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Numerical Evaluation on Seismic Performance of an Integrated Slope Stabilisation System

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Abstract: Slope instability is a common geotechnical problem in South Gippsland, Victoria, Australia. An integrated slopestabilisation technique based on two well-developed methods, the embedded piles and the gabion-faced geogrid-reinforced retaining wall, has widely been adopted in this area to enhance the stability of slopes. Reinforced soil retaining walls are inherently flexible and are relatively insensitive to the shakingdue to earthquake (Anastasopoulos 2010). Compared with the gravity-type retaining walls, the damage from the earthquake shaking to the reinforced retaining structures is relatively minor (Koseki et al. 1995; Tatsuoka et al. 1996; Bathurst and Hatami 1998). Several survived reinforced retaining walls after a destructive earthquake have also been recorded. A two-dimensional dynamic finite element analysis is conducted on the seismic behaviour of this integrated slopestabilisation method, in which the laterally loaded embedded pile can provide additional contribution to the stability of the slope. The behaviour of the soil and the gabion basket is simulated through the elastic-perfectly plastic constitutive model associated with the Mohr-Coulomb yield criterion. The embedded piles are shown to make a considerable contribution to the stability of the reinforced slope under the seismic condition. The effect of the friction angle and the cohesion of the clay soil on the seismic behaviour of the slope has been investigated. Overall, the performance of the integrated slope-stabilisation method reinforced slope studied in this paper is acceptable under the seismic loading conditions.

Keywords: Slope stabilisation; Seismic analysis; Pile retaining structure; Gabion-faced geogrid-reinforced retaining wall; Finite element method.

1 Introduction

Determination of the slope stability under the seismic conditions is a critical topic in geotechnical engineering. In the South Gippsland area located in Victoria state in south-eastern Australia, the shaking of the earthquake also induced severe failures of the slope that traversed by the rural roads (Brown et al. 2001; Hoult et al. 2014). Therefore, a distinctive integrated slope-stabilisation system that involves the gabion-faced geogrid-reinforced retaining wall (GF-GR-RW) and the embedded piles has been widely used in this region (Smith 2014).

The analysis of the slope stability under the dynamic earthquake loading hasreceived much attention in the literature. The seismic response of the slopeshas been investigated by Terzaghi (1950) through pseudo-static approaches. Regarding the pseudo-static approach, the dynamic loads of the earthquake are represented by the static inertia load that acts at the centre of the soil mass. In addition, the limit equilibrium method (LEM) has also been adoptedto analyse the stability of the slope under the earthquake loading conditions (Ghosh 2014; Hazariet al. 2017). Ling et al. (1997)adopted the pseudo-static limit equilibrium approach which considers the limit of the permanent displacement to investigate the seismic behaviour of the slope. Sarma(1973) used the displacement analysis based on the principle of the LEM to investigate the effect of the earthquake on the stability of the slope.

In this study, we studied the seismic behaviour of the slope reinforced by the integrated slopestabilisation method under the dynamic earthquake loading conditions. Moreover, the contribution of the embedded piles to the stability of the GF-GR-RW stabilised slopes subjected to the shaking of the earthquake has also been revealedthrough Finite Element Method (FEM). The numerical results indicate that the integrated slopestabilisation method can improve the slope stability under the seismic loading condition effectively, and the friction angle and the cohesion of the soil also imposesignificant impacts on the seismic behaviour of the slope.

2 Study Area

2.1 Background information

South Gippsland, located at Victoria state in Australia, is a region susceptible to the soil slope failures. The instability of the slope in this region imposes significant impacts on the road infrastructure, and the maintenance from the local government authority is frequently required. One slope site stabilised by the integrated slope-stabilisation method in the study area is shown in Figure 1.

Figure 1. Slope site reinforced by the integrated method that comprises the pile retaining wall with GF-GR-RW

2.2 General construction process

The general construction process of this integrated slope-stabilisation method is illustrated in Figure 2. According to Figure 2, the placement of the embedded pile is prior to the construction of the reinforced retaining structure. The boringis continued in the weathered bedrock layer to form the space for the pile to embed. The I-beam post is then placed in each hole and supported when borehole is backfilled by concrete. The I-beam post protruding 1 meter above ground level and is then welded to the steel rail to form a fixed beam, which provides lateral support to the retaining wall.

Figure 2. General construction process of the integrated slope-stabilisation method

Then, the GF-GR-RW is constructed adjoining the horizontal rail. Rocks are filled in the gabion baskets with a volume of 1m^3. Each gabion basket is then connected horizontally with double twisted wire mesh to compose layers of wall facing. Twelve gabion basket layers are then stacked in a stepped pattern with a 10V:1H gradient. During the stacking process, middle ten layers of the gabion basket are wrapped by the geogrid and then the tails of the geogrid are extended into the soil as it is backfilled (see Figure 3).

Figure 3. General construction process of geogrid-reinforced soil zone

2.3 Slope configurations

The numerical model of each slope configuration is based on the site conditions. The cut slope configuration without the reinforcement has a gradient of 10V:1Has depicted in Figure4a. The second slope configuration is the GF-GR-RW stabilised road embankment as shown in Figure 4b. Regarding the third slope configuration, the cut slope configuration is reinforced by the integrated slope-stabilisation method in which the embedded pile contributes to the stability of the road embankment (see Figure 4a).

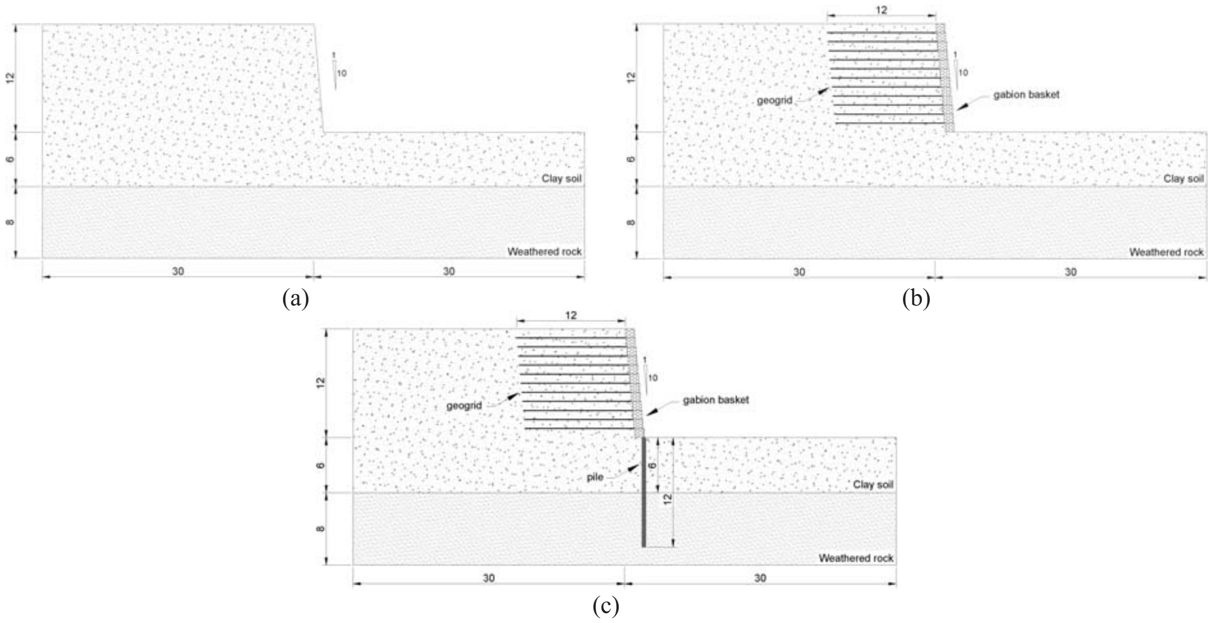


Figure 4. Three slope configurations adopted: (a) Cut slope configuration; (b) GF-GR-RW stabilised slope configuration; (c) Integrated method stabilised slope configuration (dimension in meters)

Based on the site conditions, the length of the pile is 12m and the embedded length of the pile in the weathered rock layer is 6m. Regarding the integrated method stabilised slope, the ratio of centre-to-centre spacing (S) to the pile diameter (D) adopted is 3.5 (S=1.4m and D=0.4 m).

3 Numerical Modelling Description

3.1Constitutive models

The geotechnical analysis software, *OptumG2*, is adopted in this study to conduct the two-dimensional numerical analysis. The geogrid layer is represented by the truss element. The standard beam element is adopted to simulate the behaviour of the concrete embedded pile. In addition, the elastoplastic constitutive model associated with the Mohr-Coulomb yield criterion is used to represent the behaviour of the upper natural soil layer, the lower weathered rock layer, and the gabion basket.

3.2 Material properties

Based on the material characteristics, the properties of the materials are summarised in Table 1. Moreover, the dilation angle of the clay soil is assumed to be 0°.

Table 1. Material properties

Material	γ(kN/m^3)	φ' (°)	c'(kPa)
natural soil	20	20	20
weathered rock	23	35	200
pile	23	-	-
gabion basket	17	45	560
steel	79	-	-
geosynthetic	2	-	-

3.3 Problem definition

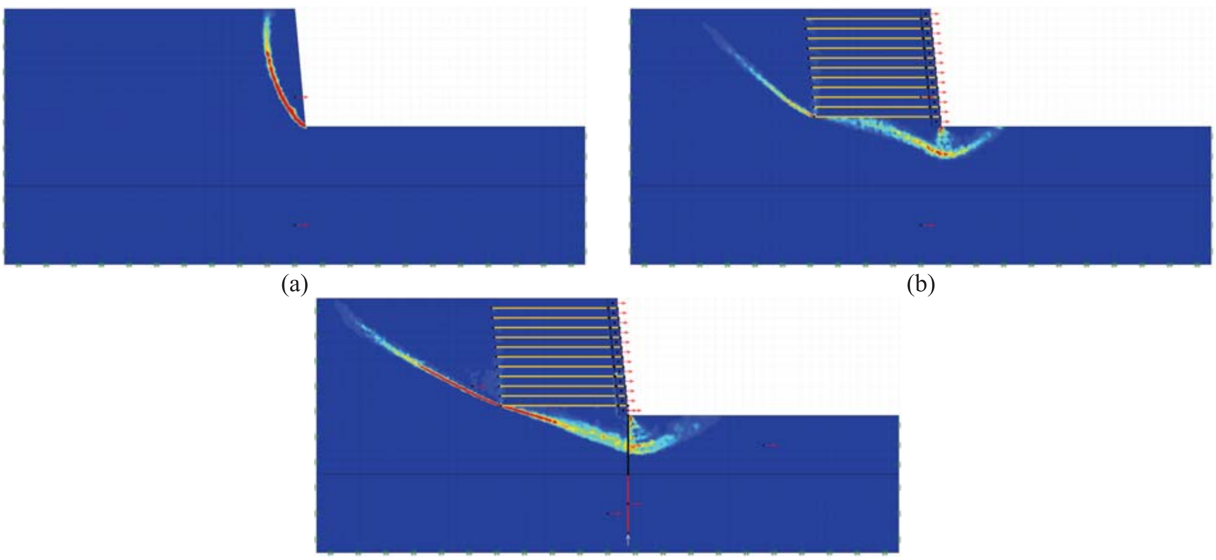
To study the seismic behaviour of the integrated method stabilised slope, the pseudo-static analysis which can be used to assess the stability of the geo-structures under the seismic loading is adopted in the current study. In this analysis, the dynamic loading induced by the shaking of the earthquake is represented by the body accelerations which can be applied statically. The vertical acceleration is kept constant as g_v=9.8 m/s^2, while the horizontal acceleration increases continuously until the occurrence of the slope failure. The ratio of vertical acceleration to the horizontal acceleration at failure of the slope, $k_c=g_v/g_h$, can be regarded as the critical seismic coefficient of the geo-structures. In addition, the value of the critical seismic coefficient corresponds to the Factor of Safety of the geo-structures (FoS) equal to unity.

In the current study, the Multiplier Body Load which represents the pseudo-static seismic load is applied tothree aforementioned slope configurations. Thereafter, the effect of the integrated slopestabilisation method under the seismic loading conditions can be demonstrated clearly through the comparison of the behaviour of three slope configurations.

4 Analysis of Results

4.1 Effect on critical slip surface

It is expected that the abovethree slope configurations show different behaviours under the seismic loading due to the existence of the reinforcement, therefore, the critical slip surface of each slope configuration has been extracted and discussed. For the behaviour of the cut slope configuration under the seismic loading condition, the critical slip surface is relatively small and abutting the facing of the road embankment (Figure 5a). The critical slip surface developed from the toe of the road embankment to the surface of the backfill. The major reason for this pattern of the critical slip surface of the cut slope configuration is the steep gradient of the facing of the road embankment. When the cut slope configuration is stabilised by the GF-GR-RW, the pattern of the critical slip surface changes significantly (Figure 5b). According to Figure 5b, the scale of the critical slip surface increases considerably which represents that more shear strength of the clay soil has been mobilised. The critical slip surface developed from the left part of the road to the left part of the backfill surface and goes through the left end of the bottom layer of the geogrid, which indicates that the friction force between the geogrid and the soil grain exceeds the tensile strength of the geogrid layer, the fracture of the geogrid layer and the internal failure mode of the reinforced soil zone are therefore avoided. Moreover, when the distinctive integrated slope-stabilisation method adopted to reinforce the road embankment, the pattern of the critical slip surface alters significantly (Figure 5c). According to Figure 5c, the length of the critical slip surface increases and still goes through the left end of the bottom geogrid layer. In addition, the depth of the critical slip surface also increases compared with the GF-GR-RW stabilised road embankment. In general, the existence of the reinforcement can alter the pattern of the critical slip surface and more shear strength of the soil which contributes to the overall slope stability can also be mobilized.



(c)

Figure 5. Critical slip surface of three slope configurations: (a) Cut slope configuration; (b) GF-GR-RW stabilised slope; (c) Integrated method stabilised slope

4.2Effect of friction angle of soil

For the stability of the soil slope under the seismic loading condition, the friction angle (φ') of the clay soil plays an important role (see Figure 6). According to Figure 6, the value of $k_c$of three slope configurations all shows an increasing trend with the increase of the φ', therefore, it can be demonstrated that the φ' of the clay soil contributes significantly to the overall stability of the slope under the seismic loading condition. In addition, the increasing trend of the $k_c$of three slope configurations is basically the same, which represents that the effect of the φ' on the stability of the slope under the dynamic loading condition is minorly influenced by the existence of the stabilisation work. Moreover, it is notable that when the cut slope configuration stabilised by the GF-GR-RW and the integrated method, the value of $k_c$increases considerably under all values of the φ'. Therefore, the effect of the reinforced retaining wall and the integrated slope-stabilisation method on improving the stability of the slope under the seismic loading condition can be demonstrated clearly. It is notable that there is a gap between the value of the $k_c$induced by the GF-GR-RW and the integrated method, and this increase in the $k_c$can be regarded as the contribution from the laterally loaded embedded pile to the stability of the slope.

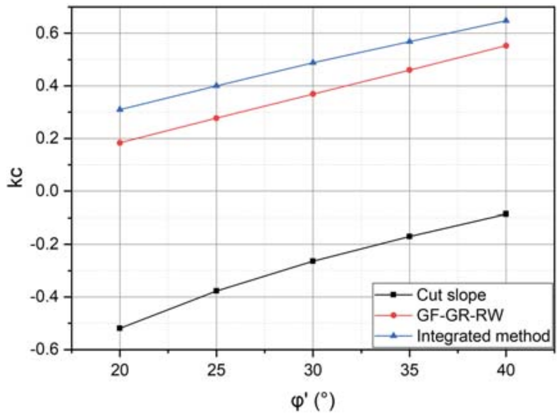


Figure 6. Critical seismic coefficient (k_c) as a function of the soil friction angle (φ')

4.3 Effect of cohesion of soil

As another important parameter related to the stability of the slope, the cohesion, c',of the soil also imposes significant impacts on the seismic behaviour of the slope (see Fig .7). It is evident that for three slope configurations analysed in this study, the value of $k_c$increases with the increase of $c'$of the soil. However, the distribution of $k_c$influenced by the c'shows a different trend compared with the effect of the φ': the increase rate of the $k_c$of cut slope configuration is relatively larger than the GF-GR-RW stabilised slope and the integrated method stabilised slope, which indicates that thec'imposes more significant influence on the unreinforced slope configuration. In addition, it is also notable that the value of $k_c$increases significantly under all values of the c' adopted after stabilised by the GF-GR-RW and the integrated method. Moreover, the increase rate of $k_c$induced by the increase of the c' is relatively lower than the increase rate of k_c induced by the increase of the φ', which indicates that the friction angle of the soil imposes more considerable influence on the stability of the slope than the cohesion of the soil under the seismic loading condition.

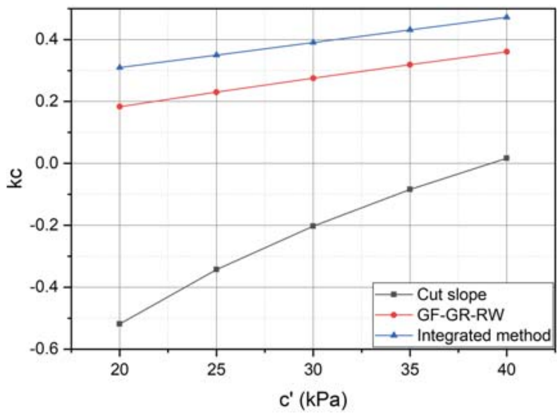


Figure 7. Critical seismic coefficient (k_c) as a function of the soil cohesion (c')

5 Conclusions

In the South Gippsland region, a distinctive reinforcement method has been adopted by integrating soil reinforcement with geogrid, embedded piles and the gabion facing. The effectiveness of this integrated slopestabilisation method has been demonstrated clearly by investigating the value of the critical seismic coefficient of the slope, the effect of the friction angle and the cohesion of the clay soil on the critical seismic coefficient has been illustrated, and the effect of the reinforcement on the distribution of the critical slip surface of the slope under the seismic loading condition has also been investigated.

Under the seismic loading condition, the existence of the reinforcement alters the pattern of the critical slip surface of the slope significantly. The scale of the critical slip surface of the cut slope configuration is relatively small, and then the existence of the integrated slopestabilisation method expands the length and width of the critical slip surface significantly. This phenomenon indicates that under the dynamic loading condition, the existence of the reinforcement can mobilise more soil shear strength which can contribute to the stability of the slope.

Several different values of the friction angle and the cohesion of the soil have been adopted in the current study.It is notable that the reinforced slope configurations always yield higher value of critical seismic coefficient under all values of the friction angle and the cohesion, the effectiveness of the integrated slopestabilisation method can be demonstrated clearly. Moreover, it is worth noting that the effect of the friction angle on the stability of the slope is basically the same for the unreinforced and the reinforced slope configurations under the seismic loading conditions; however, the effect of the cohesion imposes more significant influence on the unreinforced slope configuration than the reinforced slope configuration under the dynamic loading condition.

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