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On the seismic performance of geosynthetic reinforced earth structures

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ABSTRACT: Geosynthetic solutions are widely used in geotechnical, environmental or hydraulic engineering. The main reasons are their good performance, unique characteristics, controlled properties, broad range of applicability and among other things their cost benefit. Past experience and laboratory tests have demonstrated their outstanding performance under seismic loading, like an earthquake event. Geosynthetic solutions are therefore predestinated solutions for safe constructions in earthquake regions. This paper reports on laboratory tests, where geosynthetic reinforced earth walls have been analyzed under seismic loading and on one executed project in an earthquake region.

1 INTRODUCTION

1.1 *Geosynthetic reinforced earth construction*

Geosynthetics are widely used in the construction industry, e.g. to construct retaining walls or to build embankments on very soft soils. The main reasons for their application are their good performance, unique characteristics, controlled properties, broad range of applicability and among other things their cost benefit. Divers case studies report on their outstanding load bearing behavior as well as their performance under complex boundary conditions such as ongoing deformation due to settlement or creepy slopes (Alexiew & Silva 2007; Detert & Fantini 2017).

More interesting is their behavior under earthquake loading. Tatsuoka et al. (1998) report about their outstanding behavior in the event under seismic loading induced by earthquakes. In comparison to conventional concrete retaining walls, geosynthetic reinforced earth walls endure earthquake loadings without failure. In addition, the observed deformation after strong earthquakes are mostly within acceptable limits.

1.2 *Consideration of earthquake loading in the design*

The design can be based on analytical or numerical approaches. In general, there are three different ways to perform the design, as follows:

- Pseudo-static methods
- Displacement methods
- Dynamic numerical methods (e.g. finite element or finite difference methods)

During the earthquake, the constructions experience additional forces, which results from the seismic event. These forces result from the increased ground acceleration. In the design, the peak ground acceleration is in general considered. Depending on the regulations in every country, the criteria to consider the horizontal and vertical ground acceleration coefficients at the same time or not, are different. Several design codes and guidelines, such as from Public Works Research Institute (PWRI 1992) in Japan or from Federal Highway Administration

(FHWA 1996) and American Association of State Highway and Transportation Officials (AASHTO 1998) in the US, assume that the horizontal and vertical waves do not reach the structure at the same time and therefore either one has to be applied. In Italy, the standard code for construction NTC 2018, requires to consider the worse combination between horizontal and vertical acceleration acting at the same time; fixing the vertical component as 50% of the horizontal acceleration. For retaining structure certainly, the horizontal coefficient will have the larger influence on the stability design, whereas for foundation systems the vertical coefficient is more important. However, this should be checked case by case.

1.3 *Relevant properties of geosynthetics in earthquake event*

To apply geosynthetics in constructions, which might experience seismic loads, one has to think about the additional requirements, which the geosynthetics should fulfill.

1.3.1 *Load-strain behavior under repeated load cycles*

Zanzinger et al. (2008) analyzed the behavior of a woven reinforcement made of PET under repeated load cycles to evaluate on the additional damage or reduction of tensile strength, which might occur under railway tracks. They found a correlation between the maximum load, the frequency and the number of cycles concerning the damage starting point. In regard to the number of load cycles during an earthquake, no reduction in tensile strength for the analyzed product types has to be expected. It should also be noted, that under small amplitudes mainly an elastic load-strain behavior does occur for the tested material.

1.4 *Load-strain behavior under fast loading steps*

Different researcher analyzed the influence of the loading speed in respect to the tensile stiffness and the maximum tensile strength. In general they found that the higher the loading speed the higher the tensile stiffness and the lower the maximum tensile strength. This means for the application under earthquake loading, that the geosynthetics react much stiffer - they add higher additional tensile forces to stabilize the system than under normal loading conditions.

1.5 *Interface properties under seismic loading*

Besides the tensile strength and tensile stiffness, also the interface properties under seismic loading have to be considered.

In different researches hardly any reduction under dynamic loading has been observed. Nevertheless, the AASHTO (1998) and also the FHWA (1996) recommend to use a by 20% reduced value for the coefficient of interaction.

2 LABORATORY TEST

2.1 *Introduction*

At the University of Columbia seismic tests on a block wall reinforced with woven PET geogrids in real scale have been conducted. The combination of rigid “column” made of concrete blocks in the front with a flexible backfill made of soil and geosynthetic can be considered as worst case for geosynthetic reinforced earth walls for earthquake applications. The main objectives of the tests have been the analysis of the internal and external performance under significant earthquake loads, the evaluation on observed behavior and loads in comparison to design calculations and the evaluation of the frictional connection between geogrid and concrete blocks. The conducted tests have been well described and documented by Ling et al. (2005).

2.2 *Test setup*

In total three walls, all 2.8 high, have been tested. A fine sand with an internal angle of a friction of 38° and an unit weight of 15 kN/m^3 has been used as backfill material. Two types of woven geogrids have been used. The first geogrid made of PET had a strength of 35 kN/m and the second geogrid made of PVA had a strength of 20 kN/m. The PVA geogrid was utilized for a test set-up, where the two top courses of blocks have been grout-filled and a raw material with a high resistance against the alkaline environment was required. The hollow core concrete blocks were 200 mm high by 300 mm deep by 450 mm wide with a weight of 34 kg each. The setback of the wall has been 12°. The walls have been constructed in three-sided steel box with the dimensions of 2 m width, 4 m depth and 3 m height. EPS boards were placed at the front and back ends of the steel box to prevent wave reflection from the steel surfaces. To reduce the friction between the backfill and the box a layer of grease has been applied. The length of the reinforcement has been chosen to be 2.05 m throughout the wall height, except for test 3. Here the length has been reduced to 1.68 m for all layers except the top layer, which had a length of 2.52 m. The vertical distance between the geogrid layers has been 60 cm for test 1 and 40 cm for test 2 and 3.

The earthquake load was taken from the well recorded and documented Kobe earthquake, which occurred on the 17th of January 1995.

The three walls have been loaded by two horizontal excitations. The peak of the first excitation has been 0.4g and 0.8g for the second. The third wall has been additionally loaded by vertical excitations, which correspond to half of the horizontal values.

2.3 *Results*

2.3.1 *Visual observation*

All walls showed a very good performance. Cracks only appeared at the rear end of the reinforcements. Settlements have only been observed after the second excitation. The change of the vertical distance between the two layers from 60 cm to 40 cm did significantly reduce those settlements.

2.3.2 *Horizontal wall displacement*

For all three walls, the horizontal displacement has been less than 10 mm after the first excitation. For the second excitation, the wall displacement was largest at peak acceleration and a part of the displacement has been recovered when the excitation ended. Test wall 1 displaced at maximum 100 mm (see Figure 1), test wall 2 about 80 mm and test wall 3 slightly less than 80 mm.

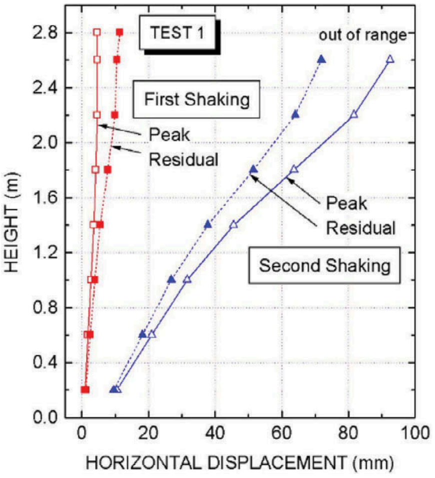

Figure 1. Horizontal Displacement of Test 1.

2.4 *Conclusion*

None of the three walls failed during the testing even at very high earthquake acceleration of about 0.8 g. Even with the vertical acceleration in test 3, which corresponded to 50% of the horizontal acceleration no failure occurred. It could be observed that a closer spacing of the geogrid layer did improve the deformation behavior of the wall significantly. The observed deformation with a peak acceleration of 0.4 g was more or less negligible. A good performance was still observed with a strong acceleration of 0.8 g.

No failure of the frictional connection between the blocks and the geogrid layers occurred during the tests.

3 CASE STUDY: FORMATION OF A LAGOON LANDSCAPE WITH GEOGRID REINFORCED BLOCK WALLS IN A EARTHQUAKE REGION- AYLA OASIS, JORDAN

3.1 *Introduction*

In the south of Jordan, directly on the Red Sea, the town of Aqaba is located. The western town limit is also the international border with Israel. To the south of Aqaba is the Red Sea. The port of Aqaba is Jordan's exclusive access to the sea. The year round pleasant climate makes Aqaba a popular leisure and holiday resort. Directly off the coast there is a popular diving area with coral reefs. These were not least the reason for the investment company, Ayla Oasis Development Company, investing here in the construction of a lagoon landscape.

Over a period of approximately 9 years, an area of 4,300,000 m² desert landscape will be converted into a green oasis. 3000 residential units, 1700 rooms in high quality hotels as well as shopping, conference and leisure centers will be built on the spacious site. In addition to this, there will be a golf course and three large lagoons, one above the other, connected to each other by waterfalls. The lowest level lagoon is navigable and has a direct access to the Red Sea as well as a marina in the town center of the site. Luxury villas on separate islands in the lagoons are planned. The uppermost and middle lagoons are completely water tight, to prevent excessive loss of water and salinization of the soil. The continuous supply of water to the uppermost and middle lagoons is made possible by means of large pumping stations and the water from the Red Sea. The lowest lagoon is subjected to the fluctuations in the water level of the Red Sea. A total of 17 km of beach and promenade will be created, of which approximately 15 km will be made of geogrid reinforced block walls. Figure 2 shows an animation of the planned lagoon landscape.

3.2 *Structural implementation*

As shown in Figure 2, the boundaries of the lagoons and islands have very irregular layouts and can be converted in this form without any problems using reinforced block walls

Figure 2. Overview animation of the lagoon landscape (*https://www.ayla.com*).

(Figure 3). From an aesthetic viewpoint, the block walls with their ability to utilize different colored blocks should fit well into the environment. This is achieved by extracting local aggregates on site, and by using this for making the blocks. Therefore, the block color blends in with the natural surroundings. A further important advantage of geosynthetic reinforced block walls is their frequently observed and tested ductile behavior in the event of earthquakes. Among others Tatsuoka et al. (1998) reported on the outstanding behavior of geosynthetic reinforced earth retaining walls in earthquake occurrences in Japan. Ling et al. (2003) investigated the behavior of geosynthetic reinforced block walls under seismic loads in the laboratory and also observed the outstandingly good behavior of the structure.

3.3 *Basis for designing block walls*

The design of retaining structures was in accordance with Eurocode 7 and 8, including the national appendices.

The walls are from 2 m to max. 6 m high. Behind the walls either foundation loads of multi-story buildings or traffic loads from roads are acting. As a rule, the water level in front of the wall is considered in the calculation to be a constant in the uppermost and middle lagoons and a variable in the lowest one. In several sections of the lowest lagoon the depth increases in front of the block walls by about 1.0 m at a distance of approximately 5.0 m from the wall. This is necessary to permit a certain depth of water for yachts and sailing boats.

During construction there is no water in the lagoons. Behind and on top of the walls material is stored in some places, so that different load cases had to be analyzed separately.

As already described above, Aqaba is situated in a tectonically active region (see Figure 4).

The African plate is moving away at approximately 1 cm per year from the Asiatic plate. Earthquakes of a magnitude of 7 are to be expected. For this reason a ground acceleration of 0.2 g and a 10% probability that this value will be exceeded in 50 years, is to be expected.

The calculations are carried out using horizontal and vertical seismic coefficients with pseudo-static approach.

The seismic coefficients can be calculated as follows: The local foundation properties can, according to Eurocode 8 – Part 1, be described as foundation class C "Deep deposits of dense and medium dense sand, gravel or rigid clay of thicknesses of several tens to several hundred of meters". With regard to the elastic response spectrum the foundation is classified as type 2, which gives an adverse value for the soil parameter S of 1.5. The factor r for calculating the horizontal seismic coefficient depends on the nature of the retaining structure. The retaining structure is classified in the category of "Free gravity walls with a displacement capacity of up to dr = 300*α*S (mm)", which gives, according to Eurocode 8 - Part 5, for the factor r the value of 2. The horizontal seismic coefficient is thus: $k_h = \alpha^*S/r = 0.2^*1.5/2 = 0.15$. According

Figure 3. Finished lagoon edge with irregular layout.

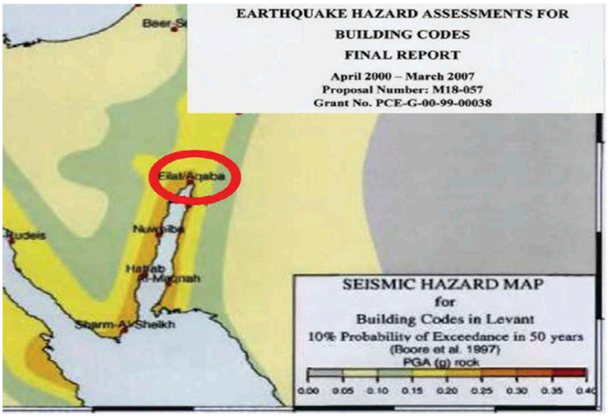

Figure 4. Seismic outline map.

to EC 8 - Part 5 the effects of vertical accelerations on retaining structures can be neglected, if they do not relate to gravity walls. This applies to geosynthetic reinforced block walls as well as to cantilever retaining walls. Nevertheless, it was decided in this project to also take into account the vertical seismic coefficient. The vertical seismic coefficient in this case is: kv = ±0.5*kh = ± 0.075. In case of an earthquake, a sudden fall in the water level in front of the wall might occur. This was taken into consideration that the water level in front of the wall was estimated to be 60 cm lower than within the wall. At the same time structural drainage pipes were integrated into the front of the block walls to facilitate a rapid reduction in the water level differences. In addition, what is known as an "uncontrolled additional erosion" of 50 cm in front of the wall had to be taken into account. This results from the dredging which takes place at regular intervals, and is intended to prevent the lagoons from silting up.

These strict but cautious calculation parameters gave ratios of reinforcement length to wall height which lay well above the frequently used rule of thumb formula of "0.7 * wall height". It should be noted that this formula is principally used for an initial assessment of walls which are not located in water or earthquake regions.

3.4 *Sealing the lagoons*

The site has a slope of several meters towards the Red Sea, which helps with staggering the heights of the lagoons. The water from the uppermost lagoon flows over a waterfall into the middle one and from there it cascades over a further waterfall into the lowest lagoon. This is directly connected to the Red Sea and is thus subjected to the natural changes in water level. To reduce the water loss and salinization of the soil the uppermost and middle lagoons are completely sealed with geomembrane. First of all a protective non-woven geotextile is laid on the prepared ground. Then the sealing sheets are placed on top and welded together. At the top a further protective non-woven geotextile is laid and covered with sand before a thin concrete layer is added as additional protection (Figure 5).

3.5 *Structural formation of the sealing in the area of the reinforced block walls*

Geosynthetic reinforced block walls are usually considered, assuming the use of normal fills, to be water permeable, free draining structures. However, as required to prevent excessive water loss from the uppermost and middle lagoons, measures are needed to ensure that no water can penetrate through the front or the geosynthetic reinforced earth banks to the soil behind. To achieve this, the geomembranes are wrapped around the reinforced earth (Figure 6).

Figure 5. Aerial photo – laid geomembranes partly with concrete covering.

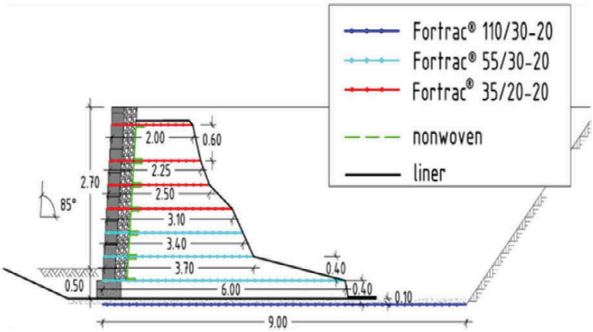

Figure 6. Example cross section of block wall with the line of the sealing.

As the foundations are to be built a few meters behind the front of the reinforced walls, the geomembranes are installed directly behind the rein-forced earth block walls. The building foundations can thus be built in the dry. Since the lowest reinforcement layer is relatively long compared to the rest, the geomembranes are placed above this layer and then folded back to reduce the necessary quantity of the membrane.

To prevent unintentional damage to the geomembranes through subsequent excavation work, concrete bricks are laid on top of the geomembranes as a protection.

Laying the geomembranes produces a sliding surface with reduced shear strength under the block wall which has to be given particular attention in the calculations.

3.6 *Structural formation of the block walls against ship collisions*

As the lowest lagoon is directly connected to the Red Sea, no sealing is required here. The marina is situated within the lowest lagoon. Consequently the impact of a ship collision with the block walls had to be taken into consideration. In this aspect there were concerns about the resistance of the block walls referring to the relatively low unit weight of the blocks. Thus, an approximate 30 cm thick concrete wall is placed behind the blocks as reinforcement (see Figure 7).

The stability of polyester reinforcement in direct contact with high pH values, such as occurs, for example, with green concrete, has not been entirely clarified yet. For this reason the structure of the block walls is slightly different. A facing, produced from blocks with concrete backfill, and a separate geosynthetic reinforced earth wall built in a technic that is known as the "wrap around method", are connected by means of short polyvinyl alcohol (PVA) geogrids with proven pH resistance. The wall is constructed in layers, which allows the construction of the wrap around secondary wall and the placing of the blocks with the concrete back-fill at the

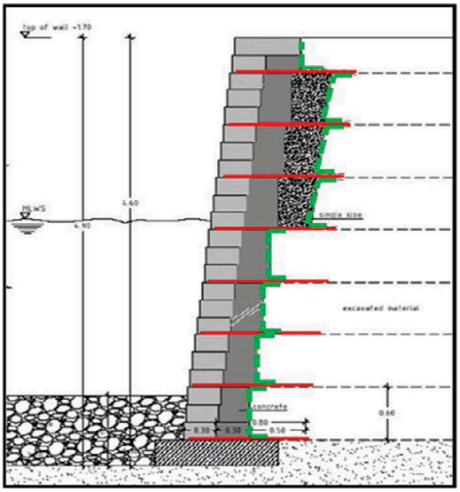

Figure 7. Cross section of the block wall with concrete backfill.

same time. The connecting PVA geogrids (shown in red in Figure 13) are concrete-cast on one side and anchored into the wrap around secondary wall on the other. This produces an assured connection between the concrete strengthened block wall and the reinforced earth walls. This type of construction further ensures that even, if the front is completely destroyed, the stability of the reinforced earth walls is not endangered. Individual damaged stones can subsequently be replaced without any problems. It should be considered, however, that by backfilling a block wall with concrete the ductility of those kinds of constructions is lost. The relatively high temperatures in Aqaba and the large dimensions of the walls mean that expansion joints need to be implemented to avoid small surface cracks and tension cracks in the stones. Geogrids as secondary reinforcements behind cantilever retaining walls on certain areas of the site reinforced concrete cantilever retaining walls are built, for example, in the case of the cascades. The calculation with the previously described basic conditions resulted in additional measures to safeguard against possible deep seated slip circles associated with an earthquake event. The possibility of securing these with vertical structural elements, such as, for example, sheet piles or piling was rejected for cost reasons. The laying of a horizontal high tensile geogrid was chosen as a technically feasible and a more economical alternative.

3.7 *Summary*

The section reports on the impressive construction work in the town of Aqaba, Jordan, where geo-synthetic reinforced walls are used. The design of the geosynthetic block walls is affected by the geographical location of the site in a tectonically active area as well as particular requirements resulting from the use as lagoon surrounds. This project again confirms the excellent application possibilities, as well as the growing acceptance and constantly increasing confidence in geosynthetic, in earth works and in foundation engineering.

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