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GEOPOLYMER REINFORCEMENT OF ROAD EMBANKMENT SLOPES UNDER LOW SEISMIC LOADING CONDITIONS

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Abstract. Lithuania is classified as a region of low seismic hazard; however, even low-intensity dynamic actions may affect the stability of marginally stable geotechnical structures. Road embankment slopes are particularly sensitive to changes in stress state caused by traffic loads and dynamic effects. This study evaluates the stability of a road embankment slope reinforced with geopolymer (georesin) columns under static and simplified seismic loading conditions. Slope stability analyses were performed using an analytical limit equilibrium approach implemented in the GEO5 Slope Stability software, applying the Morgenstern–Price method. Dynamic effects were introduced using pseudo-static horizontal and vertical acceleration coefficients K_h and K_v. A dense sand embankment with a height of 5.0 m and a slope angle of 40° was analyzed. Geopolymer reinforcement was simulated using columns with thicknesses of 50 mm, 100 mm, and 150 mm. Stability was evaluated using the utilization factor V_u. The results show that geopolymer reinforcement reduces the utilization factor by approximately 2.5–7.6%, while horizontal dynamic actions increase utilization by approximately 8–9%. Vertical dynamic effects were found to be less critical. The study confirms that geopolymer reinforcement is an effective solution for improving road embankment slope stability in regions of low seismic hazard.

Keywords: geopolymers, georesin, slope stability, road embankment, pseudo-static analysis, seismic loading, ground improvement.

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1. Introduction

Lithuania is generally classified as a low seismic hazard region within Europe (Pagani et al., 2018). The country is located on the stable East European Craton, where tectonic activity is limited and strong earthquakes are rare. Historical records indicate that only a small number of seismic events have been documented since the 17th century, most of them with magnitudes below 5.0 (Lazauskienė et al., 2012). Nevertheless, the seismicity of the Baltic region cannot be considered entirely negligible. The 2004 Kaliningrad earthquakes (M 5.0–5.3), which were felt across Lithuania, demonstrated that even moderate seismic events may affect large areas and highlighted the need to reassess seismic effects on engineering structures.

According to the EFEHR Risk Map (2025), Lithuania belongs to the lowest seismic hazard category, with peak ground acceleration (PGA) values typically below 0.04 g. Global seismic hazard models confirm this classification, indicating very low but non-zero seismic risk, for example assigning Vilnius city a PGA of approximately 0.008 g for a 10% probability of exceedance in 50 years. While such acceleration levels are small compared to those in seismically active regions, they may still be relevant for geotechnical structures that are sensitive to changes in stress state or external dynamic actions. In addition to natural earthquakes, transport infrastructure may also be affected by vibration-type loads originating from traffic, construction activities, or other transient dynamic sources, which in some cases may occur more frequently than seismic events.

In geotechnical engineering practice, the influence of seismic actions on slope stability is often evaluated using simplified pseudo-static approaches. Earthquake effects are introduced into stability analyses through horizontal and vertical acceleration coefficients, commonly expressed as the factor of horizontal acceleration K_h and the coefficient of vertical earthquake K_v (Janutyte et al., 2013). The horizontal acceleration factor K_h represents the ratio between horizontal seismic acceleration and gravitational acceleration and introduces an additional horizontal force acting on the soil mass, directly reducing the factor of safety. The vertical coefficient K_v modifies the effective unit weight of soil and surcharge loads and may either increase or decrease the stabilizing forces depending on its sign and magnitude. Previous studies have shown that vertical seismic effects can be significant and, in certain conditions, comparable to or even greater than horizontal effects (Tsai & Liu, 2019). Therefore, both coefficients should be considered when assessing slope stability under dynamic loading conditions.

Road embankment slopes represent one of the most vulnerable elements of transport infrastructure, as their stability depends on soil strength parameters, geometry, drainage conditions, and loading regime. Many embankments are constructed from heterogeneous or relatively weak soils and operate with limited safety margins under static conditions. Even low-intensity dynamic actions, such as those represented by small K_h and K_v values, may reduce stability and increase deformations, especially in slopes that are already close to critical equilibrium (Das & Maheshwari, 2019). This sensitivity makes road embankment slopes a suitable object for evaluating the combined influence of static and simplified seismic loading.

In recent years, increasing attention has been paid to innovative ground improvement techniques aimed at enhancing slope stability without extensive reconstruction. One such method is soil strengthening using geopolymers, commonly referred to as georesins. Polyurethane-based georesins are injected into the soil, where they expand and bind soil particles, forming a composite material with improved stiffness, cohesion, and resistance to environmental influences (Sabri & Shashkin, 2018). Previous applications have demonstrated their effectiveness in stabilizing slopes, improving pavement performance, and reinforcing granular materials under variable loading conditions (Barabanova, 2021; Liu et al., 2024). Compared to traditional reinforcement methods, georesin solutions are relatively fast to install, minimally invasive, and adaptable to local instability zones (Skuodis et al., 2024).

Although Lithuania is characterized by low seismicity, the combined effect of weak dynamic actions and marginally stable embankment slopes should not be neglected, particularly when evaluating the performance of innovative soil improvement methods. The lack of studies addressing slope stabilization with georesins under seismic or pseudo-static loading conditions in low seismic regions represents a practical and scientific gap. Therefore, this study aims to evaluate the stability of road embankment slopes reinforced with georesin by applying simplified seismic loading through K_h and K_v coefficients. The results contribute to a better understanding of the effectiveness of georesin-based stabilization measures and their potential application in transport infrastructure even in regions of low seismic hazard.

2. Methodology

The stability analysis was performed for a road embankment slope using an analytical limit equilibrium approach implemented in the GEO5 Slope Stability software. The analyzed geometry represents a typical transport infrastructure embankment, as shown in Figure 1, where the slope height is 5.0 m and the inclination angle is 40°. The embankment is composed of dense sand and supports a traffic-loaded road at the crest.

The soil mass was modeled as a homogeneous layer using the Mohr–Coulomb failure criterion under effective stress conditions. The geotechnical parameters used in the slope stability calculations are presented in Table 1.

Traffic-induced surcharge loads were applied at the crest of the slope in accordance with LST EN 1991-2 (2012), adjusted for geotechnical structures following the

Table 1. Soil parameters used in the slope stability analysis

Sand			
Parameter	Symbol	Value	Unit
Unit weight	γ	17.0	kN/m³
Saturated unit weight	γ_{sat}	17.5	kN/m³
Effective friction angle	φ′	41.5	°
Effective cohesion	c′	1.0	kPa

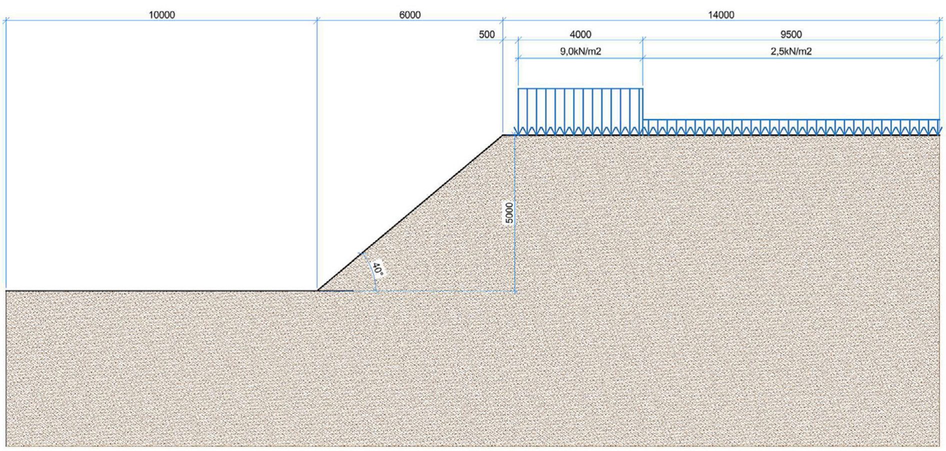

Figure 1. Calculation scheme of the road embankment slope with applied traffic loads

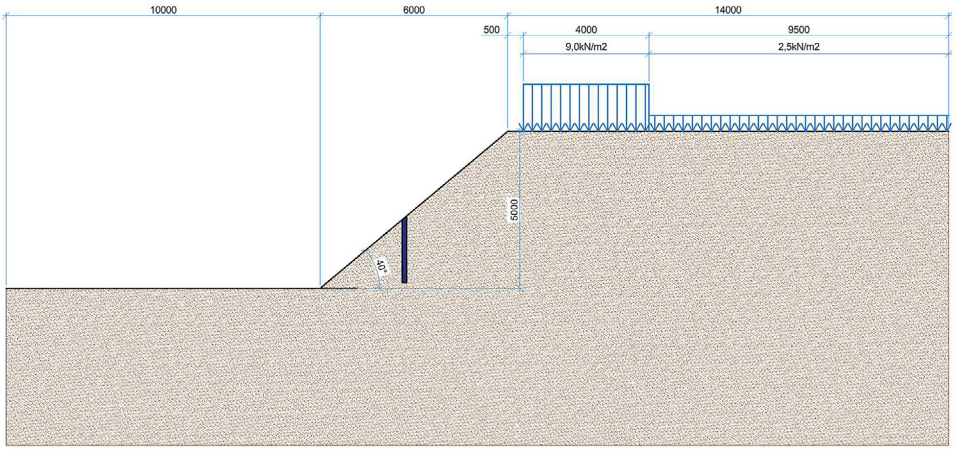

Figure 2. Calculation scheme of the road embankment slope reinforced with geopolymer columns

recommendations of the Finnish Transport Agency NCCI 7 guidelines (2017). Based on these provisions, two characteristic distributed loads were considered: p_1 = 9.0 kPa acting over a 4.0 m wide zone near the slope crest, and p_2 = 2.5 kPa acting over the remaining part of the embankment crest, as illustrated in Figure 1.

Slope stability was evaluated using the Morgenstern–Price method, which is implemented in GEO5 as a rigorous limit equilibrium method. This method satisfies all three equilibrium conditions (horizontal forces, vertical forces, and moments) and allows non-zero interslice forces with variable inclination. The factor of safety is obtained through an iterative procedure involving both the inclination of interslice forces and the safety factor itself. This method was selected due to its reliability and suitability for analyzing slopes under combined static and pseudo-static loading.

Dynamic effects were introduced using a pseudo-static approach by applying horizontal and vertical acceleration coefficients K_h and K_v. The analyzed values ranged from 0.00025 to 0.05, covering low-intensity dynamic actions characteristic of regions with low seismic activity. Horizontal acceleration K_h was applied as an additional inertial force acting on the soil mass, while the vertical coefficient K_v modified the effective unit weight of soil and surcharge loads.

Slope reinforcement was simulated using geopolymer (georesin) columns installed within the slope body, as shown schematically in Figure 2. The geopolymer columns were assumed to be 2.0 m long, and three different thicknesses were analyzed: 50 mm, 100 mm, and 150 mm. The geopolymer material was modeled using a Mohr–Coulomb criterion with a unit weight γ = 0.5 kN/m^3 and undrained cohesion c_u = 70 kPa, representing the improved mechanical behavior of soil treated with polyurethane-based resin.

The stability results were expressed using the utilization factor V_u, which is calculated as the ratio between the sliding moment M_a and the resisting moment M_p. A slope is considered stable when V_u < 100%. This representation allows a clear comparison between different reinforcement configurations and loading scenarios.

3. Results

The results of the slope stability analysis indicate that geopolymer reinforcement significantly improves the stability of the embankment slope under both static and dynamic loading conditions. In the reference configuration, the utilization factor remained below 100%, confirming acceptable stability. The influence of geopolymer thickness on slope performance is clearly demonstrated in Figure 3. For geopolymer thicknesses of 50 mm, 100 mm, and 150 mm, the stability improvement corresponded to approximately 2.5%, 5.8%, and 7.6% reductions in utilization, respectively, compared to the unreinforced slope. This confirms that increasing geopolymer thickness enhances shear resistance along potential slip surfaces and increases the overall stability margin.

The effects of horizontal and vertical dynamic actions differ significantly. Increasing the horizontal acceleration coefficient K_h leads to a progressive increase in utilization for all geopolymer thicknesses. As shown in Figure 4, when

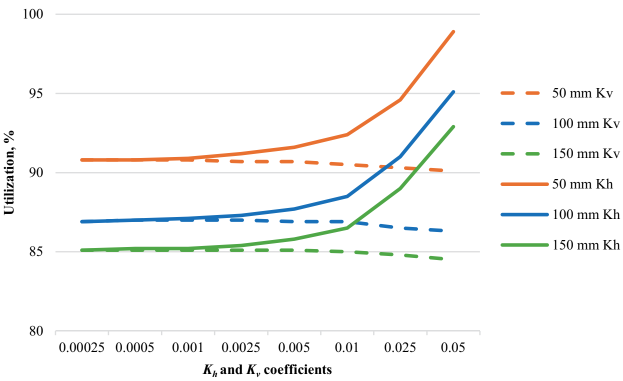

Figure 3. Influence of geopolymer thickness on slope stability expressed by utilization factor V_u

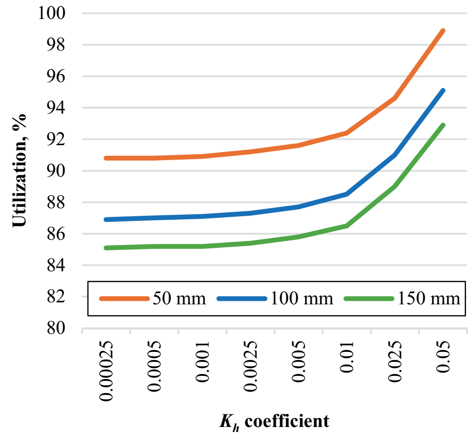

Figure 4. Influence of horizontal acceleration coefficient K_h on slope stability for different geopolymer thicknesses

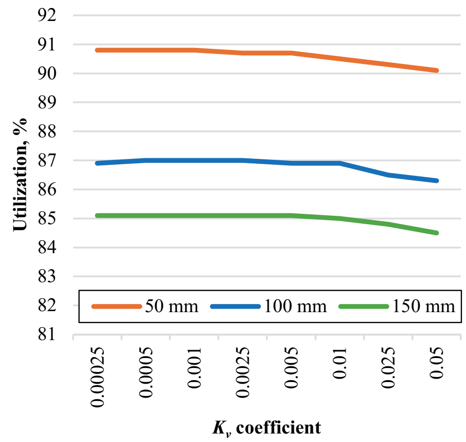

Figure 5. Influence of vertical acceleration coefficient K_v on slope stability for different geopolymer thicknesses

K_h increases from 0.00025 to 0.05, the utilization factor increases by approximately 8–9%, indicating a clear reduction in slope stability. This trend is consistent across all reinforcement configurations and highlights the dominant role of horizontal dynamic actions.

In contrast, the influence of the vertical acceleration coefficient K_v is less critical. As illustrated in Figure 5, increasing K_v values results in a slight decrease or only marginal change in utilization. This behavior is associated with the reduction of effective unit weight caused by positive K_v values, which reduces driving forces acting on the slope. For the analyzed geometry and soil conditions, vertical dynamic effects did not lead to unfavorable stability conditions.

Combined K_h and K_v analyses confirm that horizontal acceleration governs the dynamic response of the slope (Figure 6). Although increasing K_v reduces stability, geopolymer-reinforced slopes consistently exhibit lower utilization values compared to the unreinforced case. Among the analyzed configurations, the 150 mm geopolymer thickness provided the most favorable performance under

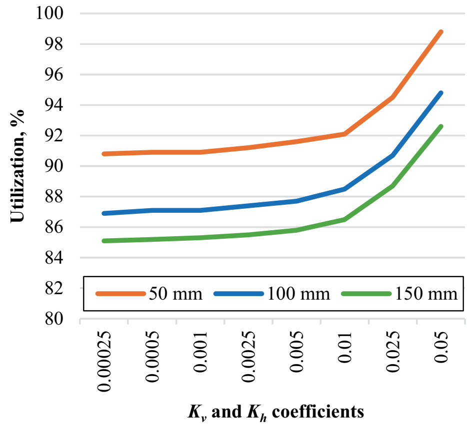

Figure 6. Combined influence of horizontal and vertical acceleration coefficients (K_h and K_v) on slope stability

combined dynamic loading, maintaining utilization well below the critical limit.

Overall, the results demonstrate that geopolymer reinforcement is an effective method for improving the stability of road embankment slopes. Even under simplified seismic loading conditions, reinforced slopes retain a higher safety margin, indicating that georesin-based solutions can enhance the resilience of transport infrastructure in regions characterized by low seismic hazard.

4. Conclusions

Based on the performed analytical slope stability analyses under static and simplified seismic loading conditions, the following conclusions can be drawn:

1. The analyses showed that geopolymer (georesin) reinforcement effectively improves the stability of road embankment slopes. Increasing geopolymer thickness from 50 mm to 150 mm reduced the utilization factor V_u by approximately 2.5–7.6%, demonstrating a clear stabilizing effect.
2. Horizontal dynamic actions represented by the coefficient K_h have a significant influence on slope stability. Increasing K_h values from 0.00025 to 0.05 resulted in an increase of the utilization factor by approximately 8–9%, indicating that horizontal acceleration governs the dynamic response of the slope.
3. Vertical dynamic actions represented by the coefficient K_v showed a minor influence on slope stability. For the analyzed geometry and soil conditions, increasing K_v values caused only small changes or a slight improvement in stability.
4. The results confirm that even in regions of low seismic hazard, simplified seismic loading may noticeably affect marginally stable road embankment slopes, while geopolymer reinforcement provides an effective measure to maintain an adequate safety margin.

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Author contributions

VK conceived the research problem and contributed to the formulation of the problem statement, practical background, and application-oriented aspects of the study. AS performed the calculations. MZ conducted the literature review, analyzed the results, and wrote the manuscript. RK contributed to all stages of the work and performed overall verification and review. All authors read and approved the final manuscript.

Disclosure statement

The authors declare that they have no competing financial, professional, or personal interests.

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GEOPOLIMERAIS SUSTIPRINTŲ KELIŲ PYLIMŲ ŠLAITŲ STABILUMAS MAŽO SEISMINIO AKTYVUMO SĄLYGOMS

Santrauka. Lietuva priskiriama mažo seisminio aktyvumo regionui, tačiau net ir nedideli dinaminiai poveikiai gali turėti įtakos ribinio stabilumo praradimui geotechninėse konstrukcijose. Kelių pylimų šlaitai yra ypač jautrūs transporto sukeliamiems dinaminiams poveikiams. Šiame darbe vertinamas geopolimeru sustiprinto kelių pylimo šlaito stabilumas esant statinėms ir supaprastintoms seisminėms apkrovoms. Skaičiavimai atlikti taikant analitinį ribinės pusiausvyros metodą naudojant GEO5 *Slope Stability* programą ir Morgenstern–Price metodiką. Dinaminiai poveikiai įvertinti pseudostatiniais horizontalaus ir vertikalaus pagreičio koeficientais K_h ir K_v. Analizuotas 5,0 m aukščio ir 40° nuolydžio smėlio pylimas. Stiprinimas geopolimeru modeliuotas taikant 50 mm, 100 mm ir 150 mm storio kolonas. Stabilumas vertintas taikant išnaudojimo koeficientą V_u. Nustatyta, kad stiprinimas geopolimeru sumažina išnaudojimo koeficientą apie 2,5–7,6 %. Horizontalių dinaminių poveikių didėjimas išnaudojimo koeficientą padidina apie 8–9 %, o vertikalūs dinaminiai poveikiai turėjo mažesnę įtaką. Gauti rezultatai rodo, kad geopolimerai yra efektyvi priemonė didinant kelių pylimų šlaitų stabilumą net ir mažo seisminio aktyvumo regionuose.

Reikšminiai žodžiai: geopolimerai, poliuretaninė derva, šlaito stabilumas, kelių pylimai, pseudostatinė analizė, seisminė apkrova, grunto stiprinimas.