ISGSR 2011 - Vogt, Schuppener, Straub & Bräu (eds) - © 2011 Bundesanstalt für Wasserbau ISBN 978-3-939230-01-4

Assessment of reliability and inherent risk levels of geogrid reinforced soil structures

F. Bussert
Tensar International Ltd., Blackburn, United Kingdom

ABSTRACT: Geogrid reinforced soil structures are planned and constructed in increasing amounts due to their various benefits. Little amounts of failures or deformations beyond serviceability limit state are reported. Multiple factors can influence the behavior of reinforced walls and elements that cause risk and reduce reliability have to be assessed. All aspects contributing to reinforced walls as roles and responsibilities, site investigation, applicability of the structure, design methods, materials as well as construction are evaluated and their reliability and risk levels regarding structural behavior investigated. Identification of roles and responsibilities will be assessed as part of the risk assessment under the light of outsourcing and subcontracting. Apart from these influences the construction process will be looked at and conclusions drawn.

Keywords: construction, design, reinforced soil, site investigation

1 INTRODUCTION

The use of geogrid reinforced structures for temporary and permanent slope and wall stabilization is an economical and ecological alternative to traditional structural solutions as gravity or cantilever walls. Especially the economic advantages, multiple structural options and the reliable nature of the constructed walls lead to a significant increase in the use of geogrid reinforced structures over the last decades. Technically the benefits of high load carrying capacity, applicability over soft and variable ground conditions and insensitivity to differential settlement combined with small deformation characteristics increased the reputation of these structures.

These advantages raised the confidence in geogrid reinforced structures and in turn lead to a considerable increase in constructed wall heights for all structural types in recent years. Construction of slopes in excess of 20m height or walls with heights up to 60m have been completed successfully in recent years and pushed the applicability to new levels (figure 1).

Figure 1. **Tensar***tech* GreenSlope at Greater Bargoed (2010), **Tensar***tech* TW1 Wall at Dubai-Fujairah Freeway (2010)

1.1 *Design requirements*

In most European countries the calculation methods are separated into two parts: the ultimate limit state (ULS) or complete structural failure and the serviceability limit state (SLS) where excessive deformations prevent the structure from being used for the intended purpose or where due to excessive deformation collapse is suspected. The proof of limit states of reinforced soil structures is based on the principles set out by the British Standard BS8006-1 (2010).

Deformations can be the result of deformations within subsoil, retained or reinforced fill. Calculation of the reinforced soil deformation is usually approximated by deriving theoretical geogrid strains from the calculated tension force. Dependent on the expected design life, the geogrid strains are derived from the isochrones curves. It has been shown numerous times that the anticipated strains by this method overestimate the measured deformations by far.

1.2 *Occasional observed structural behavior*

Numerous publications in the past indicate that geogrid reinforced soil structures fulfill all requirements set. Recently achieved heights (exceeding 60m) indicate that reinforced soil is regarded as a value solution providing multiple advantages when compared with traditional structures. However, publications (e.g. Bachus, 2010) describe several structures that showed partial collapse or excessive deformations. The structures had to be reconstructed resulting in negative reputation and doubts on the reliability of reinforced soil structures. The reliability and the risk towards failure of reinforced soil structures will be assessed for individual parameters that could contribute to failures:

- Design responsibilities
- Design methods
- Soil investigation
- Construction materials (geogrids, soils)
- Construction

In the following paragraphs every aspect will be analyzed individually and the reliability towards failure rated. Afterwards conclusions are drawn and an approach presented how risk can be minimized further.

2 DESIGN RESPONSIBILITIES

Within a project multiple parties are involved carrying out different parts of the design resulting in different responsibilities to individuals which may sometimes not be straightforward to identify. By submitting feasibility studies, initial designs or full design submissions for a structure different party in a project can assume that certain issues are dealt with by others. The knowledge on how responsibilities is therefore sometimes not fully understood and there is little knowledge on how this can contribute to failures taking place. A large set of exclusions stated by a party involved may appear as if responsibilities are distributed to other parties involved, their validity however is often not fully understood and may be beyond a specific scope.

Within the introduced “Construction (Design & Management) Regulations 2007” the responsibilities of individuals in each project is clearly identified and requirements on actions and activities drawn. The regulations were written with the intention to focus on effective planning and consecutively manage risk and ensure everyone knows its responsibilities which improves health and safety within the construction industry. As for reinforced structures several people/ companies are involved within the design and construction each individual has several tasks which need to be fulfilled in order to comply with the regulation.

2.1 *Designer*

The Designer takes over a crucial part in this process as several demands are placed on him. He has to be competent for the work or has to be guided by a competent person and need to work with other engineers involved in the project in order to manage risk. He has the duty to verify the competence for other designners involved to ensure consistency. As the CDM coordinator collects all relevant information he has to ensure that the CDM coordinator is aware of potential risks. Where soil parameters might be crucial he has to liaise with the geotechnical engineer in order to verify that the made assumptions are relevant or has to verify the soil properties in case any doubts or inconsistencies occur.

When the input parameters are sufficiently determined the designer is required to work according to the latest standards considering all relevant information. If he comes across any uncertainties it is a "duty to warn" to make the CDM coordinator/ contractor or other designers involved aware and ensures that the risk is eliminated wherever possible.

2.2 *Client*

The client himself (e.g. a public body) under whose instructions a reinforced structure is build has to make sure that all people and companies involved in the job have sufficient competence and resources to allow the design or construction of the reinforced structure. As the client may not have sufficient information to take over this work by himself he can appoint a CDM coordinator who takes over his responsibilities. He further has to ensure that a suitable management system is in place as well as sufficient time and resources for all stages. This often becomes crucial for reinforced structures. As they are often regarded as an economical alternative to traditional methods they are brought into the design process quite late which leaves only little time to prepare designs or calculations. Reasonable design time should be ensured at all times in order to prevent failures happening.

2.3 *Contractor*

Last but not lease the duties of the contractor are multisided as on one hand he has to collect the required information and provide a stable and durable structure minimizing the risk of his employees. In order to safeguard a reliable construction the principal contractor has to check the competence of all appointees and verify that all workers had training and sufficient site induction. He has to liaise with the CDM coordinator for all ongoing designs which is usually the case for reinforced soil structures.

Finally the contractor has to check that the client is aware of his duties and that a CDM coordinator has been appointed and the HSE has been notified before the work. This is an elementary point as most reinforced soil structures are done before the "real" construction work starts and may be regarded as initial work procedures which are only shortly looked at. It is his duty to inform the principal contractor when any problems or issues arise with designs or the constructability of the whole structure or parts of them.

As the regulations are quite clear in their responsibilities and they encourage all parties to communicate on possible issues and the responsibilities taken over. This should therefore not be an issue for significant risk.

3 DESIGN METHOD

In line with current practice, the design methods for reinforced soil structures are based on limit states principles. The partial factors included are based on previous experience and statistical variations. They have been calibrated to maintain consistency with current practice (BS8006-1:2010). However, in contrast to some design methods (e.g. EBGEO, 2010) which are based on EC7 (BS EN 1997-1:2004), BS8006-1:2010 specifically excludes the use of BS EN 1997-1:2004 as it "is not for use in the design and execution of reinforced soil". This leads to a hybrid approach currently used in the design: proof of external stability, without intersection of a single layer of reinforcement, according to BS EN 1997-1:2004 while stability of any slip circle that intersects reinforcement is calculated according to BS8006-1:2010. This approach was chosen as the mechanical principle and the load transfer within a reinforced soil structure is not fully understood and cannot be given a specific factor of safety. As the determination of reinforcement length is made by ensuring global stability the different approaches to be used might be a source for confusion.

3.1 *External stability*

External stability describes a global failure of an assumed rigid block (the reinforced soil). Global stability ensures a sufficient grid length and prevents sliding, overturning, bearing capacity failure or slope failure. An adequate safety factor against structural sliding along the base is calculated using the sliding interaction coefficient based on the lower value of reinforced fill or subsoil. Due to geogrid nature this is usually calculated using a sliding coefficient of 0.7 * φ. The weight of the reinforced soil block and the

soil-geogrid friction provides the resisting force while the driving force is represented from the retained soil and loads applied behind the structure. Overturning is derived using similar action and reaction forces. A sufficient factor of safety is achieved when the resulting force is within the middle third of the structure. For the assessment of a sufficient factor of safety against bearing capacity failure the traditional methods are used, the base of the assumed rigid block represents the foundation width. Well established design methods (e.g. DIN 4017) are used for the assessment with their safe approach being proven since many years. Similarly global stability is calculated by Bishop's method of slices being acknowledged as a safe measure for calculation. Presence of any toe or top slope has to be assessed carefully and considered as these may have a significant effect on the required geogrid length to ensure external stability.

These calculation principles represent a well proven approach demonstrated numerous times. With reliable soil data available and a proper site investigation carried out sufficient information on the subsoil conditions and soil properties can be derived. They provide only little possibilities for errors.

3.2 *Internal stability*

According to BS8006-1:2010 equilibrium between an assumed monolithic body (active zone) and the available geogrid tension forces to tie this body into the passive (resisting) zone has to be guaranteed. As the most critical wedge is unknown, every possible wedge has to be analysed. At the same time more complex geometries, due to the presence of two-part-wedges are analysed and the highest required tension force derived from this analysis (see figure 2). The layout of the available geogrid strength present in different structural heights is derived to optimise the design.

As only a limited amount of geogrid strengths are available, the next higher grade in tensile strength is used in design when the given strength of the present geogrid is not sufficient. To avoid mistakes in construction each geogrid strength is used for several layers which form a consistent block in which the total available tension force is usually significant larger than required tension force. Overstressing of individual layers (if occurring at all) is therefore counterbalanced by numerous other grid layers.

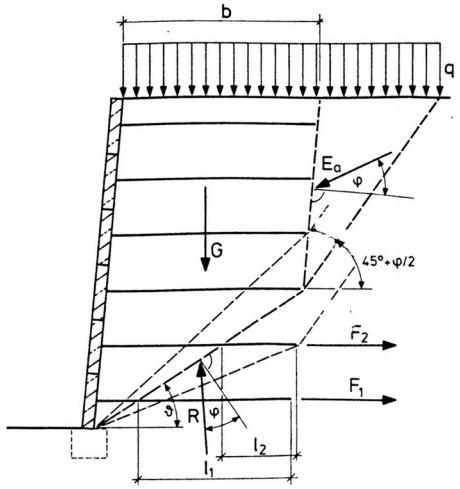

Figure 2. Assumed wedges for the calculation of internal stability

The geogrid anchorage length in the passive body needs to be sufficient to avoid that the geogrids are pulled out of the passive zone. The geogrid strength needs to be sufficient to withstand the activated tensile forces at the end of the design life. The design against pullout is based on conservative assumptions derived from laboratory pull-out tests. These parameters are on the safe side and can due to several implications not become a source for failure: the actual pull-out capacity is underestimated, pull-out can only take part in the upper ~1.5m of a structure, pull-out is not a separate mechanism (to be considered in association with geogrid tensile failure) and pull-out assumes a stress transfer in the reinforced soil that is not yet verified in-situ.

The design methods cannot be considered a source of failure when the appropriate design codes are fulfilled and the stability is analyzed using appropriate material factors for soil and geogrids.

4 SITE INVESTIGATION

A proper site investigation is the basis for every structures. Reliable analysis of required foundation dimensions or the load bearing capacity of the in-soil behavior is essential to avoid structural failure or ex-

cessive deformations. It has to be ensured that the site investigation covers all requirements for the planned construction (early involvement of geotechnical engineer in the planning process), a sufficient quality of the site investigation (reasonable amount of borehole logs, in-situ or soil tests to derive design parameters) is ensured and that the geotechnical engineer is incorporated in the whole planning process and an independent site supervision takes place.

It is inevitable that within the selective choice of boreholes a large risk is present as the conclusions drawn may not be representative for the whole site. It is therefore a risk assessment of the impact of assumed soil parameters from a site investigation. On the other hand the assumptions made should not be too conservative to make structures uneconomical.

4.1 *Foundation soil properties*

For the calculation of external stability the foundation soil properties have to be sufficiently known to calculate external stability. While the reinforced soil properties and the backfill material are usually well known as they are imported or site won (visible and assessed before installation), the foundation soils cannot be verified which indicates the importance of the site investigation report. Possible shear planes due to soil inhomogeneities or a varying groundwater head that affect bearing capacity have to be investigated. Information on sloping ground is to be provided as it may reduce bearing capacity significantly. In case insufficient data is available parameters are assumed for feasibility studies, but additional investigation or independent advice is required before construction takes place in order to avoid failures.

4.2 *Backfill soil properties*

In contrast to the foundation soil parameters the backfill soil properties are likely to be specified more appropriate. As for construction of a reinforced structure excavation behind the structure has to take pace in order to derive a safe working place, the excavated material (normally used as backfill) is visible and can be tested if required. In case the parameters vary significantly a redesign of the required geogrid length is possible or a different backfill material having the parameters assumed in design can be used. Due to the information that can be gained on the backfill soil, the inherent risk is small compared to the foundation soil properties. Additionally the backfill soil properties have due to the calculation method less influence on stability and deformation characteristics of reinforced soil

4.3 *Reinforced soil properties*

Reinforced soil properties are usually well controlled during the construction process as the source of the material is known or the material properties assessed easily. For structures with a face angle >70degree granular material is a requirement given by the relevant design codes. Structural fill avoids long term settlement when sufficient compaction is achieved. This is easily tested by the relevant methods. A well compacted structural fill ensures due to its controlled properties that no long-term deformations occur which could result in deformations that exceed allowable limits.

For structures with a face angle <70degree however, all soil material can be used. Special care is required when these soils are used to avoid long term influences as excessive settlement and associated deformation behavior. Additionally it has to be ensured that a sufficient pore pressure ration is considered in design when cohesive soils are used and compacted in situ. Due to the nature of the soil being compacted in given lift heights the properties can be controlled sufficiently well in order to consider them in the design so that usually theses parameter should not result in major structural deficiencies.

4.4 *Boundary conditions*

All boundary conditions or special circumstances should be considered carefully. Toe or top slopes should be pointed out as well as unusual water conditions. Considerations of water levels or water within the structure should be properly assessed. Reinforced soil structures are usually insensitive to water flow but if inappropriate measures are undertaken they have been reported in the past as being mostly influenced by neglected water conditions (Jaecklin, 2006).

5 CONSTRUCTION MATERIALS

As geogrids and soil within a reinforced structure form a composite with unknown parameters it has to be ensured that the individual properties of the composite are capable of carrying the addressed load in the design. Each individual construction element will be looked at and their assessment described to verify the possibility of each individual element

5.1 *Geogrid*

Geogrids are, like most construction material, continuously assessed and their properties checked as part of internal quality control. Additionally they have to be tested in specific intervals to ensure their reliability. As geogrids are polymer materials their properties change through the design life as part of their rheological behavior. Therefore two types of tests are regularly conducted: short term ultimate tensile tests and long term creep tests (figure 3).
Ultimate tensile tests (BS EN ISO 10319) are short routine test to verify that the stated material properties of the specified material are present and that the material has sufficient short term tensile properties. They are conducted at a strain rate of 20% and have the advantage that the results are available within the test time.

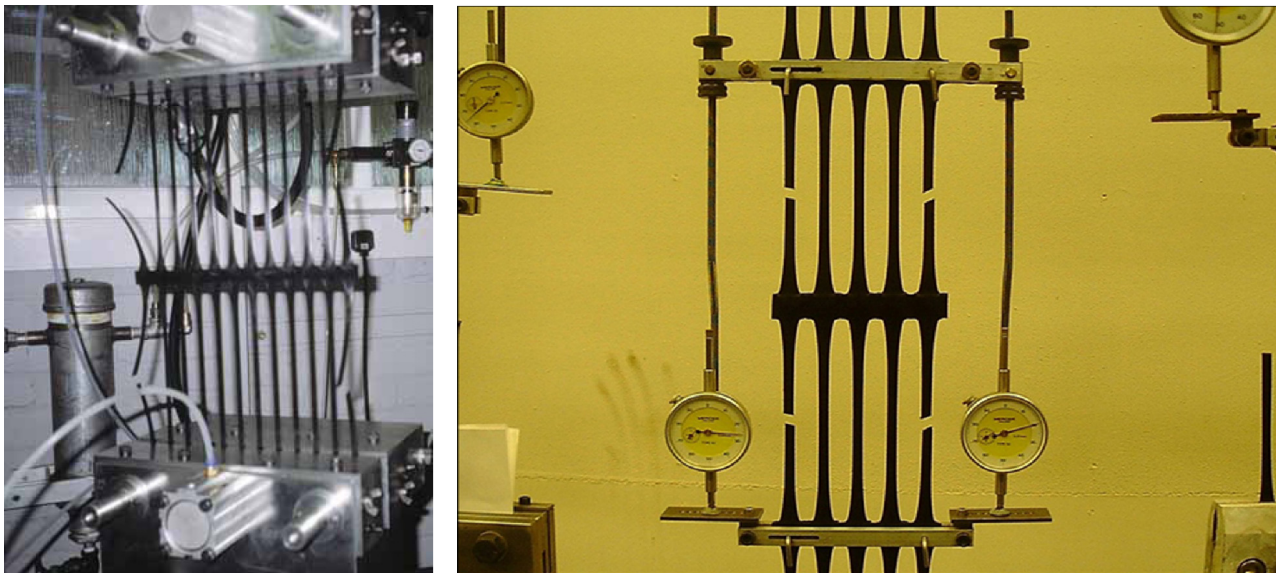

Figure 3. Ultimate tensile test (left) and tests arrangement for creep tests

For a specific project it would result in large time requirements to conduct individual creep tests as their assessment can take up to several months. Their assessment is regulated by BS EN ISO 13431 (1999). The grid is loaded with sustained loads at certain percentages of the short term tensile load under different temperatures (usually 10, 20, 30, 40 and 50 degree) and the load-strain relationship constantly measured. From the time to geogrid rupture under different temperatures the design strength can be derived. While the short term strength has importance for the quality control the designers are interested in the long term design strength as they represent the loads relevant to the design. Usually the long term strength is assessed by external standardization authorities as the BBA (Technical Assessment for Construction). They verify that the materials have the stated long terms strength properties which ensure the designer that the specified loads are verified. IT is the manufacturers' responsibility to ensure the stated material properties. Due to this and the regular assessment of the certificates the risk within the geogrids for a structural failure are extremely small.

5.2 *Facing*

In addition to the geogrid assessment a BBA certificate for whole systems ensures that the connection of geogrid and chosen facing is durable and capable of transferring the specified loads. A failure of the connection is indicated in figure 4. A durable connection of facing and a geogrid is achieved when maximum available geogrid tension force can be transferred by the connection. This can be achieved by a moulded polymer connector that hooks around the transverse bars of the geogrid and is then locked in to place be-

tween the blocks. The high efficiency connection is an important feature. One of the limiting factors on the design strength of the geogrid is the connection efficiency at the face, which may be as low as 25% in systems using a frictional connection only. This is of particular concern where the vertical confining stresses are low, such as in walls up to 8 metres high.

An approved system e.g. according to BBA ensures that a system is indicated as fit for purpose and therefore reduces the clients exposure to risk. It is therefore in the interest of designer, contractor and client to choose proven structural solutions to minimize risk of failures.

5.3 *Soil*

Soil property assessment in contrast to the geogrid strength assessment is a bit more complex due to the natural variation of soil properties and the influence of compaction, shape and particle size distribution on the properties. For structures usually a well graded granular fill is whose parameters can be assumed in reasonable variations. Safe side assumptions are undertaken to account for material variability. However, as the material properties of the placed and compacted materials are visible and well known they represent only a small source of error. The interaction with the geogrids and the confinement of the soil particles within the geogrid apertures has a positive effect on the soil as the soil dilatancy is restricted which increases the soil shear strength. The usual infill material of a reinforced structure can due to the positive effects also not be regarded as a source of failures.

Figure 4. Facing failure, connection ensuring 95% of tensile strength

6 CONSTRUCTION

The construction process is due to the variability and the varying boundary conditions a constant risk for failures. To minimise the risk of structural failures or excessive deformations simple to construct systems have been developed which are assembled on site. With initial installation guidance the risk of installation for e.g. a modular block walls is minimised. The compaction energy used on site and the appropriateness for the soil need to be specified in advance and may require additional tests. As the geogrid manufacturer cannot take any responsibilities for this usual reference to a minimum compaction standard are made. This has to be reached in order to minimise settlements occurring due to insufficient compaction.

Once the formation level is prepared the in-situ concrete strip footing for the facing is cast to line and level. As a precaution the footing is designed wider than the blocks to assist with the load spreading over usual weak foundation. The HDPE geogrids are simply cut from the delivered roll to the length dictated by the design. The vertical spacing between layers for this project is usually 450mm (every 3 courses of blockwork). Once connected to the face it is important to take out any slack present in the geogrid and connection. If left in, this slack would in time manifest itself as a post constructional forward movement of the face. When using conventional granular fill materials this is not a problem as the geogrid may be tensioned lightly using a steel beam and bar mechanism. The dense granular fill provides the perfect reaction to this tensioning effort.

It is in the interest of the manufacturer to reduce inherent risk within structural system solutions. Only easy to install, virtually risk free structures which are durable enough to withstand the applied used will be reused. During the developing process constant communication with construction sites are undertaken to limit all negative influencing factors. The installation is therefore also not the main contributor to failures or significant deformations.

7 CONCLUSIONS

Several parameters that may influence the integrity of a reinforced structure where described and their inherent risk analyzed from practical points. Responsibilities within a project, the design methods and the construction materials are identified, well proven and based on simplifying conservative mechanisms or continuously verified and may therefore not be regarded crucial towards failure.

The site conditions however can be crucial and, as mentioned, need to be assessed carefully. Failure in the site investigation inevitably leads to high risk when the subsoil does not have the assumed strength properties. On the other hand the simplicity of construction is in itself a source for possible failure.

As the construction is rather easy to do it is considered as "I can do that by myself" without consultation of a geotechnical engineer or appropriate design. In fact, as indicated by Bacchus, 2010, most failures were reported for mid-height structures build on private ground where no appropriate risk assessment was carried out and structures build without reasonable soil investigation. Every construction outside of state-of-the-art principles comprises risks that are beyond eventualities of a project. When these principles are violated failures are inevitable and occur with every construction material. Due to the conservatism present within the calculation and the construction materials geogrid reinforced structures can virtually be installed by everyone. With a less conservative approach it may even be possible that structures constructed to state-of-the-art principles are constructed safely while more private structures indicate failure.

Geogrid reinforced structures are a safe means to withstand high applied loads, construction over soft and variable ground and have been proven for long term stability and very small deformations, e.g. Bussert, Naciri, 2008. As most structures are planned by order of public authorities or in conjunction with other construction special considerations are undertaken which prevent failures occurring as they need to undergo established principles and are overlooked by dedicated personnel. Failures occurring on private ground neglecting approved principles cannot be prevented but can also not be regarded as standard and are therefore not representative for reinforced soil structures. They indicate poor workmanship outside current standards and state-of-the-art principles.

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