrence of extreme weather conditions. The instability phenomena are more pronounced during the winter months and pose a risk to the safe movement of passing vehicles along the road. During the extreme weather events of September 2023, but also previously, in December 2021, rock falls and sliding of soil materials occurred in some locations of the Provincial Road, resulting in its disconnection, without damages. Due to severe flooding phenomena of

September of 2023 and to avoid accidents, the road had been closed from 7 September 2023 till 30 April 2024 as a precautionary measure.
Ten (10) general areas of soil instability with uniform characteristics (geological conditions, type, size and mechanism) and a total of twenty-nine individual locations of activated or potential instabilities were identified (EDAFOS S.A, Region of Attica, 2024).
On the rocky slopes of the road, as well as in the wider area, during the occurrence of intense rainfall and flooding events in September 2023, instability phenomena were activated such as:

- Rock blocks failures of toppling and wedge mechanisms (Tavoularis et al., 2021),
- Flows and slides of scree and talus cone materials,
- Planar failure of the rock mass along unfavorable oriented bedding or discontinuities

In the area of interest (Figure 1), apart from the manifested failures, the presence of a significant number of large rock blocks has been noted, most of which are in marginal equilibrium, with a risk of toppling, sliding and falling within the road.

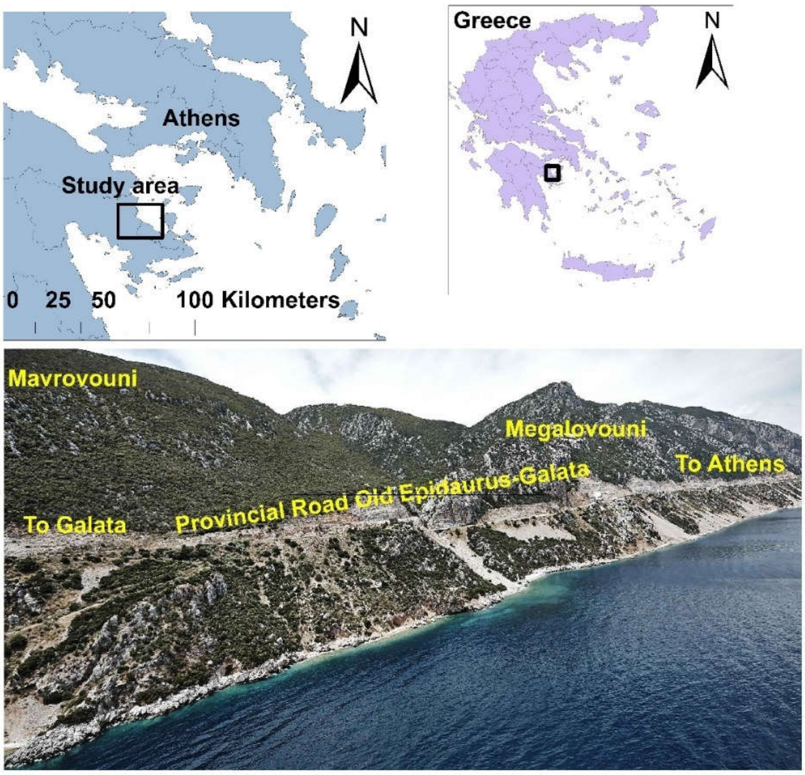

Figure 1. Overview of the study area of the Provincial Road Old Epidaurus-Galata (view from Trip in View site)

As previously mentioned, the road was closed from the beginning of this event (e.g. 7 September of 2023) till the end of April of 2024, where restoration works fulfilled. During this period, the Department of Technical Works of the Piraeus & Islands Regional Unit (Regional Authority of Attica, Greece) supervised the restoration of the damage and the removal of risks manifested in the above-mentioned area.
In this paper, the geological and geotechnical characteristics of the conditions and issues of potential instabilities that were activated after the extreme weather phenomena, and proposals and immediate measures to address them are presented (so that road conditions are restored and made safer than the previous operational state). Furthermore, the paper implements two well-known existing rockfall hazard assessment methodologies; a qualitative (Rock Hazard Rating System) and a quantitative one (Quantitative Risk Assessment) that attempted to validate the hazard in selected part of the area under consideration.
Since this section of the provincial road is connected with important tourist resorts as well as being the basic road line to many towns and villages in the Piraeus & Islands Regional Unit, the immediate and secure restoration of the described damage and removal of risk was of major importance for the Regional Authority of Attica.

1.1 Geomorphological setting

The study area is developed between Old Epidaurus and the settlement of Kalloni and is morphologically located on the foothills of the mountain ranges Megalovouni and Mavrovouni with peaks at approximately +850 m and +600 m respectively and is characterized by a basically mountainous terrain with moderate to steep slopes of natural slopes. The absolute altitude along the road varies between +85 m and +135 m (Figure 1). The morphology of the wider area reflects the combined effect of geological structure, recent tectonic evolution and erosion processes and largely determines the processes involved in the activation of soil instabilities (EDAFOS S.A, Region of Attica, 2024).
Based on the geological structure and the composition of the rocks, the area is placed in a mountainous terrain zone, within the limestone formations that dominate the entire area.
The hydrographic network is generally sparse, locally more frequent in places where mainly tectonic structures such as faults, fault lines, fault zones, etc. pass through and its branches are mainly oriented NE - SW with a west to east flow direction. At the locations of the streams and gullies, the accumulation and transport of large amounts of debris from recent rainfall was found to have accumulated and transported on the slopes and inside the road.
The infiltration, estimated to be in excess of 50-60 %, occurs primarily by underground seepage, but it is also estimated that surface runoff is similarly significant due to the pronounced dolomitization of the formation. The watercourses have a significant flow and are characterized by their high carrying capacity, particularly during heavy rainfall events.
The main geomorphological features observed that affect the occurrence of soil instabilities are a) the steep overhanging slopes and b) the intense erosions and gullies within the streams and torrents that flow into the road (Figure 2).

Figure 2. Debris cone and alluvial material at the base of the slope and within the road, from material accumulated through the two talweg - gullies.

Due to the intense flooding events of recent years, the carrying capacity of watercourses (solid flow) has increased which directly affects the activation of slides. Three (3) such locations were identified in the study section which constitute those with the highest accumulation of unstable materials.

1.2. Geological setting

According to the geological map (Sheet LIGURIO, 1:50.000) of Greek Institute of Geological and Mining Exploration (IGME), the following geological formations were identified in the area of interest (EDAFOS S.A, Region of Attica, 2024):

- Fill materials
- Debris flows and gully materials (Tavoularis, 2023). The flows of soil and rock materials that have accumulated in the rock traps and / or on the road deck are associated with the presence of slope debris and alluvial materials, loose and unconsolidated, which during the recent floods moved in the form of saturated material flows, downstream and the outlet of the watercourses to the Provincial Road.

- Rock blocks - Products of rockfalls occurred in rocky limestone formations.
- "Pantokratoras" Limestones»: (a) Brecciated "Pantokratoras" Limestones, (b) Highly fractured and moderately to very weathered "Pantokratoras" Limestones, (c) Slightly fractured and weathered “Pantokratoras" Limestones.

The detachments of large sized rock blocks from slopes consisted of scree matrices and / or from the crowns of steep slopes.

1.3 Geotechnical setting

Twenty-nine segments were identified with geotechnical issues (existing and potential geotechnical instabilities) during the fieldwork and attributed to the severe weather phenomena that took place on 05-07/09/2023. It is noted that some of these may existed prior to the recent flooding, however it is considered that they need to be resolved for the safe operation of the road and its return to its previous condition. For the necessity of the upcoming described methodologies, one particular segment of the road is briefly presented (EDAFOS S.A, Region of Attica, 2024).

Section from ch. 5+490 km to ch. 5+590 km

There is a predominant occurrence of "Pantokrator" limestone, a formation which, as has been reported, constitutes the geological background throughout the section under consideration. The slope has a maximum height of about 50 – 55 m and a bench at a height of about 22-23 m from its base. At the area of interest, two grades of rock mass qualities were distinguished; one with fair characteristics that corresponds to thin bedded limestone, intensely fractured, with presence of secondary infilling materials and moderately to highly weathered discontinuities’ surfaces by fine-stratified structure, intense fractured, presence of secondary soil fills and moderate - high discontinuity weathering, and one with good characteristics that correspond to medium to very thin bedded limestone, moderately fractured to widely spaced discontinuities, with no infilling and slightly weathered discontinuities’ surfaces. The bedding planes inclined towards NW/NE with a dip angle of about 30° - 35°.
Apart from bedding planes, five (5) sets of discontinuities were encountered. According to the evaluation of the Schmidt diagrams, two common failure mechanisms were identified: rock toppling and rock wedge sliding. In actual conditions, locations of rock fragment detachment, mainly large-size rock 'wedges', and the occurrence of toppling or falling/detachment of overhangs were found. A typical rock wedge failure that caused serious damages to the existing metal barrier is presented in Figure 3.

Figure 3. Falling of an individual boulder of $8m^3$ (maximum bolder size of the rockfall) that bounced off the existing protection measures and ended up on the road deck within the provincial road, at about Ch. 5+525 km. Close-up view of debris flow (on the right)

In order to optimize the available budget allocation for this project, two systematically used hazard and risk assessment methodologies were applied.

2 Methods

2.1 Rockfall Hazard Rating System (RHRS)

The instability events manifested in the Old Epidaurus- Galata Provincial Road after "Daniel" event, represent a major hazard because they can cause severe damage to infrastructure and loss to human lives. An efficient way to reduce potential future damage, is to improve land-use planning using, qualitative as well as quantitative hazard assessment approaches at the local and site-specific scales for one main reason, which is the recent dramatic climatic changes that have totally increased the frequency of slope instability events (Ferrari et al. 2016).

In this paper, a qualitative method, the well-known Rockfall Hazard Rating System (RHRS) is used, firstly developed from Oregon Department of Transportation (USA) in the late 1980s in order to set rockfall project priorities and allocate limited funds (Pierson, 1992). RHRS is a slope rating system, typically adopted to provide a relative ranking of potentially unstable slopes. The main goal is to obtain consistent and comparable information for a series of locations to plan for safety improvements. As a planning tool, RHRS facilitates a proactive approach, but it can also be used in response to a rockfall event on a single slope to both describe the event and compare it to other rockfall events in a consistent manner. Since, for the restoration of the study area a similar economic constraint existed, the use of an economical tool such as RHRS can be used, in order to prioritize the slopes most at risk of collapsing. According to this, nine parameters – categories are necessary to identify rock cuts that require a detailed geological - geotechnical analysis (Table 1). The description and explanation of using these parameters can be found on Pierson (1992) and Ferrari et al. (2016) research findings.

Table 1. Application of the RHRS (Pierson et al., 2005). Bold indicates the score of the study section.

Parameter - Category	Rating criteria and scores				
	3 points	9 points	27 points	81 points	Estimated value from: 5+490 - 5+590
1. Slope height (m)	7.6	15.2	22.9	**30.5**	**81**
1. Ditch effectiveness	Good catchment	Moderate catchment	**Limited catchment**	No catchment	**27**
2. Average vehicle risk	**25% of the time**	50% of the time	75% of the time	100% of the time	**3**
3. Percent of decision sight distance	Adequate, 100 % of low design value	**Moderate, 80 % of low design value**	Limited, 60 % of low design value	Very limited, 40 % of low design value	**9**
5. Paved road width (m)	13.4	**11**	8.5	6.1	**9**
6. Geologic character					
Case 1:					
Structural condition	Discontinuous joints, favorable orientation	Discontinuous joints, random orientation	Discontinuous joints, adverse orientation	Continuous joints, adverse orientation	
Rock friction	Rough, irregular	Undulating	Planar	Clay infilling or slickensided	
Case 2:					
Structural condition	Few erosion features	Occasional erosion features	Many erosion features	**Major erosion features**	**81**
Difference in erosional rates	Small difference	**Moderate difference**	Large difference	Extreme difference	**9**
7. Block size (m)	0.3	0.6	0.9	**1.2**	**81**
8. Volume per event (m^3)	2.3	**4.6**	6.9	9.2	**9**
9. Climate and presence of water on slope	Slow to moderate precipitation or no freezing periods or no water on slope	Moderate precipitation or short freezing periods or intermittent water on slope	**High precip. or long freezing periods or continual water on slope**	High precip. and long freezing periods or continual water on slope and long freezing period	**27**
10. Rockfall history	**Few falls**	Occasional falls	Many falls	Constant falls	**3**
				Total Score	**339**

According to Hoek (1999), RHRS classification is based on a set of simple visual observations, most of which can be carried out from a slow-moving vehicle as would be required for the preliminary evaluation of miles of mountain highway. The system also contains all the components required for a complete engineering evaluation of the risks to the public. These include highway design factors as well as geometrical and geotechnical factors, all presented in clear and unambiguous terms.
According to Ferrari et al. (2016), the detailed ratings rank the slopes from least to most hazardous, using nine categories, scored exponentially from 3 to 81, with the intention of maximum allowable score for all categories being 100. Thus, slopes with higher scores are associated with greater hazards.
Once the score has been attributed to each parameter/category, the sum is the overall score. In the selected case study (ch. 5+490 – ch. 5+590), the ultimate final score is equal to 339 and as Hoek (1999) mentions, this score justifies the hazard of the segment and explains the reason why appropriate mitigation measures should be taken.
However, even though RHRS system laid the foundations for modern rockfall hazard assessments and inspired several successive methods (Ferrari et al., 2016), its main disadvantage is that it depends on the capabilities of the expert – evaluator, since the scores may be estimated differently and the final RHRS score is hardly reproducible (Vandewater et al. 2005).

2.2 Quantitative Risk Assessment (QRA)

The previously mentioned disadvantage can be solved by using additionally a quantitative method where it takes a step further the initial screening level of RHRS evaluation of the most dangerous areas. In particular, **Q**uantitative **R**isk **A**ssessment (QRA) has been developed to quantify the probability of potential losses that are related to the occurrence of a hazardous incident by estimating the number of destroyed belongings, and losses of human lives. Some of the benefits of the use of quantitative risk assessment in landslide risk management include (Fell et al., 2005):

- It allows comparison of risks across for example cut slopes on highways, and thereby allows prioritization of remedial works, and potentially setting of risk-based standards for acceptable designs.
- It provides a framework to insert uncertainties and engineering judgement into a system, resulting in an awareness to consider what can go wrong, and their potential consequences, together with how the uncertainties can be best managed.

In the following example, certain elements of landslide risk assessment are presented. The main scope is to calculate the risk to persons travelling on the Provincial Road of Old Epidaurus – Galata as shown in the Figure 4.

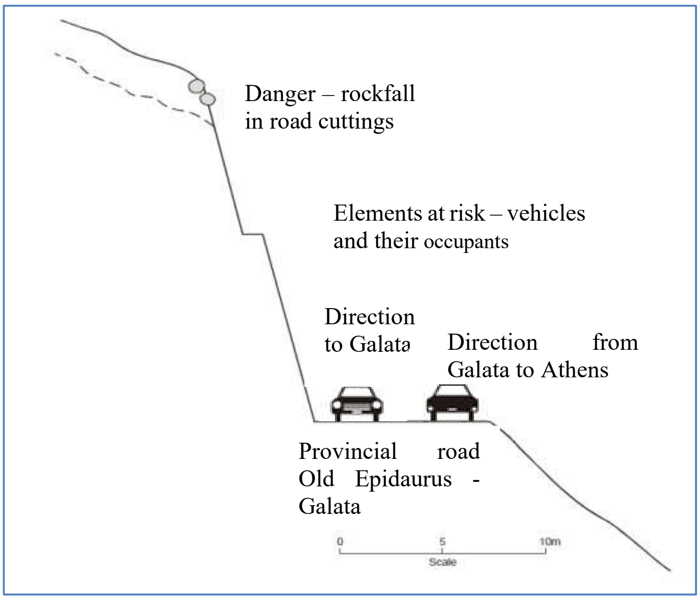

Figure 4. Characteristic segment of the Provincial Road Old Epidaurus – Galata which is part of the suburban road network of Attica Region.

Risk Analysis

The annual probability that a particular person may lose his/her life can be calculated from (Fell et al., 2005): $P_{(LOL)}=P_{(L)} * P_{(T:L)} * P_{(S:T)} * V_{(D:T)}$, where
$P_{(LOL)}$ is the annual probability that the person will be killed
$P_{(L)}$ is the frequency of the landsliding
$P_{(T:L)}$ is the probability of the landslide reaching the element at risk
$P_{(S:T)}$ is the temporal spatial probability of the element at risk
$V_{(D:T)}$ is the vulnerability of the person to the landslide event

(a) Danger characterization

This road was constructed at the beginning of the first decade of millennium. The 31 cuts in the road were constructed at relatively steep slopes. The last at least twenty years, in many parts of the slopes, there are remnant effects of poor blasting practices used in excavating rock slopes as well as stress relief following excavation. According to historical recordings from the Directorate of Technical Works of Regional Unit of Piraeus & Island, there have been occasionally rockfall incidents per year with boulders ranging in size from 25 cm diameter to 1.2 m diameter. The cuttings are in similar climatic conditions, geological background and topographical characteristics. Based on the recorded boulder impacts on the road surface, it is assessed that 50 % of rock falling from the slope will impact on lane with direction to Galata and 50 % of rock falling from the slope will impact on Lane with direction to Athens (Figure 4).

(b) Frequency analysis

The average frequency of rockfalls for each cutting is 1 per year. There are a total of 31 cuts along the provincial road Old Epidaurus-Galata, giving a total of 1/31 rockfalls per year or 0.000088/day, the average frequency (N_R) of rockfalls onto lane with direction to Galata is $N_{GALATA}=0.5*0.000088=0.000044$/day, and on lane with direction to Athens is $N_{Athens}=0.5*0.000088=0.000044$/day.

(c) Consequence analysis

(i) Temporal spatial probability ($P_{(S:T)}$) of vehicles
The probability of a vehicle occupying the length of road onto which the rockfalls is given by:
$P(S:T)=Nv/24 * L/1000*1/Vv$, where
N_v= average number of vehicles/day
L= average length of vehicles (metres)
V_v= velocity of vehicle (km/hour)

For each lane, the estimated (based on empirical basis) average number of vehicles per day over the year is 1000*, the average length of the vehicles is 6 metres, and they are travelling at 70 km/hr, ignoring the width of the boulder:

Figure 5. Illustration of the Induction Loops on a road (Federal Highway Administration, U.S. Department of Transportation, 2006)

* The Department of Technical Works of Piraeus & Islands Regional Unit is about to install in a particular segment of the Provincial Road Old Epidaurus-Galata, a system named "Induction loops". These are sensors placed next to each other on all lanes of the road. Their task is to record the flow of traffic on the road. The sensors record the volume and other information

about each vehicle that passes over the induction loop: what kind of vehicle it is (e.g. motorcycle, passenger car, truck), when it passed and at what speed it passed. The useful data collected by the inductive loops will be transmitted to the Traffic Management Centre of the Region of Attica for analysis and evaluation (Figure 5).

For each lane, the temporal probability is: $P_{(S:T)}$=1000/24 * 6/1000 * 1/70 = 41.66*0.006*0.014=0.0035
For a particular vehicle travelling once each day in one direction: $P_{(S:T)}$=1/24 * 6/1000 * 1/70 =0.0416*0.006*0.014=0.0000035.

(d) Vulnerability of the persons in the vehicles

Based on empirical judgement, it is estimated that the vulnerability of persons in vehicles in two lanes is 0.15.

(e) Risk estimation

The annual probability of the person most at risk losing his/her life by driving along the provincial road is:

$P_{(LOL)}=P_{(L)} * P_{(T:L)} * P_{(S:T)} * V_{(D:T)}$ = 0.000044 * 0.5 * 0.0000035 * 0.15 = $1.155*10^{-11}$ per year for each vehicle for each lane.

where $P_{(T:L)}$, which is the probability of the landslide reaching the element at risk (e.g., vehicle), is estimated from empirical methods calculating travel distance equal to 0.5.

For a person who only travels on the road once per year in each direction, $P_{(LOL)}$ = $3.164*10^{-14}$/annum ($1.155*10^{-11}$/365).

The total annual risk assuming each of the 1000 vehicles/day carries an average of 4 persons is: $1000*365*4*3.164*10^{-14}$ per year =$4.62*10^{-8}$ persons/year.

Risk Assessment

From Table 2 (Fell et al., 2005), the tolerable individual risk for existing slopes is $1*10^{-4}$ persons/year. Thus, for the individual most at risk, with $P_{(LOL)}$= $1.155*10^{-11}$, the risk is within the tolerable limit.

Table 2. AGS (2000) suggested tolerable risk criteria

Situation	Suggested tolerable risk for loss of life
Existing engineered slopes	10^{-4}/annum person most at risk
	10^{-5}/annum average of persons at risk
New engineered slopes	10^{-5}/annum person most at risk
	10^{-6}/annum average of the persons at risk

Taking into account the outcomes of the above risk assessment approach, risk mitigation options should not be considered. However, due to the fact that the Provincial Road Old Epidaurus-Galata constructed 20 years ago, remnant effects of poor blasting practices used in excavating rock slopes have been noticed, the appearance of stress relief following excavation is evident along the road, not to mention the importance of the safe operation of the provincial road for the economic development of the wider region, appropriate mitigations measures must be taken.

3 Results

Along the study area, technical works have been constructed during the last 20 years to prevent rockfall phenomena, most of which have functioned adequately during the recent flooding events. However, during the fieldwork that followed “Daniel” incident, locations with rock slope failures and erosion issues were identified, which may be exacerbated in the event of heavy rainfall and/or dynamic (seismic) loading. Furthermore, taking into consideration the outcomes of the two previous described hazard assessment methodologies, additional interventions - mitigation works were prioritized to ensure the safe operation of the Provincial Road, such as:

1. In some locations, precarious rock blocks perched on the top of slopes were identified. Their potential failure risked the subsequent accumulation of a significant volume of material in the rock fences, rock traps and road deck. For these reasons, scaling and rock removal works took place to improve the stability of the existing slopes and to safely perform further the interventions.

2. The accumulation of debris flow materials was found on the benches and behind the rock traps and metal fences along almost the entire section of the road, which were removed to ensure their proper function and to allow collection of similar future phenomena.
3. Permanent deformation and/or complete failure of existing measures was observed in several locations. At these locations, their functionality was checked and the repair and/or replacement of existing structures that have been deformed or completely failed (Rock barriers, rock fences, steel meshes, reinforced concrete walls, etc.) was required.
4. Repair works of embankments and deck sections of the road were executed.
5. Anchoring of free meshes was implemented.
6. In some locations, the scaling of "keyblocks" was considered ineffective due to the potential precipitation of larger scale failures. In these cases, spot bolting of individual rock blocks was carried out.

In the Figure 6, characteristic views from the restoration works are presented in contrast to the ones before mitigation measures and after the occurrence of Daniel.

Figure 6. Characteristic views after the devastating heavy rainfall "Daniel" (left side) and restoration works (right side)

4 Conclusion

The purpose of this study is to present the soil instabilities and rockfalls that occurred on the slopes of part of the Provincial Road Old Epidaurus-Galata during the period of 05 to 07 September 2023 with the occurrence of extreme weather events (e.g., "Daniel") and briefly describe the appropriate measures implemented in order to address and avoid future such phenomena.

In addition, two hazard assessment methodologies were presented at a specific location of the road

alignment that confirmed quantitatively (QRA) and qualitatively (RHRS) the value of the preliminary examination and prioritization of the planned measures to address existing and potential instability issues.
It must be noted that the above interventions (e.g., scaling and rock removal works, restoration of rock barriers, rock fences, steel meshes, reinforced concrete walls, anchoring of free meshes, spot bolting of individual rock blocks) were aimed at restoring the road to its previous condition (i.e., before the flooding events of "Daniel" taken place), so that it could be re-opened as soon as possible. It is highlighted that in order to eliminate the hazard to minimum, the correct sizing of interventions requires additional specialized studies (e.g. geological, geotechnical, structural and road design), something that the Department of Technical Works of the Piraeus & Islands Regional Unit has already planned to implement.
It is emphasized that because the phenomena occurring in the study area are dynamic, it is necessary to constantly monitor the behavior of the slopes. This necessity increases during the winter period. It is therefore proposed to monitor the condition of the slopes and the possible development of failures during rainy periods, so that it will be possible to extend the monitoring to other locations, if it is necessary, through the use of early warning systems.

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The work is dedicated to the memory of the Dr, Evert Hoek, who was one of the first engineers who understood and moved to another level the value of Engineering Geology into civil engineering projects.

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