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On the Performance and Related Design Considerations of Geosynthetic Reinforced Soil Structures under Seismic Conditions

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Abstract This paper focuses on the methodology of geosynthetic reinforced soil (GRS) used in the construction of retaining structures in seismically active regions. The use of GRS in the construction of steep slopes, retaining walls and bridge abutments is well established with many successful examples around the world. These structures show favourable performance under complex boundary conditions such as extremely dynamic loads. Compared to conventional retaining walls, GRS resist seismic loads with less deformation and less risk of failure due to their flexible and ductile nature. Seismic shake table tests on a block wall reinforced with woven geogrids were carried out by Ling et al. (2003). The test setup, program and main results of this study are summarised. The second part is devoted to the seismic geotechnical design of GRS. Established design approaches are presented and the normative requirements of Eurocode 7, Eurocode 8 and some national annexes are outlined. The paper concludes with two case studies in seismically active regions.

Keywords geosynthetic reinforced soil, Earthquake, Block wall, geogrid

Introduction

In the construction industry, geosynthetics are often used for the construction of embankments on soft soils, base courses, protective barriers or retaining structures. Their good performance, distinctive properties, wide range of applications and cost effectiveness are the main reasons for their use. Numerous case studies reflect their exceptional load-bearing capacity, stability and effectiveness under challenging conditions such as progressive settlement or slope deformation (Alexiew and Silva 2007; Detert and Fantini 2017).

When exposed to large ground movements (such as large settlements on compressible soils, or even larger and more abrupt movements as can occur in mining subsidence areas), reinforced earth structures are known to respond effectively (BS 8006-1:2010). The remarkable flexibility of geosynthetic retaining structures allows them to be built in very confined spaces and under challenging conditions, such as densely populated urban areas or mountainous regions (Alexiew and Hangen 2012). According to Tatsuoka et al. (1998), they exhibit exceptional behaviour during earthquake-induced seismic loading events. Even if subjected to extreme seismic events, such structures demonstrate the ability to absorb seismic energy and act as a coherent structure, minimizing the resulting deformations (Ling et al. 2005).

Seismic hazards in Serbia

All critical infrastructure projects, including transport routes, bridges, dams, and structures of civil defence, shall be adequately designed to withstand ground shaking without collapse. The impact of seismic activity on both ultimate and serviceability states of the designed structures should be considered. In the Balkan Peninsula, as well as in Serbia, seismicity needs to be properly considered. Fig. 1 shows the gravitational acceleration for Serbia for a return period of 475 years with a probability of exceedance of 10% in 50 years (SSS 2018).

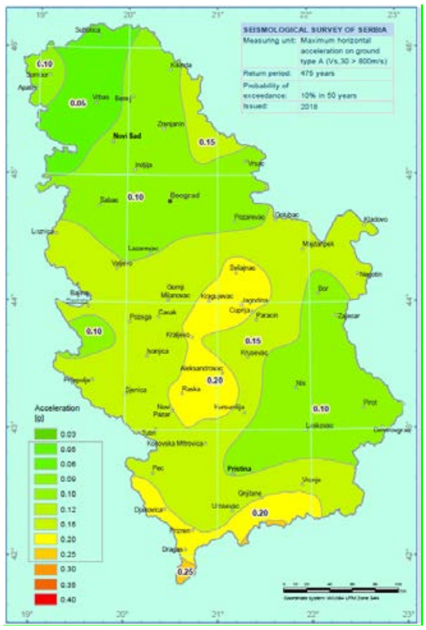

Figure 1 Seismic hazard map of Serbia showing the probability exceedance of 10% in 50 years (Seismological Survey of Serbia 2018).

Furthermore, Fig. 2 shows the earthquake zonation in Serbia based on macroseismic intensity. As can be seen, the whole terrain of Serbia can be seismically active. However, the distribution is not uniform (SSS 2018). A comprehensive study on the seismic situation of Serbia has been done by Blagojevic et al. (2023). Blagojevic et al. (2023) have worked on the classification of residential buildings in Serbia and in the seismic areas. In this study it has been shown that for the return period of 475-year PGA values between 0.05 g to 0.25 g can be expected in Sebia depending on the region. Moreover, for the two populated cities of Belgrade and Novi Sad PGA values of 0.10-0.14 can be expected Therefore, it can be concluded that the design of retaining structures in Serbia should be conducted with careful consideration of the related codes for seismic design.

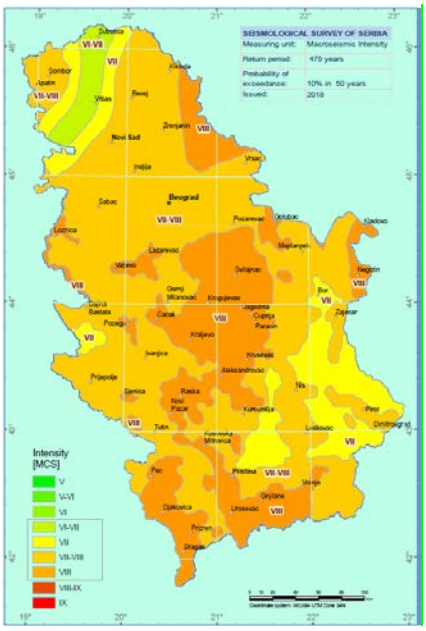

Figure 2 Seismic hazard map of Serbia showing the intensity zones (Seismological Survey of Serbia 2018).

Seismic design methods and standards

There are various methods used to design GRS structures used worldwide. Both analytical and numerical tools can be used for the design purposes. Three categories can be constructed from the existing methods:

- Pseudo-static methods (based on Mononobe-Okabe approach)
- Pseudo-Dynamic methods
- Displacement methods (based on Newmark sliding block models)

The pseudo static design approach is used in the Eurocode and in most standards dealing with seismic design. The effects of the earthquake are represented by a force applied to the structure. This force is often applied as a percentage of the gravity force. The design acceleration differs in different parts of the world and is defined by standards of national origin.

Consideration of GRS in seismic design

The conditions under which the horizontal kh and vertical ground acceleration coefficients kv are considered simultaneously vary around the world. Since the vertical coefficient is more important for the foundation systems, the horizontal coefficient will undoubtedly have a greater impact on the stability design of retaining structures (Detert and Russo 2019).

As with a static design, a seismic design of a GRS retaining wall must satisfy both external and internal stability requirements. Sliding, overturning (eccentricity), global stability and bearing capacity are external failure modes. Rupture, pull-out, stripping of reinforcement or failure of other structural elements such as facing are internal modes of failure.

The most relevant properties of the geosynthetic reinforcement materials used in GRS retaining structures that need be considered in a seismic design are:

- Long-term tensile strength
- Load-strain behavior Interaction with surrounding soil.

Consideration of tensile strength

The seismic action on GRS retaining walls consists of the inertial load on the wall itself, the seismic active load from the retained soil and surcharge loads. The tensile strength of the reinforcement must be sufficient to resist the tensile forces produced by seismic and static actions.

Consideration of load-strain behavior

Load-strain properties of the reinforcement are important for correct modelling since they determine the deformation behaviour of GRS (El-Emam and Bathurst 2004).

Numerical analysis data on the performance of GRS under seismic conditions indicate that, under static conditions, total wall displacements decrease with increasing reinforcement stiffness. Among other factors, foundation conditions, i.e., whether the reinforced soil system is free to slide or restricted to rotation at the toe, have a significant effect on wall displacements for structures subjected to harmonic ground motions. As the stiffness of the reinforcement increases, the effect of the toe constraint on wall displacements decreases (Bathurst and Hatami 1998).

Consideration of interaction in GRS

The interaction between the geosynthetic and the soil as well as the interaction between a reinforced soil block and the retained soil, is critical for seismic design. For cohesionless soils, it is assumed that there is no change in the peak friction angle due to seismic excitation. For internal stability analysis (facing-to-GRS), the interfacial friction angle δ is assumed to be equal to $2\phi/3$. For external stability analysis (GRS-to-retained soil) the interface friction angle is assumed to be equal to ϕ (Bathurst and Cai 1995).

As another advantage of the geogrids in the seismic situation, the flexibility of the geogrids can be named. The flexibility of geogrids allows them to deform under loading, redistributing stresses and effectively dissipating seismic forces. Detert and Lavasan (2018), investigated the interaction relevant characteristics of geosynthetics under static and dynamic loading. The authors showed that the geogrids with very high bending stiffness absorb the compaction energy and may reduce the resistance of the soil particles due to an elastic rebound from the stiff geosynthetic which consequently can cause small cavities in the compacted soil. In contrast a higher density and consequently higher shear strength can be achieved using geogrids with relatively low bending stiffness due to the higher adaptability of the geogrid between soil particles. This fact causes higher confinement effect which results in lower deformations in the structure. This matter becomes more significant in the case of the dynamic loading and in the seismic situations since the stress state, changes permanently in the system and the soil particles require a permanent confinement. In the same way the rebounding effect of stiff geogrids can be more extreme in the dynamic loading situation (Detert and Lavasan 2018).

Large-scale seismic shaking table tests

In the last years several studies on the performance of GRS retaining walls under seismic loading were carried out using shaking table technique. A series of tests were performed on a half-scale shaking table test model of a metal strip-reinforced earth wall by Chida et al. (1985). A numerical model created by Segrestin and Bastick (1988) using finite element modelling (FEM) showed good agreement with the findings of Chida et al. (1985). The results of shaking table testing on a reinforced embankment confined by two 2.5 m high walls made of gabion baskets and an outer continuous concrete panel were published by Murata et al. in 1994. Sakaguchi (1996) tested a 1.5-meter-tall model of a reinforced wall on a shaking table (Hatami and Bathurst 1998). Seven reduced-scale GRS models were investigated by Cubrinovski, Bowman and Jackson under seismic excitation using the University of Canterbury shake-table (2010). As part of TRB's National Cooperative Highway Research Program (2012), a large-scale shake table test was conducted to investigate the performance of a GRS-supported bridge abutment.

Although, the test programmes mentioned above confirm the favourable findings by Tatsuoka et al. (1998), the small number of experimental and numerical studies, the limited nature of each study, and the wide range of results do not allow for a precise quantification of the seismic response of GRS retaining structures.

Full Scale Seismic Testing by Ling et al.

In 2003, the University of Columbia conducted full-scale seismic testing of a block wall reinforced with woven PET geogrids to assess its performance in heavy seismic loads. The testing aimed to analyze the internal and external behavior, evaluate the frictional bond between geogrid and concrete blocks, and compare actual behavior and loads with design predictions (Ling et al. 2005). Three 2.8 m high retaining walls were tested using fine sand as the backfill material and two types of woven geogrid with different tensile strengths and made of different raw materials. The hollow core concrete blocks used weighed 34 kg each and were 200 mm high, 300 mm deep, and 450 mm wide. The detail of the connection between the Allan Blocks and the Huesker geogrid is shown in Fig. 3.

Figure 3 Blocks to geogrids connection detail (Ling et al., 2005).

Three tests were carried out using horizontal and vertical excitations with different peak accelerations. The peak was scaled to 0.4g in the first shaking and 0.8g in the second. The results showed that the block wall system with woven geogrid reinforcement performed effectively under seismic conditions.

Settlement was detected after the second excitation and reducing the vertical space between geogrid layers from 60 cm to 40 cm greatly reduced settlement. Horizontal displacement was less than 10 mm after the first stimulus, but was greater during the second stimulus, with test walls 1, 2, and 3 being displaced by a maximum of 100 mm, approximately 80 mm, and slightly less than 80 mm, respectively. The horizontal displacements induced in test 1 are shown in Fig. 4.

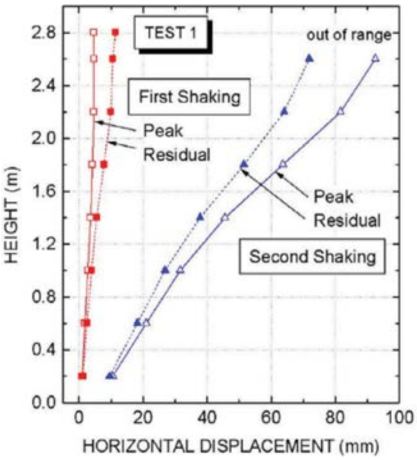

Figure 4 Horizontal displacements at Test 1 (Ling et al., 2005).

Even at very high seismic accelerations of around 0.8g, none of the three walls failed. With a vertical acceleration of 50% of the horizontal acceleration in test 3, no failure occurred. It was found that a closer spacing of the geogrid layer significantly improved the deformation behaviour of the wall. At a maximum acceleration of 0.4g, the measured deformation was insignificant. At a significant acceleration of 0.8g, good performance was still recorded. No collapse of the frictional bond between the blocks and the geogrid layers was observed during the test.

Case study in seismically active regions

Many GRS retaining walls, steep slopes and bridge abutments have been built in recent years in seismic regions, e.g., on the Balkan Peninsula. Due to the high attractiveness of these structures in terms of construction speed and cost, adaptability, low environmental impact, excellent performance under seismic loads, etc., their number is constantly increasing.

One of the most recent projects in the Balkan Peninsula is the Vlora bypass in Albania. It is part of the Adriatic-Ionian Highway and is one of the most important national infrastructure projects in Albania. Its purpose is to improve the flow of traffic along the Ionian coast for travelers and tourists heading for the Riviera. The project consists of 29 km of dual carriageway, including 5 bridges, 2 underpasses, 15 interchanges and 3.6 km of retaining walls, most of which were constructed using GRS. An overview of one of the sections with GRS is shown in Fig. 5.

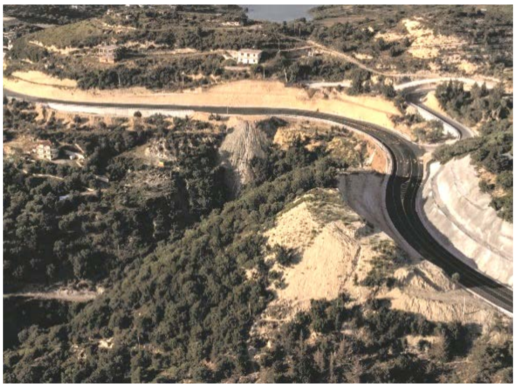

Figure 5 Overview of one of the GRS sections (WBIF, www.wbif.eu).

The site extends over mountainous terrain and is characterized by complex topography with steep irregular slopes, challenging geological and hydrological conditions and a lack of access for construction. There is also a high level of seismic activity in the area. With PGA values of 0.2g and a 475-year return period, a seismic design had to be carried out alongside the static design (Pagani et al. 2018).

Due to the specific topography of the site, with steep mountain slopes, all the retaining structures had to be constructed in a very confined space, with little access for the delivery of materials and construction equipment. Some slopes had to be cut and excavated, while other parts of the designed road had to be backfilled. GRS retaining walls were used to maintain the required geometry, retain soil masses, and ensure the stability of the road structures. Fig. 6 shows some of the cut and fill sections of the road.

Figure 6 Cut and fill sections (TIRANA post, www.tiranapost.al).

Fortrac Natur facing system, developed by Huesker, was used because it allows the GRS retaining walls to be constructed quickly and cost-effectively. The system consists of the following components:

- Flexible geogrids for reinforcement, i.e., to provide tensile strength and improve the stability and serviceability of the wall
- Soil as fill material
- Erosion protection grids or mats to protect the fill from erosion
- Temporary frontal formwork made of bended steel mesh with bracing bars to facilitate installation of the geogrids

Fig. 7 shows a typical cross-section detail of Fortrac Natur facing system.

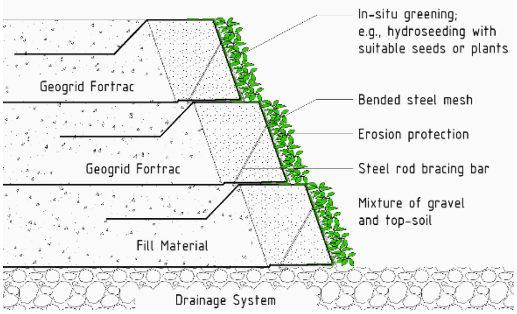

Figure 7 Fortrac Natur facing system detail (Huesker).

The slope to the vertical of the facing was set at 70°. The flexibility of the GRS solution allowed elements such as concrete culverts or bridge abutments to be easily integrated into the retaining walls. One of the GRS retaining walls is shown in Fig. 8.

Figure 8 GRS retaining wall (Huesker).

The GRS retaining walls were designed in accordance with the requirements of Eurocode 7 (EN 1997-1:2004) and Eurocode 8 (EN 1998-1:2004, EN 1998-5:2004) using the partial safety factor approach. Both static (permanent) and seismic design situations were analysed. Internal, compound and external (global) stability were estimated using the Bishop circular slice method (Fig. 9) and the vertical slice method, which analyses polygonal slip planes similar to the Janbu approach, but taking into account the shear resistance between the blocks. Bearing capacity, sliding, and overturning checks were also carried out.

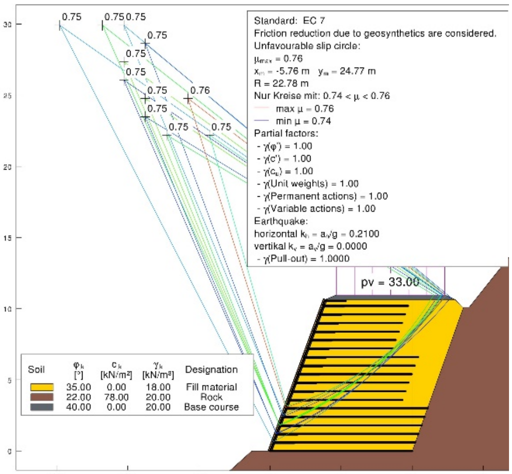

Figure 9 Stability analysis, Bishop method (Huesker).

Coefficient of horizontal acceleration for internal forces k_h was estimated to be equal to 0.21. The calculation was carried out according to §4.1.3.3 of EN 1998-5:2004 for a PGA value of 0.3g, an importance factor of 1.4 (importance class IV, Table 4.3 EN 1998-5:2004) and a soil factor of 1.0 (ground type A, Table 3.2 EN 1998-5:2004).

A large part of the project (approx. 85%) was successfully completed in 2021 and 2022. The simplicity and low equipment requirements of the GRS principle allowed the retaining walls to be constructed quickly, facilitating access to other road sections or structures.

As another example of the constructed projects in the Balkan Peninsula, the geogrid retaining structure within the Sofia ring road project can be named. The Sofia ring road surrounds the Sofia city and has a total length of 61.8 km and is divided into four arcs (subsections). Some arcs of the road have been upgraded in the last years and several subsections need to be still improved. The purpose of the road is to improve the traffic flow between different parts of the city. The project consists of dual carriageway, including bridges, underpasses, interchanges and retaining walls, constructed using GRS retaining walls. The retaining structure was constructed using Fortrac block facing.

In May 2012 an earthquake occurred in Sofia with an intensity of Mw5.6. The earthquake was felt in entire Bulgaria and the neighboring countries. The earthquake had no casualties but several moderate damages to some building in Sofia and the cities around it were reported (Rykova et al. 2017). Investigation after the earthquake have shown that no damage occurred in the GRS retaining structure or its facing (Fig. 10).

Figure 10 Fortrac Block GRS retaining wall in Sofia ring road project after earthquake in 2012 (Huesker).

Conclusion

Both experience and research results indicate that GRS retaining walls have excellent performance under seismic conditions. Although there are many different approaches to the seismic design of GRS retaining walls, a sound and safe design is possible. Conducted shaking table and numerical studies have shown high stability and low deformation of these structures even when significant ground motions are applied, e.g., in the case of the simulated Kobe earthquake. The application of GRS principles to the construction of retaining walls offers high feasibility in challenging conditions, including the potential for high seismic effects or complex environments, e.g., mountainous regions or limited space. space. Furthermore, the flexibility of the geogrid which provides a good soil-geogrid interaction can support higher confinement of the compacted soil particles which causes lower deformations. This fact also plays an important role in the stability of the GRS retaining structures in seismic area.

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