

# Research of Landslide Areas Developed in the Influence Zone of the Right Slope of the Zhinvali Reservoir to Determine Their Dynamics for the Purpose of Traffic Safety

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**How to cite this paper:** Varazashvili, Z., Kakulia, Z., Ramishvili, I., Gaprindashvili, G., Chakhaia, G., Tlashadze, G., & Chutkerashvili, D. (2025). Research of Landslide Areas Developed in the Influence Zone of the Right Slope of the Zhinvali Reservoir to Determine Their Dynamics for the Purpose of Traffic Safety. *Journal of Geoscience and Environment Protection*, 13, 10-21. <https://doi.org/10.4236/gep.2025.132002>

**Received:** December 14, 2024

**Accepted:** February 10, 2025

**Published:** February 13, 2025

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## Abstract

The article presents the results of field, office and laboratory research of landslide areas developed on the right slope of the Zhinvali Reservoir section of the Georgian Military Road, according to which the area of spread of these events, the dynamics of development, the threats arising from them in terms of restricting traffic, and a plan for developing landslide prevention measures are recorded. The underlying rocks of the slopes have been studied, cross-sections have been created, their types and physical and mechanical characteristics have been determined, and the natural and anthropogenic (technogenic) factors that contribute to the origin and development of the aforementioned phenomena have been identified. Based on the results of the study, it can be said that landslide areas developed along the transportation lane are mostly associated with erosion processes developing in small ravines, where the rocks forming the slope are highly eroded and disintegrated. Unregulated surface water runoff has a great impact on their development. There are frequent cases when the landslide dynamics develop in a reverse direction, gradually covering the upper layers of the slope and closely approaching the roadway. Based on desk work and laboratory data, a numerical calculation of the stability conditions (K coefficient) was carried out for typical landslide sites, considering natural factors (seismic events and increased rock moisture). Based on the data obtained as a result of the research, it became possible to develop various types of landslide prevention measures.

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## Keywords

Landslide, Georgia, Geology, Slope Stability, Laboratory

## 1. Introduction

Georgia's mountainous territory and its climatic, geographical and geological environment create all the prerequisites for the spread of natural hazards across most of the country. Among them, landslides occupy a special place. Nowadays, there is almost no mountainous region where the population and industrial or agricultural facilities do not suffer damage from landslides (Gaprindashvili et al., 2021; Varazashvili et al., 2024a; Gaprindashvili et al., 2018; Tedoradze, 2019).

The above-mentioned natural hazard also poses significant threats to transport, especially to the Georgian Military Road along the right slope of Aragvi River Gorge (Figure 1). It should also be noted that the functioning and capacity of this highway are very important not only for Georgia, but also for other countries in the Caucasus and the South. These loads have been further increased by the events of recent years and will probably increase even more in the future, for which our state must be prepared.

In this regard, it must be noted that the aforementioned transport corridor is located in a mountainous terrain. The landscape and geological conditions are complicated, which plays a major role in the development of landslides, all of which negatively affects the safe operation of the road and often causes delays (Figure 1).

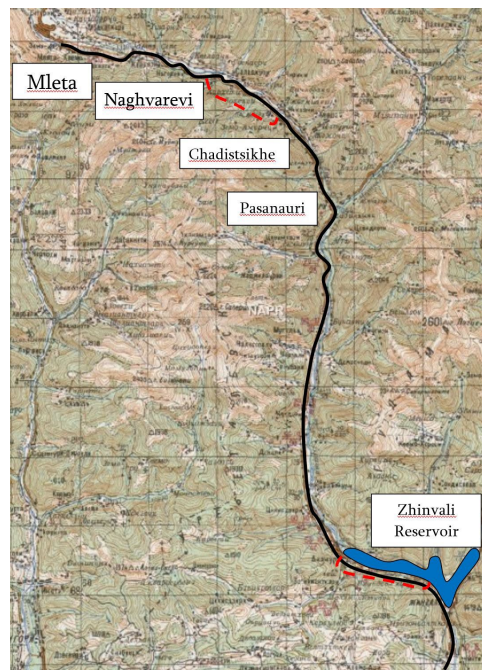
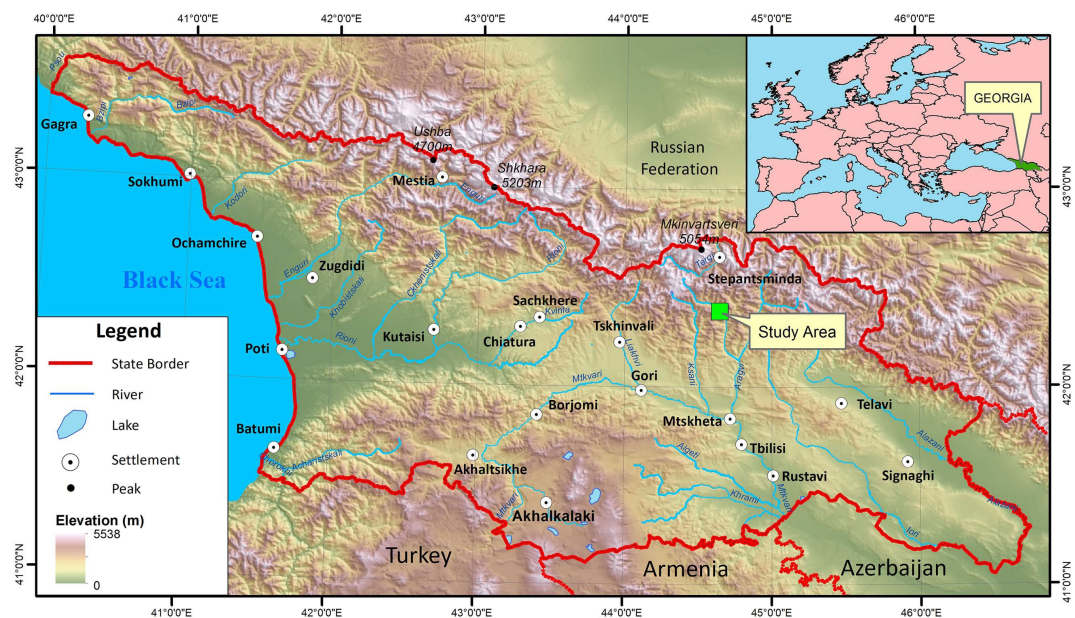


Figure 1. Natakhtari-Mleta road and landslide areas along it.

One group of landslide events prevalent within the study area is concentrated in the vicinity of the Zhinvali Reservoir. They follow the right slope in a continuous line from the reservoir dam almost to the Ananuri fortress and are more or less actively embedded in the heads of erosional cuts formed on this slope, which are closely adjacent to the roadway (**Figure 2**) and pose a threat to traffic. Therefore, by the decision of the authors of the article, this part of our research is dedicated to the area of development of the aforementioned landslide events.

## 2. Study Area

Based on Administrative zoning, study area is located in Dusheti Municipality, Mtskheta-Mtianeti Region. Morphologically is situated in moderate and high mountainous relief subzone, with erosive-tectonic ridges and gorges shown in **Figure 2**, developed on upper Jurassic and Cretaceous suites.



**Figure 2.** Study area.

According to climatic conditions, the study area is characterized by harsh winters and cool summers typical of the medium and high mountainous regions of the southern slopes of the Eastern Caucasus. The average annual temperature is 5 - 6 degrees, the maximum is 30 degrees, the minimum is - 32 degrees. Spring and early summer are characterized by sharp temperature fluctuations: While the average temperature in May does not exceed 8 - 10 degrees, on certain days it can reach 25 degree, which contributes to the rapid melting of snow, and the height of the snow cover exceeds 3.0 m in certain periods.

Another important climatic characteristic is the annual amount of precipitation, which is 1000 mm, especially the daily maximum of 100 - 110 mm, which creates one of the main forming conditions for debris/mudflows (**Construction Climatology, 2008**).

Among the geological factors, the lithological structure is noteworthy. The study area is included in the Mestia-Tianeti tectonic zone and is represented by carbonate-terrigenous flysch of the Berriasian-Valanginian and Hotrivian stages. These layers are built up of clastic limestones and sandstones, turbidites, pelagic marls, limestones, mudstones and shales. Rocks of such geological structure easily succumb to weathering processes, which creates an important prerequisite for the formation of landslide-erosion centers at the head of this valley (Gaprindashvili et al., 2021; Varazashvili et al., 2024b; Lomtadze, 1984).

Unregulated surface water from the roadway also has a significant impact on the development of landslides, draining into the landslide body and increasing the moisture content of the rocks. In addition, they contribute to the further activation of erosion processes.

It should also be noted the impact of seismic activity. The study area is part of the southern Caucasus fold system and is included in the 8-point zone according to the seismic zoning of Georgia. 5 - 6-point earthquakes are not uncommon here (Seismic-Resistant Construction, 2009).

### 3. Methodology and Results

In the study area we have selected, 9 landslide areas are distinguished, which are characterized by relatively higher activity and pose a real threat. These landslides, as mentioned above, are associated with erosional intrusions and their development significantly determines the activity of these landslides, since the deepening of these processes increases the slope steepness, which contributes to the weakening of the stability of the slopes.

Due to the limited scope of the article, it was not possible to provide a detailed description of the nine districts, so two of them were selected, which are typical and contain a large number of common characteristics. These are landslide #4 and landslide #7.

Area #4 is developed in the bed of an eroded ravine and includes both of its slopes, the tongue of which reaches the banks of the reservoir, shown in Figures 3-8.



**Figure 3.** Landslide areas on the right slope of the Zhinvali Reservoir.



**Figure 4.** General view of landslide site #4.



**Figure 5.** Top view of landslide #4.



**Figure 6.** Main rupture of the landslide (#4).



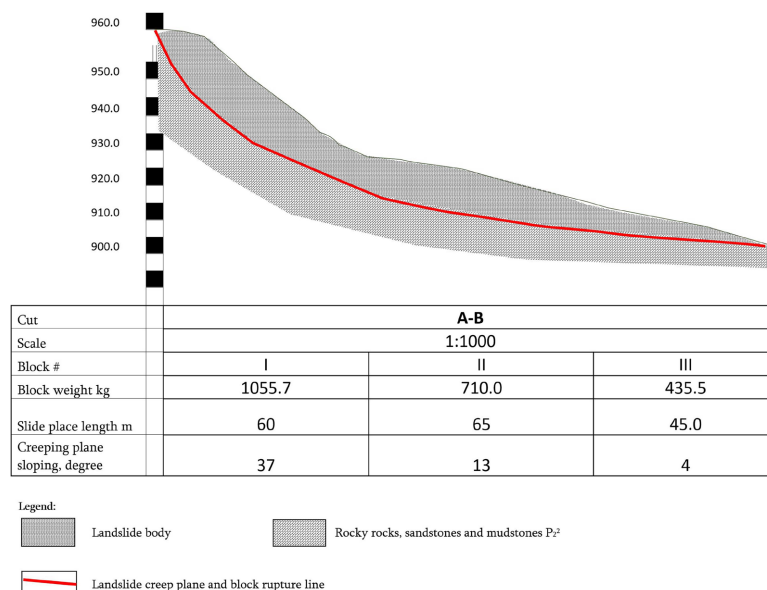
**Figure 7.** Erosion on landslide body #4.



**Figure 8.** The main rupture stage of the landslide body, which is close to the roadway.

Natural and artificial slopes can become unstable. Slope stability analysis is a static or dynamic, analytical or numerical method for assessing slope stability and understanding the causes of a slope failure or the factors that trigger a slope movement. The ratio between shear strength and shear stress expressed as a safety factor defines the slope stability (Rotaru et al., 2022; Fredlund, 1984; Mansour, 2011).

In this regard, samples of the undisturbed structure of the cover rocks were taken. Their physical properties were determined. Their mechanical characteristics were selected based on normative documents. Based on the existing topographic maps and field survey drawings, the estimated landslide creep plane was determined and a schematic section was constructed, on which the slope stability characteristic K coefficient was calculated (Figure 9, Table 1), considering various natural factors (seismic events and rock moisture) (Lomtadze, 1977; Lapiashvili, 2013; Abbaspour et al., 2018; Zhang et al., 2022). Below are the results of the calculations.



**Figure 9.** Geological section of landslide body #4.

**Table 1.** Slope stability assessment in natural and wet conditions (Landslide #4).

| <b>Slope stability assessment, section A-B (soils in natural state, without taking into account seismicity coefficient)</b>     |                |        |               |       |          |                             |          |                  |                        |                              |            |
|---|----------------|--------|---------------|-------|----------|-----------------------------|----------|------------------|------------------------|------------------------------|------------|
| Block #   | Block weight P |        | Slide surface |       |          | Resistance to rock movement |          | Cohesion C       | Seismicity coefficient | Sustainability coefficient K |            |
|   |                |        |               |       |          | $\phi$                      | $tg\phi$ |                  |                        | Block                        | Average    |
|   | t              | degree | sin a         | cos a | Length m | degree                      | tan      | t/m <sup>2</sup> |                        |                              |            |
| I   | 1055.7         | 37     | 0.60          | 0.80  | 60.0     | 18                          | 0.32     | 0.28             | 0                      | 0.46                         |            |
| II  | 710.0          | 13     | 0.22          | 0.97  | 65.0     | 20                          | 0.36     | 0.20             | 0                      | 1.66                         | <b>1.8</b> |
| III   | 435.0          | 4      | 0.07          | 1.00  | 45.0     | 12                          | 0.21     | 0.14             | 0                      | 3.25                         |            |
| <b>Slope stability assessment, section A-B (soils in wet condition, without taking into account the seismicity coefficient)</b> |                |        |               |       |          |                             |          |                  |                        |                              |            |
| Block #   | Block weight P |        | Slide surface |       |          | Resistance to rock movement |          | Cohesion C       | Seismicity coefficient | Sustainability coefficient K |            |
|   |                |        |               |       |          | $\phi$                      | $tg\phi$ |                  |                        | Block                        | Average    |
|   | t              | degree | sin a         | cos a | Length m | degree                      | tan      | t/m <sup>2</sup> |                        |                              |            |
| I   | 1055.7         | 37     | 0.60          | 0.80  | 60.0     | 13                          | 0.23     | 0.16             | 0                      | 0.32                         |            |
| II  | 710.0          | 13     | 0.22          | 0.97  | 65.0     | 13                          | 0.23     | 0.15             | 0                      | 1.06                         | <b>1.3</b> |
| III   | 435.0          | 4      | 0.07          | 1.00  | 45.0     | 9                           | 0.16     | 0.17             | 0                      | 2.52                         |            |
| <b>Slope stability assessment, section A-B (soils in natural state, taking into account seismicity coefficient)</b>             |                |        |               |       |          |                             |          |                  |                        |                              |            |
| Block #   | Block weight P |        | Slide surface |       |          | Resistance to rock movement |          | Cohesion C       | Seismicity coefficient | Sustainability coefficient K |            |
|   |                |        |               |       |          | $\phi$                      | $tg\phi$ |                  |                        | Block                        | Average    |
|   | t              | degree | sin a         | cos a | Length m | degree                      | tan      | t/m <sup>2</sup> |                        |                              |            |
| I   | 1055.7         | 34     | 0.56          | 0.83  | 60.0     | 18                          | 0.32     | 0.28             | 0.05                   | 0.46                         |            |
| II  | 710.0          | 12     | 0.21          | 0.98  | 65.0     | 20                          | 0.36     | 0.20             | 0.05                   | 1.44                         | <b>1.4</b> |
| III   | 435.0          | 3      | 0.05          | 1.00  | 45.0     | 12                          | 0.21     | 0.14             | 0.05                   | 2.21                         |            |
| <b>Slope stability assessment, section A-B (soils in wet condition, taking into account seismicity coefficient)</b>             |                |        |               |       |          |                             |          |                  |                        |                              |            |
| Block #   | Block weight P |        | Slide surface |       |          | Resistance to rock movement |          | Cohesion C       | Seismicity coefficient | Sustainability coefficient K |            |
|   |                |        |               |       |          | $\phi$                      | $tg\phi$ |                  |                        | Block                        | Average    |
|   | t              | degree | sin a         | cos a | Length m | degree                      | tan      | t/m <sup>2</sup> |                        |                              |            |
| I   | 1055.7         | 37     | 0.60          | 0.80  | 60.0     | 13                          | 0.23     | 0.16             | 0.05                   | 0.29                         |            |
| II  | 710.0          | 13     | 0.22          | 0.97  | 65.0     | 13                          | 0.23     | 0.15             | 0.05                   | 0.86                         | <b>0.9</b> |
| III   | 435.0          | 4      | 0.07          | 1.00  | 45.0     | 9                           | 0.16     | 0.17             | 0.05                   | 1.46                         |            |

Similar studies were conducted at landslide site #7, shown in **Figures 10-15** and **Table 2**.



**Figure 10.** Geological section of landslide body #4.



**Figure 11.** Fragment of the main landslide cutoff.



**Figure 12.** Creeping blocks observed in the landslide area.



**Figure 13.** Landslide area, “Drunken Forest”.



Figure 14. Blocky-stepped relief typical of the landslide area.

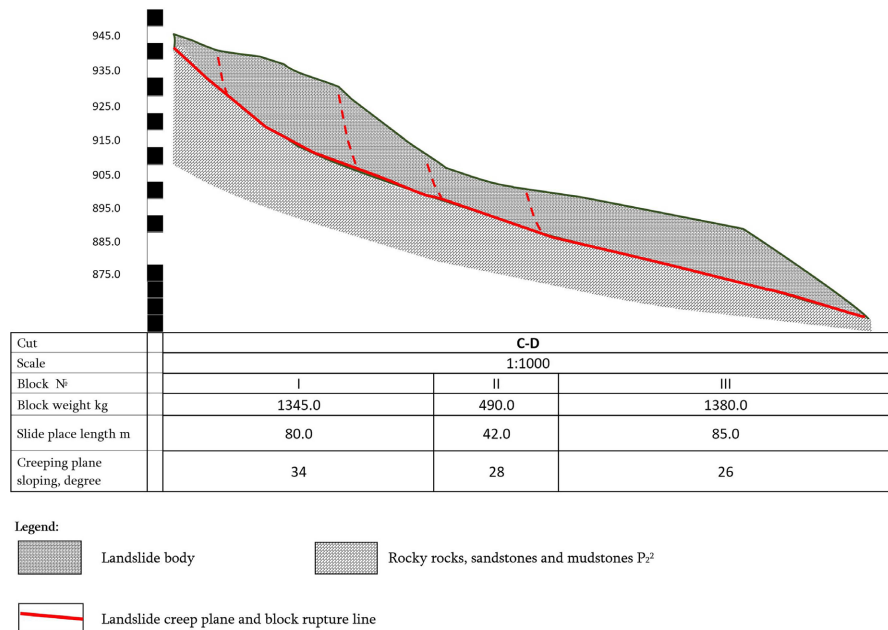


Figure 15. Geological section of landslide body #7.

Table 2. Slope stability assessment in natural and wet conditions (Landslide #7).

| Slope stability assessment, section C-D (soils in natural state, taking into account seismicity coefficient) |                |        |               |       |          |                             |          |                  |                        |                              |            |
|--|----------------|--------|---------------|-------|----------|-----------------------------|----------|------------------|------------------------|------------------------------|------------|
| Block #  | Block weight P |        | Slide surface |       |          | Resistance to rock movement |          | Cohesion C       | Seismicity coefficient | Sustainability coefficient K |            |
|  |                |        |               |       |          | $\phi$                      | $tg\phi$ |                  |                        | Block                        | Average    |
|  | t              | degree | sin a         | cos a | Length m | degree                      | tan      | t/m <sup>2</sup> |                        |                              |            |
| I  | 1345.0         | 32     | 0.53          | 0.85  | 80.0     | 33                          | 0.65     | 0.3              | 0                      | 1.07                         |            |
| II   | 490.0          | 28     | 0.47          | 0.88  | 42.0     | 36                          | 0.73     | 0.31             | 0                      | 1.42                         | <b>1.2</b> |
| III  | 1380.0         | 26     | 0.44          | 0.90  | 85.0     | 28                          | 0.53     | 0.26             | 0                      | 1.13                         |            |

| Slope stability assessment, section C-D (soils in wet condition, taking into account seismicity coefficient) |                |        |               |       |          |                             |          |                  |                        |                              |         |
|--|----------------|--------|---------------|-------|----------|-----------------------------|----------|------------------|------------------------|------------------------------|---------|
| Block #  | Block weight P |        | Slide surface |       |          | Resistance to rock movement |          | Cohesion C       | Seismicity coefficient | Sustainability coefficient K |         |
|  |                |        |               |       |          | $\phi$                      | $tg\phi$ |                  |                        | Block                        | Average |
|  | t              | degree | sin a         | cos a | Length m | degree                      | tan      | t/m <sup>2</sup> |                        |                              |         |

Continued

| I   | 1345.0         | 32     | 0.53          | 0.85  | 80.0     | 21                          | 0.38     | 0.23       | 0                      | 0.64                         |            |
|---|----------------|--------|---------------|-------|----------|-----------------------------|----------|------------|------------------------|------------------------------|------------|
| II  | 490.0          | 28     | 0.47          | 0.88  | 42.0     | 26                          | 0.49     | 0.23       | 0                      | 0.96                         | <b>0.9</b> |
| III   | 1380.0         | 26     | 0.44          | 0.90  | 85.0     | 27                          | 0.51     | 0.21       | 0                      | 1.07                         |            |
| <b>Slope stability assessment, section C-D (soils in natural state, taking into account seismicity coefficient)</b> |                |        |               |       |          |                             |          |            |                        |                              |            |
| Block #   | Block weight P |        | Slide surface |       |          | Resistance to rock movement |          | Cohesion C | Seismicity coefficient | Sustainability coefficient K |            |
|   | t              | degree | sin a         | cos a | Length m | $\phi$                      | $tg\phi$ |            |                        | Block                        | Average    |
| I   | 1345.0         | 32     | 0.53          | 0.85  | 80.0     | 33                          | 0.65     | 0.3        | 0.05                   | 0.96                         |            |
| II  | 490.0          | 28     | 0.47          | 0.88  | 42.0     | 36                          | 0.73     | 0.31       | 0.05                   | 1.27                         | <b>1.1</b> |
| III   | 1380.0         | 26     | 0.44          | 0.90  | 85.0     | 28                          | 0.53     | 0.26       | 0.05                   | 1.00                         |            |
| <b>Slope stability assessment, section C-D (soils in wet condition, taking into account seismicity coefficient)</b> |                |        |               |       |          |                             |          |            |                        |                              |            |
| Block #   | Block weight P |        | Slide surface |       |          | Resistance to rock movement |          | Cohesion C | Seismicity coefficient | Sustainability coefficient K |            |
|   | t              | degree | sin a         | cos a | Length m | $\phi$                      | $tan$    |            |                        | t/m <sup>2</sup>             | Block      |
| I   | 1345.0         | 32     | 0.53          | 0.85  | 80.0     | 21                          | 0.38     | 0.23       | 0.05                   | 0.57                         |            |
| II  | 490.0          | 28     | 0.47          | 0.88  | 42.0     | 26                          | 0.49     | 0.23       | 0.05                   | 0.85                         | <b>0.8</b> |
| III   | 1380.0         | 26     | 0.44          | 0.90  | 85.0     | 27                          | 0.51     | 0.21       | 0.05                   | 0.95                         |            |

Below is **Table 3**, which clearly shows the impact that increasing two main factors—rock moisture and seismic shocks.

**Table 3.** Landslide slope stability coefficient.

| Landslide #           | Landslide slope stability coefficient K   |  |   |  |
|-----------------------|---|--|---|--|
|                       | Natural state of the soil, without taking into account the seismicity coefficient | Wet condition of soils, without taking into account the seismicity coefficient | Natural condition of the soil, taking into account the seismicity coefficient | Soils in a wet state, taking into account the seismicity coefficient |
| Landslide #4, Cut A-B | 1.8   | 1.3  | 1.4   | 0.9  |
| Landslide #7, Cut C-D | 1.2   | 0.9  | 1.1   | 0.8  |

#### 4. Conclusion

- The landslide bodies developed on the right slope of the Zhivnali Reservoir are mainly connected to the headwaters of erosion ravines and the adjacent slopes, which is why they are closely adjacent to the transport corridor of the Natkhtari-Mleta section of the Georgian Military Road.
- As a result of the conducted field, laboratory and office work, 9 main landslide areas (bodies) were identified within the study area, which attracted attention

to their size, development dynamics and the prospect of possible hazards. Calculations were conducted on two of them to determine numerical stability indicators, which clearly showed that landslide bodies will activate under certain factors, and if we consider their location in relation to the road, we may get undesirable results.

- The development of these landslides is significantly influenced by factors such as increased moisture content of the underlying rocks and seismic events. Anthropogenic factors also contribute significantly to the development of these events—vibrations caused by continuous flows of heavy-duty vehicles and unregulated surface water flows that freely flow onto landslide slopes.
- The study found that in order to stabilize landslides, it is first necessary to clean and restore existing culverts and drainage channels to prevent water drained from the roadway from flowing onto landslide slopes. Light-weight slope retaining supports should be constructed, especially on damaged sections. It is necessary to prepare a project to study the Natakhtari-Mleta highway in order to assess the condition of this important transport corridor and its capacity prospects.

### Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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