Case Studies: Geogrid Reinforced Block Walls In Waterfront Projects Under Special Boundary Conditions

O. Detert & S. Schmidt
Huesker Synthetic GmbH, Gescher, Germany

ABSTRACT: The paper deals with two waterfront projects where the use of geogrid reinforced retaining block walls have been found to be the best solution to meet the project specific requirements. The paper highlights the main requirements of retaining walls in waterfront projects, the project specific characteristics (e.g. rapid water drop) and also innovative solutions (e.g. geotextile safeguard of concrete cantilever retaining walls in case of earthquake). The use of geogrid reinforced block walls has been a big success in both projects.

1 INTRODUCTION

1.1 *Waterfront projects*

It is not unusual for old open mining pits or fallow lands to be transformed into attractive recreation and tourists' areas by creating artificial lagoons with promenades and beaches. Retaining walls are often used to secure differences in height. Conventional concrete cantilever walls are more frequently becoming replaced by geogrid reinforced block walls. As well as lower construction costs in many cases, block walls offer benefits in terms of construction time, flexibility regarding geometry as well as in appearance and inclination of the wall facing.

The paper summarizes the characteristics of waterfront projects and describes two outstanding projects with innovative solutions.

1.2 *Characteristics of waterfront projects*

Retaining walls in waterfront projects have to withstand different kinds of actions and need to meet further requirements compared to retaining walls "on land".

First of all scour protection has to be considered in front of the walls to guarantee long term stability. This becomes even more critical if wave loads are an issue or propeller induced hydraulic loads from motorboats or yachts are present. Additionally maintenance works in the lagoons, e.g. dredging works to remove sediments, can cause scour in front of the walls.

Changes in water level lead to an imbalance of water pressure in front of and within the reinforced block wall. This imbalance has to be equalized by accurately designed drainage elements. In general retaining block walls are free draining structures and water can flow through the joints between the blocks. Coarse aggregate, e.g. gravel, should be used as drainage layer directly behind the blocks to improve the drainage capacity of the structure. A separation and filtration non-woven should be placed between the drainage and backfill material to avoid erosion. If a rapid water drop can occur due to waves, tides or earthquakes additional drainage pipes should be considered to allow a faster water level exchange.

A further event in waterfront projects is the impact of boats and ships. The block walls either have to be protected against those impacts or sufficiently designed to withstand it, if no protection by means of for example protective poles is foreseen. Furthermore, it is important that in the case of an extraordinary impact repair works can easily be undertaken.

In the following sections two projects will be described.

2 RESTORATION OF ABANDONED OPENCAST MINE

2.1 *Introduction*

In the community of Großpösna at the Störmthal Lake in the south of Leipzig, Germany, the restoration of an abandoned opencast mine was planned. 12.6 hectares were converted into a leisure and recreation area, including a water sports centre with harbour facilities, a surfing beach and piers for boats. This project, called "Gruna Bay Marina", was mainly financed by the Free State of Saxony and represents a particular highlight in the reclamation of the former mine and its integration into the Leipzig lake district. The developer for the project and owner is LMBV (Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH). The harbour walls and the lookout tower at the north-eastern end have been designed and completed as reinforced block walls. The crucial criteria in choosing this design included the anticipated construction costs, which overall are about 20-25% below those of conventional retaining walls, such as concrete cantilever walls. Another advantage is the relatively high tolerance of the system for differential settlement, particularly where the foundation is not homogeneous. Since the dismantling work and subsequent flooding of lignite mines usually leads to heavy acidification of the water with pH values between 2.5 and 3.5, the retaining construction has to meet higher demands in terms of its durability.

2.2 *Design concept for the harbour area*

According to the design concept of the architect commissioned with the work (DENK Architectural Engineers, Leipzig), the harbour wall at Gruna Bay is intended to fulfil two important requirements. On the one hand, the wall should fit in with the landscape as harmoniously as possible. On the other hand, a form of construction had to be found that enables fast, effective completion despite the curved layout of the harbour wall and the extremely tight building schedule between August and November 2010. The decision was taken in favour of the innovative retaining wall system using so-called geosynthetic reinforced soil. In this specific case, a 4 m high block wall was built and anchored with high tensile geogrids. The modular system offers the maximum flexibility of wall design, with a range of shaped stones in various colours and surface textures, which means that the architect's specifications could be fulfilled completely.

Figure 1. Gruna Bay design concept

2.3 *Foundation and environmental effects*

In order to analyse the foundation soil, core drilling and penetration tests were carried out in the area of the future harbour facility. According to these tests, the foundation soil consists of silty, medium-sandy fine sand which offers sufficient load bearing capacity for the proposed design. The internal angle of friction for the foundation soil was determined in a shear test following compaction to $D_{Pr} = 95\%$ to be 34°. In order to guarantee the durability of the reinforced block wall in the anticipated environmental situation special requirements have been defined in the tender documents. In the German standard DIN 1045 properties of concrete are specified depending on the possible corrosive effects of different exposure classes. Concrete composition, minimum compression strength classes and curing period of the concrete blocks were set out using the specifications for exposure class XA2. Because of the high sulphate content of the flood water (low pH value) on the one hand and the alkaline environment of the stones (high pH value) on the other hand, high demands were also made in terms of the durability of the raw materials of the geosynthetic reinforcements, which were met by the choice of polyvinyl alcohol (PVA). Currently the pH value of the water is 5.9. Ultimately, however, a neutral value is to be achieved.

2.4 *Structural design*

The lower edge of the gravel foundation for the block wall lies at 114.5 m above sea level. The block wall has a maximum height of 4.0 m, so that its upper edge reaches 118.5 m above sea level. The block wall will reach 1.5 m out of the water at the final stage. The first layer of hollow stones was embedded in the gravel foundation, following the intended course of the wall, and filled with gravel with a 5/32 mm granularity. The same material was also used as backfill material for the reinforced retaining structure, in order to achieve a good drainage effect and to prevent any possible erosion of fine particles with fluctuations in the water level. The Fortrac® MP geogrids were inserted between the stone blocks at every second row. In this bonded structure, the geosynthetic materials carry the tensile forces and the soil grains dissipate the compressive forces. The bond between the geosynthetic material and the filled blocks is created by friction and shape. The patented front lip of the Allan Block® hollow chamber stones also eliminates the need for any additional connecting elements to secure the layers and ensures a consistent front angle, which was set at 87 degrees for this project. The length and tensile strength of the geosynthetic reinforcements as well as the spacing between the layers are the results of the static calculations, which were made with the participation of Huesker Synthetic GmbH in accordance with DIN 4084:2009 and in conjunction with the recommendations for design and analysis of earth structures using gesosynthetic reinforcements (EBGEO 2010). The structure has already proved itself in numerous projects worldwide and has been used as retaining structure for major traffic routes even with high static and dynamic traffic loads (HANGEN et al., 2009)

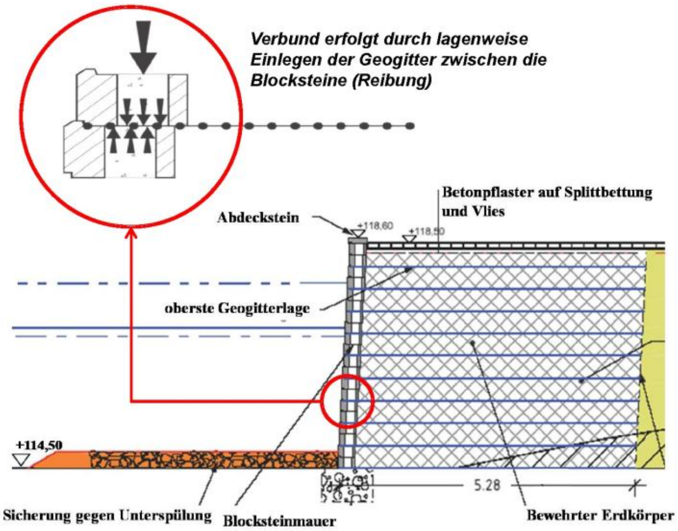

Figure 2: Standard cross-section of stone block wall

Local sand was installed behind the reinforced soil body and separated from the backfill material by a non-woven. The upper edge of the block wall was covered with special stones, which were fixed in place using high-quality, water-resistant stone adhesive. Finally, a scour protection was installed in front of the harbour wall with armourstone up to 50 cm thick.

Figure 3: Stone block wall with slip ramp shortly after completion of the relevant work

Despite the tight time frame for completion of the harbour facility, all of the relevant site profiling work could be completed in dry conditions. The final water level of 117.0 m above sea level was reached at the end of 2011.

Figure 4: The water level had risen to approx. 115.0 m above sea level about three months after the start of the building work.

2.5 *Architectural highlights*

In addition to the curved harbour wall with its shell limestone finish, the lookout tower also constructed with reinforced block walls at the north-eastern end represents a particular tourist attraction. The hexagonal shape is based on an old fortification.

Figure 5: Lookout tower with boulder still to be put in place

A particular structural challenge in building the lookout tower was the design of the corner areas, for which the blocks had to be cut precisely. The geogrid arrangement was carried out by two overlapping sheets over the entire width of the tower, while the third sheet was placed 20 cm higher, separated by one row of stones. In this way, it was possible to keep any reduction in the frictional bond between the backfill material and several reinforcing elements lying directly on top of each other in the central area to a minimum.

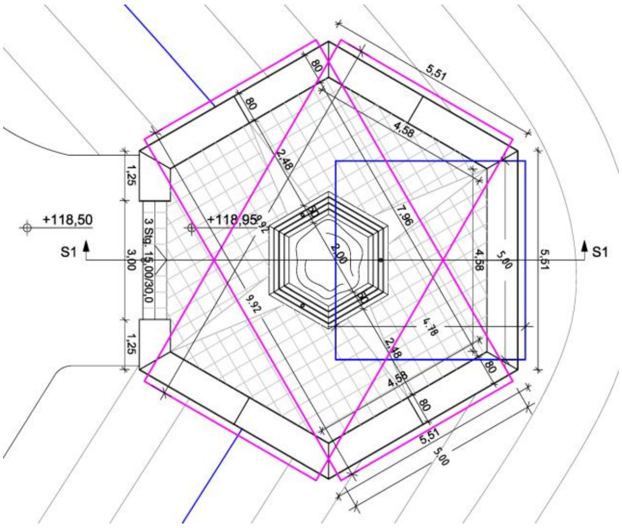

Figure 6: Layout for the hexagonal lookout tower

It was also possible to complete the building of the lookout tower on schedule and entirely in dry conditions. The successful completion of the building project was the result of very good preparation, effective interlocking of the work carried out by everyone involved in the construction and, in particular, the excellent workmanship of Hellmich GmbH Magdeburg.

2.6 *Summary*

The Espenhain former opencast pit in the community of Großpösna is currently being turned into a leisure and recreational area mainly financed by the Free State of Saxony and with LMBV (Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesell-schaft mbH) as the developer.

The architecture of the harbour area and retaining wall has been designed in such a way that it fits into the landscape as harmoniously as possible. The system chosen for the construction of the retaining wall was a reinforced block wall, which not only met the design specifications of the architect but also made it possible to keep to the ambitious building schedule of three months. The system components of the composite structure comprised concrete blocks and geosynthetic reinforcements in conjunction with a coarse grained mineral mixture as backfill material.

3 FORMATION OF A LAGOON LANDSCAPE WITH GEOGRID REINFORCED BLOCK WALLS - AYLA OASIS, JORDAN

3.1 *Introduction*

In the south of Jordan, directly on the Red Sea, lies the town of Aqaba. 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 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.

Figure. 7 Overview animation of the 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 centres 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 centre 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 salinisation 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 7 shows an animation of the planned lagoon landscape.

3.2 *Structural implementation*

As can be seen in Figure 8, 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 (see Figure 8).

From an aesthetic viewpoint, the block walls with their ability to utilise different coulored blocks should fit well into the environment. This is achieved by extracting local aggregates on site, and using this for making the blocks. Therefore, the block colour blends in with the natural surroundings (see Figure 8).

Figure 8. Finished lagoon edge with irregular layout

A further important advantage of geosynthetic reinforced block walls is their frequently observed and tested ductile behaviour in the event of earthquakes. Among others *Tatsuoka et al. (1998)* reported on the outstanding behaviour of geosynthetic reinforced earth retaining walls in earthquake occurrences in Japan. *Ling et al. (2003)* investigated the behaviour of geosynthetic reinforced block walls under seismic loads in the laboratory and also observed the outstandingly good behaviour of the structure.

3.3 *Basis for designing blockwalls*

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-storey 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 was 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 9). 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.

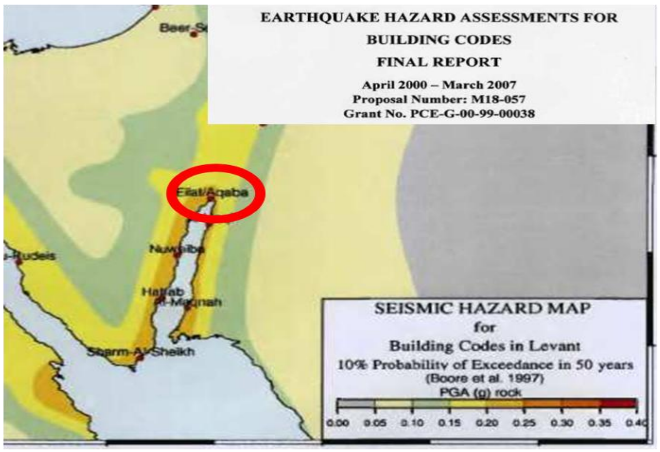

Figure 9. Seismic outline map

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 metres*". 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* $d_r = 300*\alpha*S(mm)$", 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 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:

$$k_v = \pm 0.5*k_h = \pm 0.075$$

In case of an earthquake, a sudden fall in the water level in front of the wall might occur. This was taken into consideration in 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 locatedin water or earthquake regions.

3.4 *Sealing the lagoons*

The site has a slope of several metres 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 salinisation of the soil the uppermost and middle lagoons are completely sealed with geotextile membranes. 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 (See Figure 10).

Figure 10. aerial photo – laid geotextile membrane partly with concrete covering

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 it is 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 geotextile membranes are wrapped around the reinforced earth (See Figure 11 and 12).

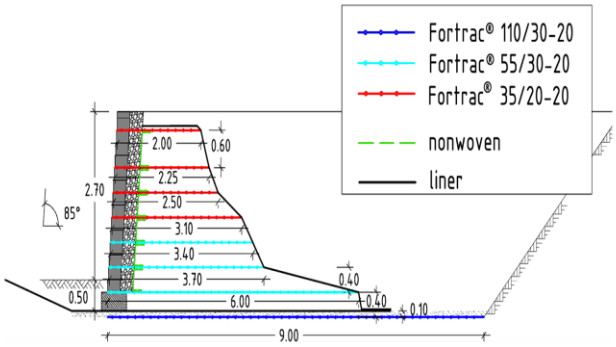

Figure 11. Example cross section of block wall with the line of the sealing

As the foundations are to be built a few metres behind the front of the reinforced walls, the geotextile membranes are installed directly behind the reinforced 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 geotextile membranes are placed above this layer and then folded back to reduce the necessary quantity of the membrane.

Figure 12. Sealing and covering the sealing sheet behind the reinforced earth block.

To prevent unintentional damage to the geotextile membranes through subsequent excavation work, concrete bricks are laid on top of the geotextile membranes as a protection (See Figure 12).

Laying the geotextile membranes 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 13).

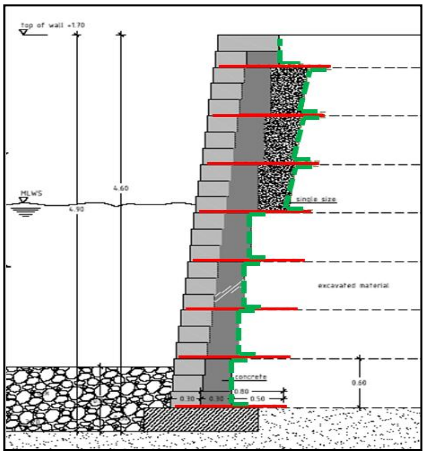

Figure 13. Cross section of the block wall with concrete backfill

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 backfill at the 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.

3.7 *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.

3.8 *Summary*

The section reports on the impressive construction work in the town of Aqaba, Jordan, where geosynthetic 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 geosynthetics, in earth works and in foundation engineering.

4 CONCLUSION

The paper describes the high demands of retaining structures within waterfront projects. Two outstanding waterfront projects have been presented in the paper in which geotextile reinforced block walls have been applied successfully as retaining walls. In both projects special requirements could be solved by the modular system. Besides explaining the different calculations, basic considerations including details for determining the seismic coefficients according to Eurocode 8, special structural solutions, such as for example the sealing of geosynthetic block walls are described.

Both presented projects are excellent examples for the great advantages of geogrid reinforced block walls.

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