Engineering performance assessment of a reinforced soil retaining wall founded on unstable ground

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ABSTRACT: Excessive settlement caused by deep ground instability problem raised the alarm for a retaining wall founded on such problematic ground conditions. The reinforced soil retaining wall is over 10 m high and functions as a separation between two levels of high value residential properties. There were genuine concerns over potential sudden rupture of reinforcement induced by excessive settlement which could result in heavy concrete facing panels falling down and large scale slope movement. Performance assessment of the retaining wall was therefore undertaken by reviewing the original retaining wall design and construction, site inspection and investigation followed by numerical modelling which enabled the engineer to not only assess the wall condition at the time but also predict the future performance as a result of further settlement. The review of the original design shows that the local and global stability assessment gives adequate factors of safety based on the assumption that the wall was constructed to the design requirements. The site inspection and investigation revealed that the connection of the top level reinforcements were intact with no signs of overstressing. The numerical modelling results further confirm the adequacy of the original design. The deformation of the reinforced soils and the tensile forces of the reinforcing elements are acceptable for the retaining all construction to its full height. Results of further models by applying the settlement level that was thought to have occurred beneath the wall suggested consistent horizontal wall movements observed on site and sufficient level of safety factor in terms of mobilised tensile stress within the reinforcement. By applying further settlement the retaining wall would suffer further damage and may cause rupture of the connection between the facing panels and the reinforcement leading to instability of the facing panels. Pullout or breakage failures of the reinforcement were anticipated to occur should the ground settle further.

Keywords:Retaining Wall, Reinforced Soil, Foundation, Settlement, Numerical Modelling

1 INTRODUCTION

The reinforced soil retaining wall (or mechanically stabilised wall) has been widely used in the civil engineering industry when spaces are required to be created at different elevations. There are two types of reinforcement material, metallic reinforcement and geosynthetic reinforcement. Sometime they are also called as inextensible reinforcement and extensible reinforcement respectively.This paper discusses a performance assessment carried out for a geosynthetic reinforced soil retailing wall.

Reinforced soil retaining wallsare normally constructed on a stable ground without excessive settlement or differential settlement. This bearing capacity requirement for a reinforced soil retailing wall foundation would normally depend on the height of the wall and should not be particularly difficult to be met due to the nature of the uniformly load distribution. The foundation stability check and settlement calculations would normally form part of the design calculations of the original reinforced retailing wall design. Various design standards or guidelines are available to provide guidance on carrying out stability calculations for the reinforced soil retailing wall, e.g. BSI (2010) and FHWA (2016).

Provided that appropriate level of design considerations are followed in the design stage and quality construction is implemented, it is rather unusual for a retaining wall to experience severe foundation problems during operation under normal circumstances. Occasionally such a problem with the retailing wall foundation would occur especially when complex ground conditions were overlooked in the design and construction stages.

This paper discusses such a foundation problem (i.e. unstable ground) for a geosynthetic reinforced soil retailing wall. The paper begins by describing the project context and conditions of the retaining wall. It then explains the review work undertaken for the original retailing wall design. This is followed by description of the investigation work carried out on site and numerical modelling works undertaken in order to further assess the engineering performance of the retaining wall and predict its future conditions.

2 PROJECT DESCRIPTION

2.1 *Project context*

The project site, which is part of a multi-million-pound coastal holiday resort development, is anonymous for commercial reasons and located in the Middle East. The site has 29 high quality expensive villas located at two different elevations separated by a reinforced soil retaining wall with an approximate height of 12 m.The villas were founded on a limestone rockfillplatform up to 30 m deep and shallow pad foundations were chosen to be the foundation type for the structures.

Soon after the completion of the villa construction, cracks began to appear in a number of the villas towards one end of the development and some of the damage was significant. There were also excessive movements appearing on the concrete facing panel of the retaining wall in the same area which had led to concerns of heavy concrete panels falling down and overall stability of the retaining wall. There had been investigations and remedial efforts recommended by the original design consultant of the development; however there was little success as the situation seemed to be getting worse.

2.2 *Reinforced soil retaining wall*

The retaining wall comprised two tiers (lower and upper) of 6 m and 5.5 m height respectively, as shown on Figure 1. It is founded on a concrete levelling bed set on the engineered rockfill. Reinforcement behind the wall was polyester single strap reinforcement placed in 600 mm layers, ranging in strength from 70 kN for the bottom four layers, 50 kN for the middle four and 30 kN for the top four layers in each section of the wall. Granular backfill was used in the wall construction, compacted in 200 to 300 mm layers. Precast reinforced concrete facing panelsare used to support the anchorage for the reinforced earth mass. The reinforced soil mass is approximately 9 m in depth and approximately 200 m in length. Drainage is provided at the back of the wall via a free draining material wrapped in a geotextile material to prevent ingress of fines.

Figure 1. Views of Retaining Wall

2.3 *Damage occurred and excessive movement*

The initial inspection of the retaining wall identified obvious signs of distress caused by the ground settlement. Localised settlement has occurred over an approximate length of 30 m of the retailing wall directly in front of Villas No.3 to No.7 on the upper level. In addition, there were crushed corners of the concrete panels at the base of the wall indicating excessive settlement had taken place, as shown on Figure 2a. When viewing the wall from the upper level numerous bulges can be observed and some panels are displaced laterally by up to 50 mm, as shown on Figure 2b. There were also leaks of drainage gravels through the enlarged gaps between the concrete panels.

Figure 2. a) Damage near the bottom of the wall; b) Panel movement observed from top

Lateral movement of the retaining wall varies over the length of the wall between Villas No.4 and No.8 at the upper level, and can be clearly demonstrated with reference to the gaps between the tie columns (supported on the capping beams to the wall) and wall panel (supported on footings bearing on the fill). Evidence of ground movements can be seen within the landscape area at the upper level behind the retaining wall.

3 REVIEW OF ORGINIAL DESIGN

3.1 *Critical design assumptions*

The retaining wall dimensions assumed in the original design are summarised in Table 1.

Table 1. Retailing Wall and Reinforcement Dimensions

Total Wall Height	Length of Reinforcement	Vertical Spacing
12.5 m	8.1 m (9.8 m for top 2 layers)	0.8 m

Soil parameters used in the original design are summarised in Table 2.

Table 2. Soil Parameters

Materials	Unit Weight (kN/m^3)	Cohesion c' (kPa)	Friction Angle ϕ' (º)
Reinforce Fill	20	0	35
Unreinforced Backfill	20	0	35
Foundation Soil	20	0	35

It should be noted that the shear strength parameters indicated in the retaining wall contractor's design file wasϕ'= 35º for the reinforced fill. This appeared tobe compatible with the reinforcement layout adopted for the retaining wall construction. However, other documents indicated a higher ϕ'value of 40º for this fill and the fill laboratory testing carried out as part of the work indicated that the higher friction angles can be achieved. This higher value would, in theory, lead to a lower reinforcement strength requirement and therefore as long as the lower values are used in any assessment the results can be taken as valid and on the conservative side.

The original design assumptions take no account of pore water pressure build-up within the reinforced fill. Granular fills in this climate would not be expected to generate significant pore water pressures and no evidence of potential pore water pressure build-up was observed during the site visit. It is likely that seepage of water through the wall face would cause staining of the face and no evidence of such staining has been seen on-site. The assumption of zero pore water pressure was therefore considered to be reasonable.

A seismic coefficient of 0.1 was indicated in the original design documents. A value as low as 0.1 would not normally be expected to require a revision of the reinforcement layout over and above that necessary for the static condition provided that a lower, short-term factor of safety is acceptable.

3.2 *Facing panels*

It was initially assumed that there are at least two connection points between the reinforcement and the facing panel at each level of reinforcement. The on-site inspection verified that this was the case for the panels investigated. As the continuous strip reinforcement passes around each connection point, the load at that point is theoretically the load from two strips of reinforcement. The information gathered during the site visit revealed three different types of connection setting (Figure 3) and the configuration for different layers of reinforcement are described below:

- The bottom layer of reinforcement has an average of 3 connections per 2 m wide panel (Type 1);
- The following 3 layers of reinforcement have an average of 2.5 connections per layer per 2 m wide panel, i.e. 3 connections in the wider part of the T shape and 2 connection in the stem (Type 2); and
- The remaining layers of reinforcement have an average of 2 connections per layer per 2 m wide panel (Type 3).

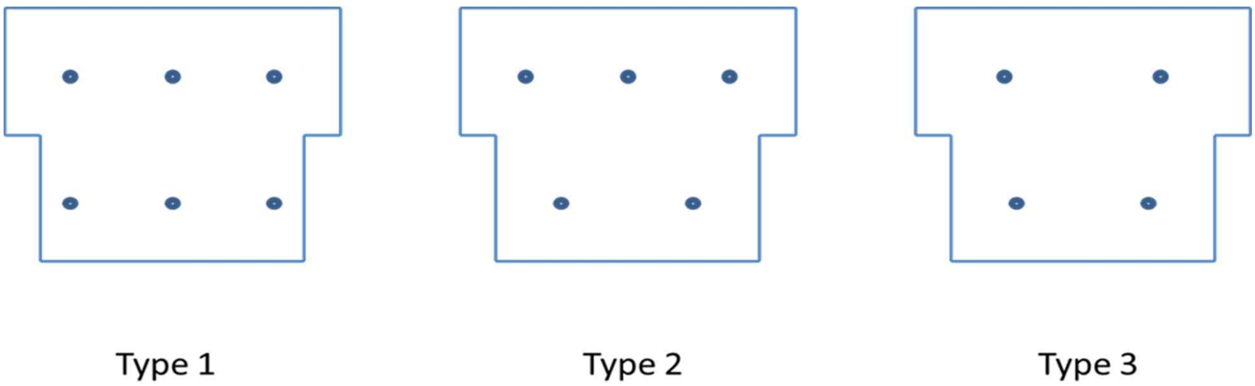


Figure 3. Connections on Concrete Facing Panels

3.3 *Reinforcement configuration*

The distribution of the reinforcement layersfrom the base of the wall is summarised in Table 3.

Table 3. Arrangement of Reinforcement Layers

Reinforcement Type	Layer No. (from bottom)	Ultimate Tensile Strength (kN)
Type 1	1 to 7	70
Type 2	8 to 10	50
Type 3	11 to 16	30

The design values of the geostrip reinforcement tensile strength are taken from the manufacturer's datasheetwith the assumption of 30ºC design temperature.

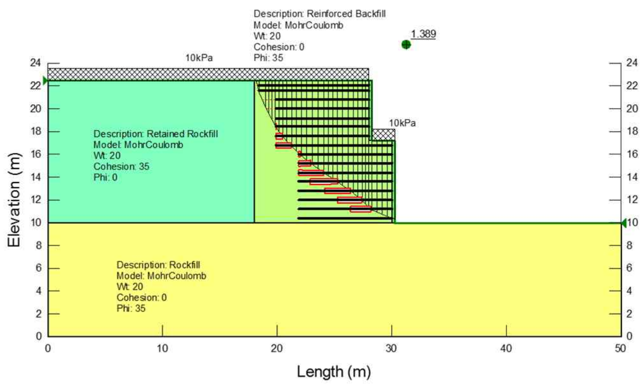
3.4 *Internal stability*

The internal stability review was carried out using the principles and methods described in BSI (2010). The calculations indicated that the reinforcement length and distribution adopted in the constructiongenerally satisfied the requirements of BSI (2010) based upon the input design parameters with the exception of the minimum reinforcement length of 0.7H. This specified minimum value is not a theoretically based figure but rather a general rule-of-thumb and therefore not an absolute critical requirement. Some design codes have different values and some do not specify a minimum at all; the minimum value in any code is 0.6H and it seemed that a value of 0.65H was adopted in the original design.However, all the external stability requirements were satisfied by the calculations in accordance with the BSI (2010) requirements.

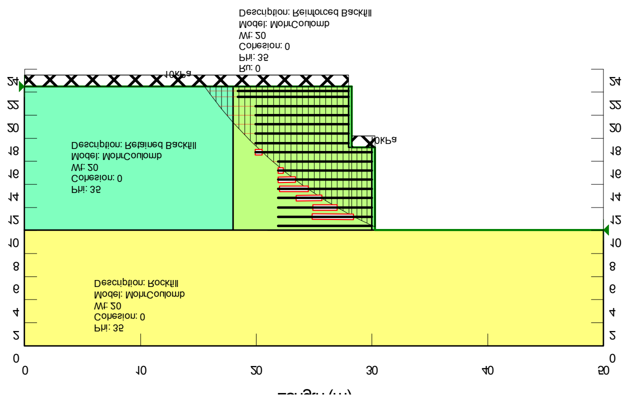
3.5 *Global Stability*

Global stability of the reinforced soil retaining wall was analysed using thegeneralised limit equilibrium method. The dimensions of the retaining wall and the configuration of the reinforcement are directly taken from the existing information as detailed above, as shown on Figure 4.

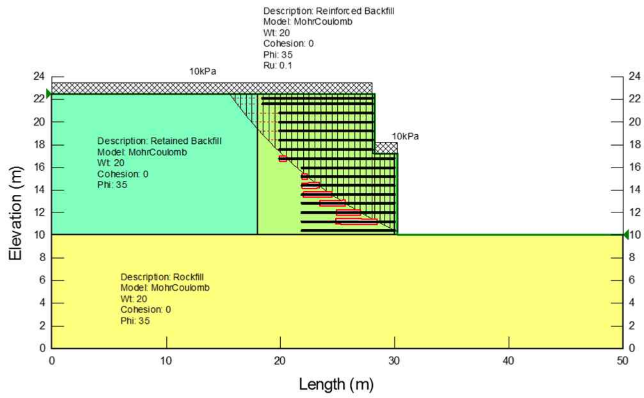
The factor of safety calculated for the dry condition (Figure 4a) using the auto located slip surface function is 1.39. When using the circular slip surface (Figure 4b), the factor of safety slightly increases to 1.41. When applying a pore water pressure which is equivalent to a r_u value of 0.1 (Figure 4c), the factor of safety reduces to 1.29. These values are satisfactory considering a minimum required value of 1.30. The effect of a seismic coefficient of 0.1 indicated in the original design was also analysed. The factor of safety is calculated as 1.23 and considered satisfactory, as shown on Figure 4d. The review therefore concluded that the compound stability of the original retailing wall design was acceptable.



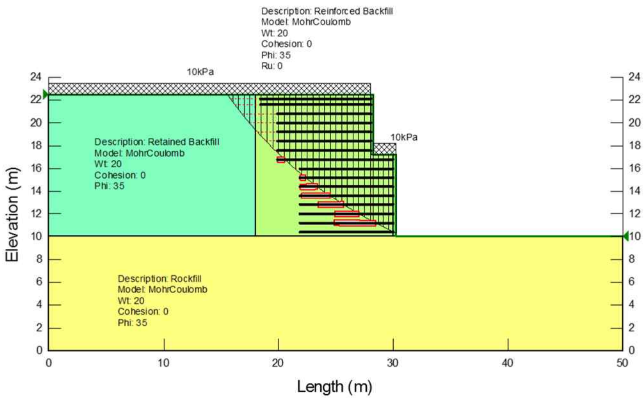
a) Auto slip surface, dry: FoS=1.39



b) Circular slip surface, dry: FoS=1.41



b) Circular slip surface, ru=0.1: FoS=1.29



d) Circular slip surface, dry, seismic: FoS=1.23

Figure 4. Global slope stability analyses

4 SITE INVESTIGATION

4.1 *Trial pitting*

Trial pitting was carried out to examine the connections between the reinforcement and the concrete panel. Four trial pits was excavated behind the face panels of the reinforced soil wall, as shown on Figure 5. The purpose of the trial pitting was threefold:

- Assess whether the deformations on-site had compromised the integrity of the connection between the reinforcement strips and the facing panels;
- Confirm the layout and detail of the connections; and

- Sample reinforced fill for laboratory testing.

Figure 5: Trial pit excavation

4.2 *Condition of connection*

The top connections to the panels were exposed in all four trial pits and found to be in a satisfactory condition with no evidence of overstressing or damage, as shown in Figure 6.

Figure 6. Condition of connections between reinforcement and facing panel

The connections in TP1 and TP2 were within the actual reinforced soil fill below the topsoil/sand layer and, in the case of TP2 below an additional 17 cm of general fill. The connections in TP3 and TP4 were above the true reinforced fill but taken down at an angle from the face to enable them to pass under the concrete levelling pad of the upper wall. The standard detail of the trial pits are presented in Figure 7.

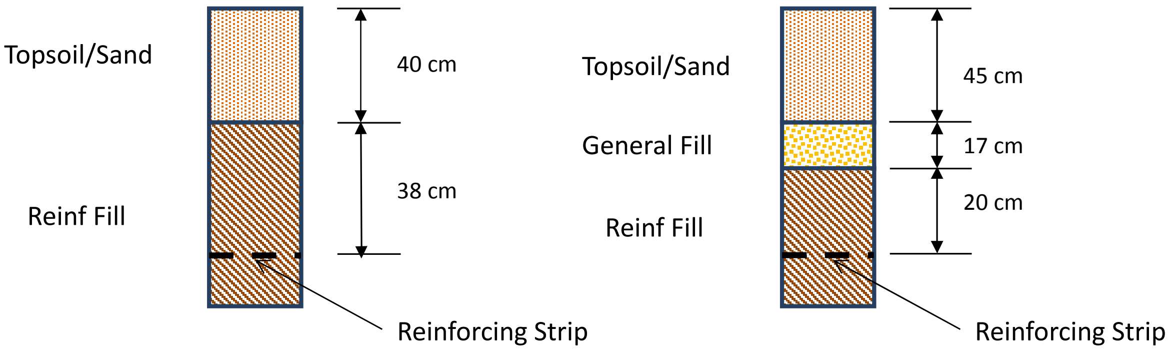


Figure 7. Ground encountered in TP1 and TP2

4.3 *Quality of fill*

Reinforced fill soil samples (well graded sandy gravel) were also taken from the trial pit (Figure 8a) and laboratory testing was carried out to confirm the quality of the reinforced fill used in the construction. The results of two large shear box tests (Figure 8b) on reinforced fill recovered from the top of the upper wall and the top of the lower wall indicateda peak friction angle 44^{o} which was much greater than the design friction angle of 35°. This, together with an inspection of the construction photographs taken during the retaining wall construction, suggested that the original construction of the reinforced soil retaining wall was satisfactory.

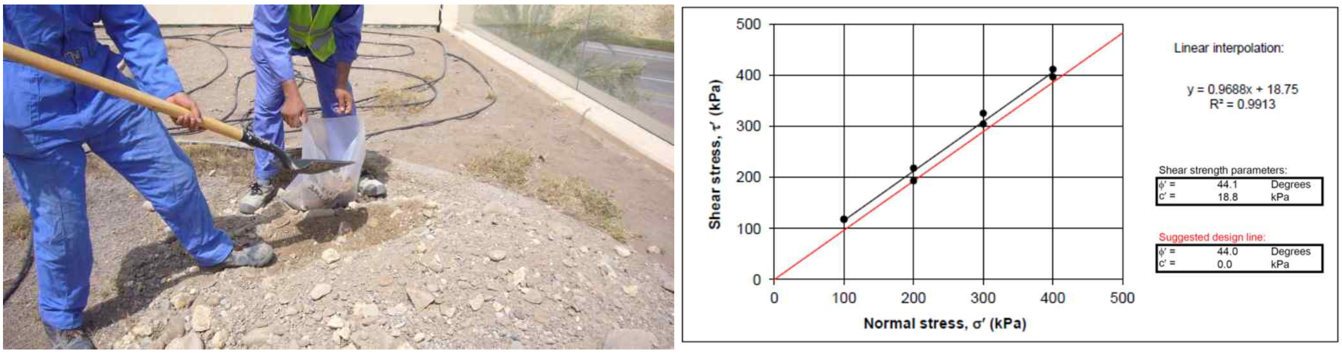


Figure 8. a) Sampling of reinforced fill; b) Shear strength assessment

5 NUMERICAL MODELLING

5.1 *Purpose of modelling*

Numerical modelling was carried out to assess the impact of the ground settlement on the stability and integrity of the reinforced soil retaining wall.There were three specific objectives that the numerical modelling work aimed to achieve as follows:

- Further validate the original design and construction;
- Estimate the level of tension developed within the reinforcement following ground settlement up to this point and assess the likely impact to the overall stability of the wall; and
- Predict the level of tension developed within the reinforcement assuming further ground settlement is to occur and assess the likely impact to the overall stability of the wall which can inform the ground improvement strategy of the site.

5.2 *Methodology*

FLAC (Fast Lagrangian Analysis of Continua) was chosen as the tool of the numerical analysis. FLAC has been used as a numerical modelling tool for the application of reinforced soil retailing wall by various researchers, e.g. Leshchinsky and Han (2004), Huang *et al.* (2009) and Abdelouhad *et al.* (2010).The FLAC modellingwas carried out in three stages:

- Stage 1: Establish a base model which represents the initial condition of the retaining wall, i.e. the pre-settlement condition (Figure 9a&b);
- Stage 2: Apply present ground settlement beneath the reinforced soils (Figure 9c) and assessment the stability and integrity of the retaining wall; and
- Stage 3: Apply further ground settlement (Figure 9c) and assessment the stability and integrity of the retaining wall.

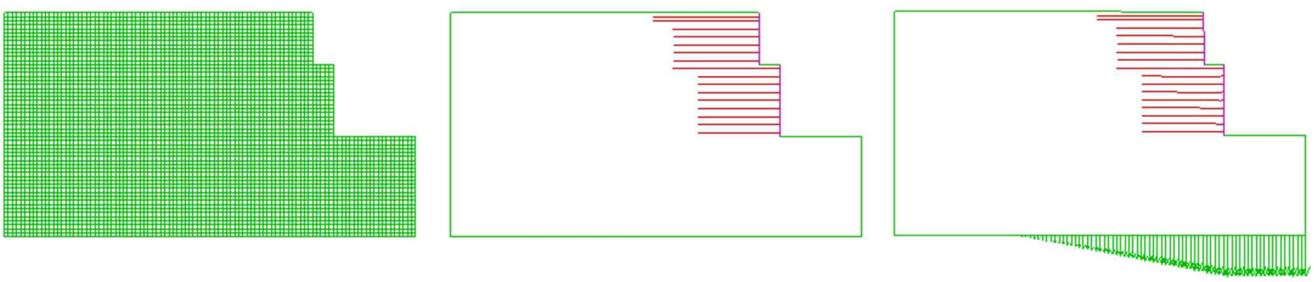


Figure 9. a) FLAC grid; b) Reinforcement elements; c) Apply ground settlement

5.3 *Modelling Results*

Stage 1 analyses further confirmed the adequacy of the original design. The deformation of the reinforced soils and the tensile forces of the reinforcing elements were acceptable for the retaining wallconstructed to the full height. Figure 10 presents some of the typical modelling result plots.

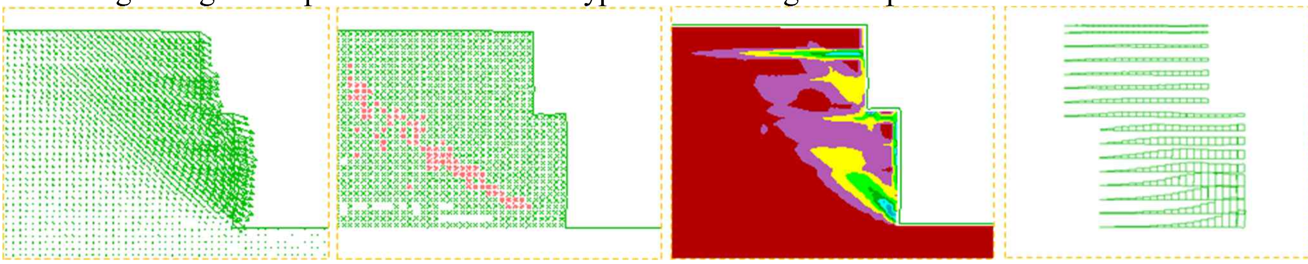


Figure 10. a) Displacement; b) Plasticity zones; c) Maximum shear strain; d) Tensile force distribution

Stage 2 analyses applied a settlement of 350 mm to the base of the reinforced soils which resulted in settlement of the upper level ground, causing damage to the upper villas observed on-site. The numerical modelling also showed that horizontal movements would occur to the retaining wall which was consistent with the observed damage to the concrete facing panels. Tensile forces developed within the reinforcing elements after the settlement were still below the design strength values of the materials used on-site with safety factors ranging from 3.3 to 6.8.

Stage 3 analyses indicated that more upper level settlement and horizontal wall displacement would occur should the ground movement beneath the reinforced soil retaining wall continue. This level of movement would cause further damage to the retaining wall facing panels and upper villa structures and may cause rupture of the connection between the facing and the reinforcement leading to instability of the facing panels. Although the calculated tensile forces within the reinforcing elements are shown to be still below the design strength values, the safety factors were shown to have significantly reduction from the current condition with the lowest value of 1.7. Pullout or breakage failures of the reinforcement would be anticipated to occur should the ground settle further.

6 SUMMARY AND CONCLUSIONS

The paper presented an assessment of the engineering performance of an existing reinforced soil retaining wall for a real estate development project. The assessment first looked at the original design which was concluded to be sufficient. This was followed by site investigation work which confirmed the integrity of the connection between the reinforcement and the concrete facing panels and validated the shear strength of the reinforced fill material. The numerical modelling work further validated the design and confirmed the integrity of the reinforcement by simulating the level of ground settlement which had already occurred on site. Further modelling work suggested that if the ground continues to settle rupture or pullout failure of reinforcement would eventually occur which could potentially cause failure of the retaining wall. These findings were used to inform the design and implementation of the ground improvement strategy of the site and proved to be instrumental to the success of the whole project.

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