Stability Analysis of Tiered Geosynthetic Reinforced Soil Wall with Pre-stressed Anchor Pile

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ABSTRACT

For the height limit of single step geosynthetic reinforced soil wall, the tiered geosynthetic reinforced soil wall is widely used now. Existed researches show that lateral deformation and stress concentration occur at the bottom of tiered geosynthetic reinforced soil wall. To insure the stability, pre-stressed anchor cable pile has been set at the bottom of wall and form a composite retaining structure. This paper draw a conclusion that the global stability of tiered geosynthetic reinforced soil wall can be calculated according to soil slope by analyze related design methods as FHWA & NCMA. Based on principle analysis of traditional limit equilibrium method and shear strength reduction method by FEM, this paper separately uses five different traditional slice methods and shear strength reduction method performs the stability calculation of composite retaining structure. Conclusions as follow: two different types of stability analytical method all fit the demand of that composite retaining structure; calculated results of slice method similar to finite element method and has its own feature; pre-stressed anchor cable anti-slide pile can apparently develop the whole stability of tiered geosynthetic reinforced soil wall; the factor of safety calculated by Janbu simplified method is smallest at each working condition; differences exist in each slice method so should choice suitable one; with the filling height increase, the factor of safety of whole composite retaining structure decreased and loads of anti-slide pile increase. Conclusions can be referenced by similar project.

KEYWORDS: Tiered geosynthetic reinforced soil wall; Pre-stressed anchor pile; Composite retaining structure; Stability of slope; Limit equilibrium theory; Shear strength reduction method; FOS(factor of safety)

INTRODUCTION

The single step geosynthetic reinforced soil retaining wall has been widely used in engineering, and form relatively perfect design guideline & theory[1], three types of calculation for reinforced soil retaining wall respectively based on limit equilibrium method, limit state method and numerical simulation method[2]. To fit the demand of high filling slope demand, optimize the engineering properties of retaining structure, the single step wall develops to tiered geosynthetic reinforced soil wall. For tiered geosynthetic reinforced soil wall's design method only has few regulations given by FHWA[3], NCMA[4] and BSI 8006(2010)[5]. China has no detail design method of tiered geosynthetic reinforced soil wall now[6][7].

Researches of tiered geosynthetic reinforced soil wall mainly focus on field observation, model test and numerical simulation. Qi Wei[8] analyzes the horizontal stress and deformation character of two-tiered geosynthetic reinforced soil wall. Yoo[9][10] analyzes the load induced reinforcement strains of two-tiered geosynthetic reinforced soil wall by full scale load test. Xiang Wang and Lin-rong Xv[11] analyze field test data observed from two-tiered reinforced soil wall on Meikan railway project. Guang-qing Yang and Yi-tao Zhou[12] analyze the behaviors of two-tiered geogrid reinforced earth retaining wall on rigid foundation. Yoo[13] presents results of a comparative study on the design approaches for geosynthetic reinforced walls in a tiered configuration. Suliman B.A.[14] performs the finite element (FE) analyses of two-tiered geosynthetic reinforced soil (GRS) wall, compared with results get by centrifuge test and FHWA design guidelines. Guang-qing Yang, Hua-bei Liu, etc. [15] study the long-term performance and safety of a 17m high two-tiered reinforced soil wall backfilled with soil-rock mixture. Guang-qing Yang, Hua-bei Liu, etc.[16] by laboratory model test shows that the max value of vertical stress at the bottom of the two-tiered geosynthetic-reinforced soil (GRS) wall is near the wall's panel.

From observation data and correlational studies, it can be seen that general problems of tiered geosynthetic reinforced soil wall are stress concentration and large lateral deformation at the bottom of wall, on the other hand because of landform limitation at mountain area it is difficult to pave full length of geosynthetic at retaining wall's bottom. For above questions, this paper proposes a solution scheme that by set pre-stressed anchor cable anti-slide pile at the bottom of tiered geosynthetic reinforced soil wall to decrease the lateral deformation and insure the stability. This paper performs calculation and comparison of composite retaining structure's global stability and other characters by traditional slice method and finite element method(FEM).

DESIGN METHOD OF TIERED GEOSYNTHETIC REINFORCED SOIL WALL

China has no detail design method of tiered geosynthetic reinforced soil wall in current engineering criterions. Related design methods are given by FHWA, NCMA, BSI 8006(2010) and some research conclusions.

FHWA divides into three conditions for calculation

D: width of platform; H_1: height of upper wall; H_2: height of lower wall.

(1) $D \leq (H_1+H_2)/20$, simplified as single step wall for design.

(2) $D \geq H_2 \tan(90° - \varphi)$, don't think of interaction, that is upper and lower wall design separately.

(3) $(H_1 + H_2)/20 \leq D \leq H_2 \tan(90° - \varphi)$, perform external and internal stability calculation of lower wall based on effect caused by upper wall as vertical pressure.

Design method of NCMA(National Concrete Masonry Association)

In upper wall's design don't think the interaction between upper and lower wall, in lower wall's design look the upper wall as uniformly distributed load applied on the top.

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The criterion use limit state method for design and only simply point that in stability analysis of tiered geosynthetic reinforced soil wall should think the effect of upper wall as load for lower wall.

Other studies

Wang, L. and Wright, S.G.[17] present a procedure for global stability analysis of multi-tiered MSE walls. Wright[18] combined with the study of multi-tiered walls by the University of Texas at Austin, presents a design procedure based on diagram. Above studies can all be looked as supplement of FHWA's design method.

Summarize above design methods and studies it can be seen that the global stability analysis of tiered geosynthetic reinforced soil wall is follow the manner of soil slope, therefore this paper use traditional slice method and shear strength reduction method by FEM study the global stability of tiered geosynthetic reinforced soil wall.

THEORY OF CALCULATION

Analysis of Slope's Stability by Limit Equilibrium Theory

A.N. Bishop[19] defines the FOS of soil slope as the ratio of shear strength τ_f along the whole potential failure surface between the real generated shear strength τ . This definition offers the foundation for analysis of slope's stability by different method.

$$FOS = \tau_f / \tau \quad (1)$$

Hyper-static problem of traditional slice method

Stability analysis of common soil slope is a hyper-static problem, the basic principle of slice method is by theory assumption or simplified conditions to solve the hyper-static problem. Each slice method has different theory assumption or simplified conditions, which leads to different application conditions and accuracy[20][21]. Although the study of slice method developed in recent years, it has to obey the above principles yet[22].

Table 1: Comparison of different slice method

Slice method	Mechanics balance conditions			
	Total moment	Moment of soil slice	Vertical force	Horizontal force
Fellenius	√	×	×	×
Bishop	√	×	√	×
Janbu Simplified	√	√	√	√
Morgenstern-Price	√	√	√	√
Spencer	√	√	√	√

Defects of traditional slice method based on limit equilibrium theory

Slice methods based on the theory of limit equilibrium, lack the describe of soil constitutive model and need assumptions to decrease the excess unknown quantity for calculation, at the same time slice method can't find the real force distribution and suppose the shape of potential failure surface for calculation.

Shear Strength Reduction Method by FEM

Basic principle of FEM shear strength reduction method

By define the factor of strength reduction to make the finite element calculation not convergence; the reduction factor is the FOS of slope, slope failure and numerical non-convergence happen at the same time. It can be seen as finite element mesh apparently deformed and nodal displacement quickly increased. Since be proposed by Griffiths[23], the method has been widely used and improved[24][25], and get into the field of reinforced soil[26][27].

As Griffiths pointed out, the factor of safety (FOS) of soil slope is defined here as the number by which the original shear strength parameters must be divided in order to bring the slope to the point of failure. It can be described as the following formula.

$$c_f^{'} = c^{'} / FOS \qquad \varphi_f^{'} = \arctan(\tan\varphi^{'} / FOS) \tag{2}$$

Features

Advantages of shear strength reduction method by FEM as follows: it can use elastic-plastic constitutive model to describe soil's characters; give the real stress state and distribution of soil structure; no assumption needs to be made of the shape & location of potential failure surface, and can be get by automatic search; it can simulate the interaction between soil and geosynthetics, anchor cable and pile, etc. On the contrary, calculation of slope's stability by FEM is on the whole cross section and hardly used on designated area.

CALCULATION SETTING

Project profile

Cross section of calculation is selected from Zhang-tang railway project. Design scheme is the reinforced soil body divided into four steps from bottom to top of the retaining wall, pre-stressed anchor cable anti-slide pile set at the first step of retaining wall, the first step's height is 7.0m. Slope ratio of above three steps is 1.0:0.3, each step height is 8.0m, width of platform between step is 6.0m. Above the retaining wall is a road shoulder, its slope ratio is 1.0:1.5 and height is 6.0m. Geogrids be horizontally paved each layer, length and type as follow. The first step use geogrid of type EG170R, paved till the dig step of original slope. The second step use geogrid of type EG170R, horizontally paved and length is 18m at bottom 8 layers, 20m at above 18 layers. The third step use geogrid of type EG130R, horizontally paved and length is 14m at bottom 8 layers, 20m at above 18 layers. The fourth step use geogrid of type EG130R, horizontally paved and length is 10m at bottom 8 layers, 12m at above 18 layers. Vertical distance of each reinforced layer is 0.3m. Reinforced concrete anti-slide pile is 18m long and 11m beneath the ground. Pre-stressed anchor cable is Φ152mm and angle on horizontal plane is 18°.

Introduction of Analysis

Methods of calculation

To insure the calculation accuracy and analyze rules of results, this paper first use traditional slice method perform calculations, then use shear strength reduction method by FEM for comparison. Traditional slice methods are Fellenius, Bishop simplified, Janbu simplified, Spencer and Morgenstern-Prince. Above methods are used to calculate the global stability of tiered geosynthetic reinforced soil wall.

Parameters

(1) According to Chinese “Code for design on subgrade of railway” [28], the value of distributed loads is $q=65kN/m^2$.

(2) Parameters of reinforcements as geogrid, pre-stressed anchor, anti-slide pile according to design instruction.

(3) Design tensile strength of HDPE uniaxial geogrid: EG90R is 34kPa, EG130R is 49kPa, and EG170R is 64.3kPa.

(4) Filling soil of retaining wall use Mohr-Coulomb elastic-plastic constitutive model, parameters can be seen in Table 2.

Table 2: Mechanics parameters of filling soil

C/ kPa	φ /°	γ/ kN/m^3
5	35	19

Phase of calculation

According to construction progress, phase of calculation as follow:

Phase 1: filling to second platform.

Phase 2: filling to third platform.

Phase 3: filling to fourth platform.

Phase 4: filling to top of cross section.

Phase 5: apply loads(railway conversion load).

Contents of analysis

(1) By FEM software Plaxis, this paper analyzes the FOS(factor of safety) of different construction stage, potential failure surface of cross section and stress distribution along the pile shaft.

(2) By traditional slice methods, this paper calculates the four working conditions as whether set pre-stress anchor cable anti-slide pile, whole cross section or only upper reinforced soil zone.

ANALYSIS OF CALCULATED RESULTS

Results of traditional slice methods

By above five traditional slice methods, this paper performs calculation of 4 working conditions as follow. Set pre-stress anchor cable anti-slide pile and only reinforced soil area is factor of safety 1(FOS1), set pre-stress anchor cable anti-slide pile and whole cross section is factor of safety 2(FOS2), without pre-stress anchor cable anti-slide pile and only reinforced soil area is factor of safety 3(FOS3), without pre-stress anchor cable anti-slide pile and whole cross section is factor of safety 4(FOS4).

Graphs of slice method

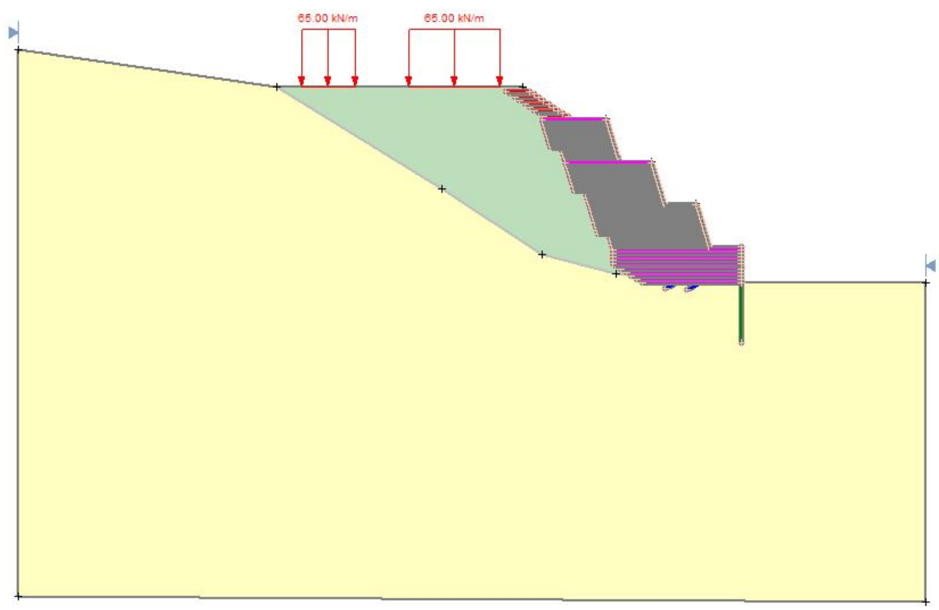
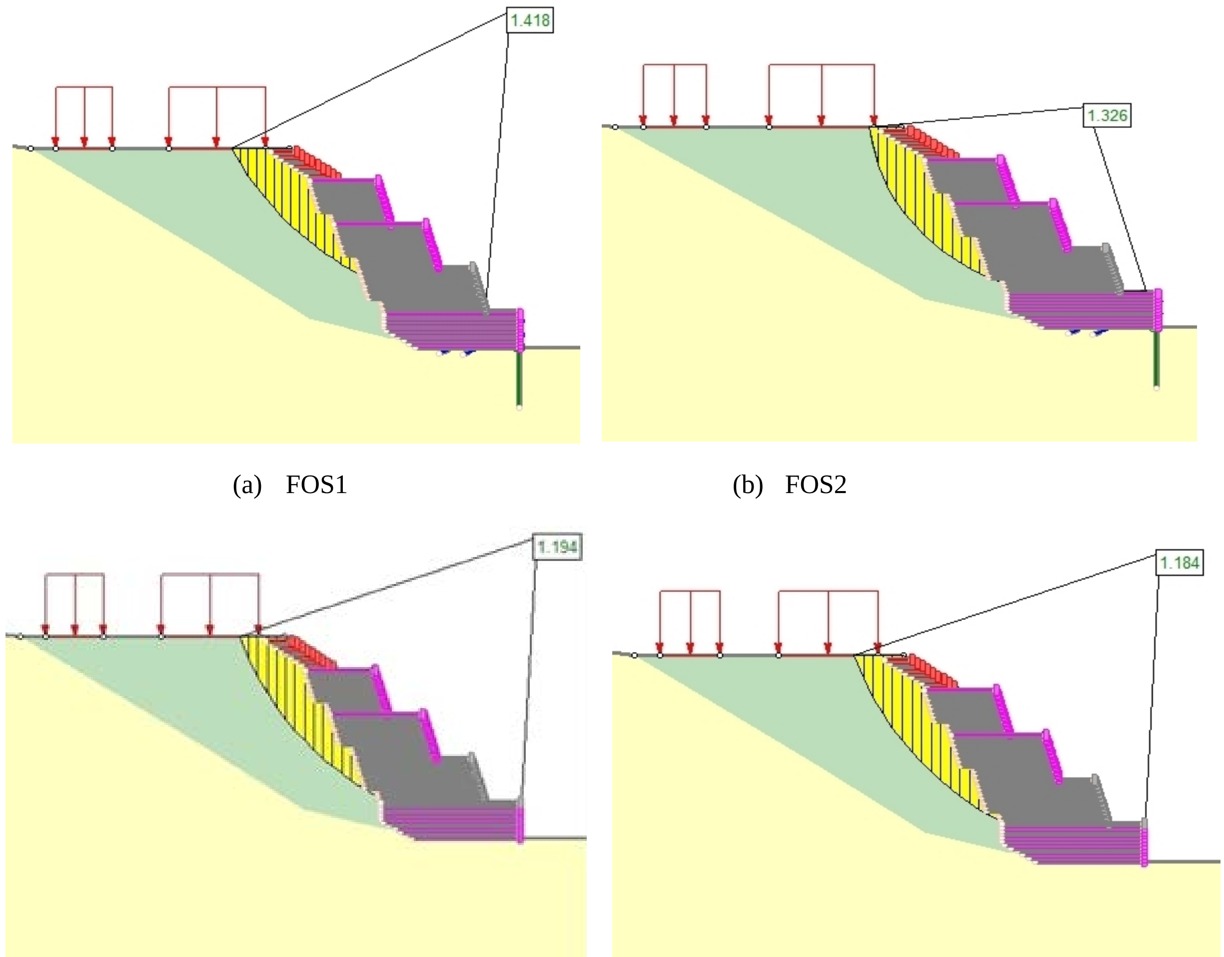


Figure 1: Cross section of calculation



(a) FOS1 (b) FOS2

(c) FOS3 (d) FOS4

Figure 2: Potential failure surface calculated by Janbu simplified method

Results of slice method

Table 3: FOS of different slice method

Method	With support at bottom		Without support at bottom	
	FOS1	FOS2	FOS3	FOS4
Bishop simplified	1.555	1.497	1.335	1.325
Morgenstern-Prince	1.544	1.503	1.327	1.317
Janbu simplified	1.418	1.326	1.194	1.184
Fellenius	1.441	1.362	1.214	1.201
Spencer	1.572	1.531	1.322	1.318

From results listed in table 3, it can be seen that by setting pre-stress anchor cable anti-slide pile at bottom can increase the stability of composite retaining structure, FOS of upper single reinforced soil zone is higher than the whole composite retaining structure, and FOS calculated by Janbu simplified method is smallest among five methods.

Results of FEM

FEM model

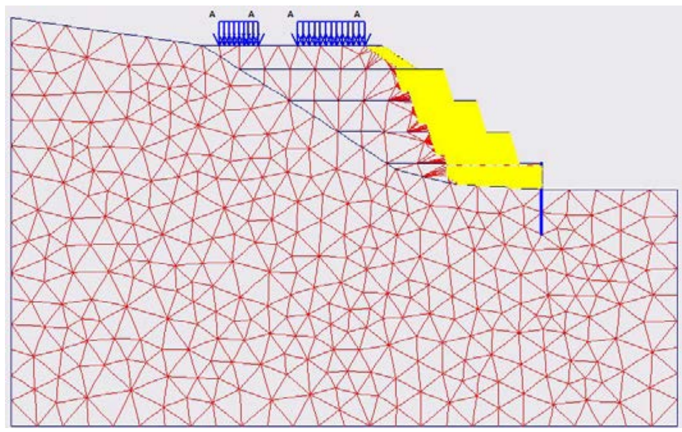


Figure 3: Meshed model

Results of calculation

This paper performs calculation according to preamble settings, analyzes the FOS and stress of pile at each phase. By take global failure surface (imply by total incremental displacements) of cross section and shear strength & bending moment of pile of each phase for demonstration.

(1) Potential failure surface

Analyze following Figure 4 and 5, it can be seen that potential failure surface pass through the bottom of anti-slide pile at phase 1 and 2, for phase 3 to phase 5 the corresponding potential failure surface mainly located at the reinforced soil zone above the anti-slide pile.

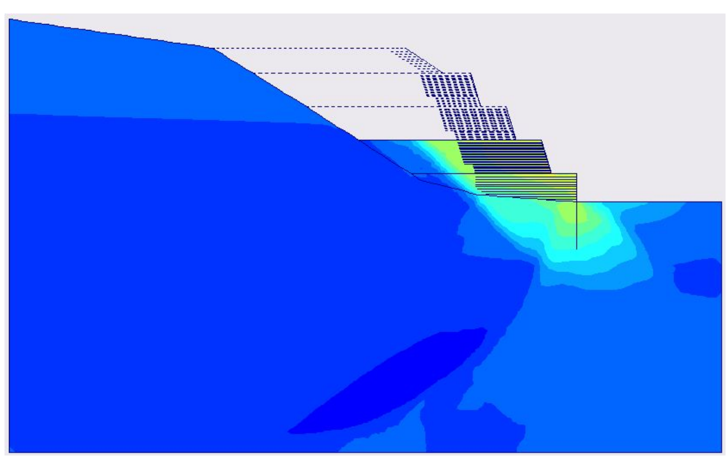
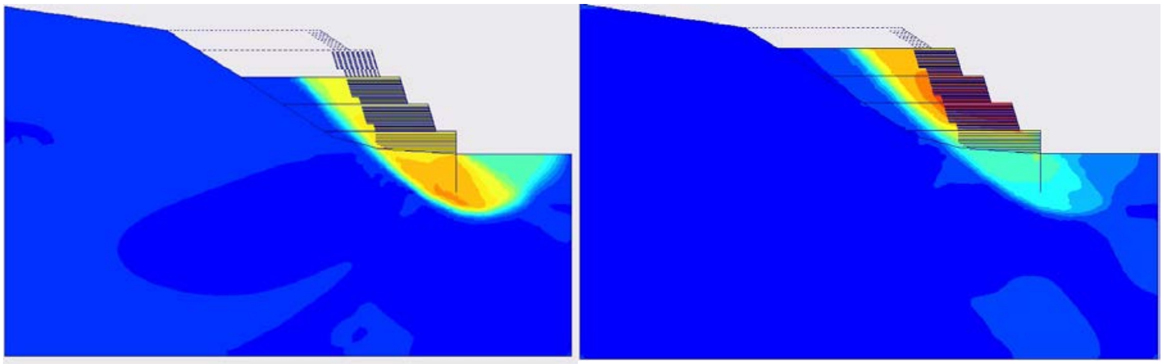
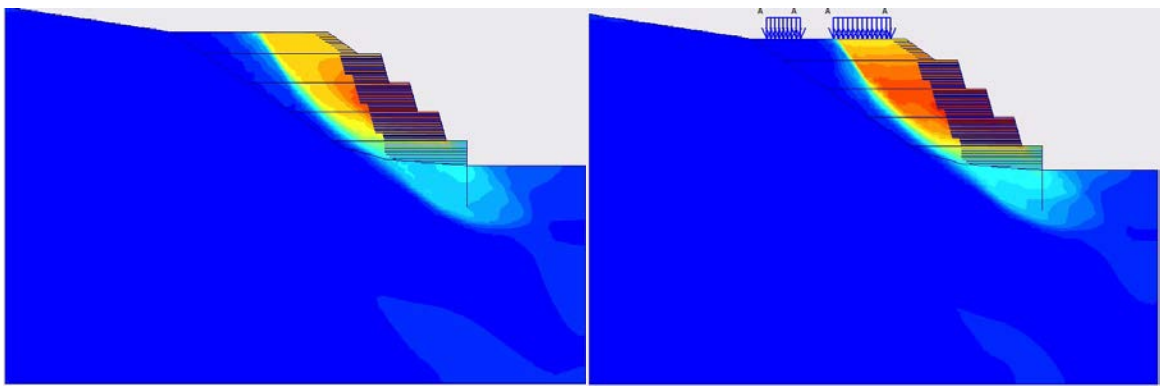


Figure 4: Potential failure surface of phase 1



(a) Phase2 (b) Phase3



(c) Phase4 (d) Phase5

Figure 5: Potential failure surface of each phase

(2) Comparison of force along pile shaft

Force along the pile shaft as bending moment and shear force shown in Figure 6 and 7, according to the order from left to right is phase 1 to 5.

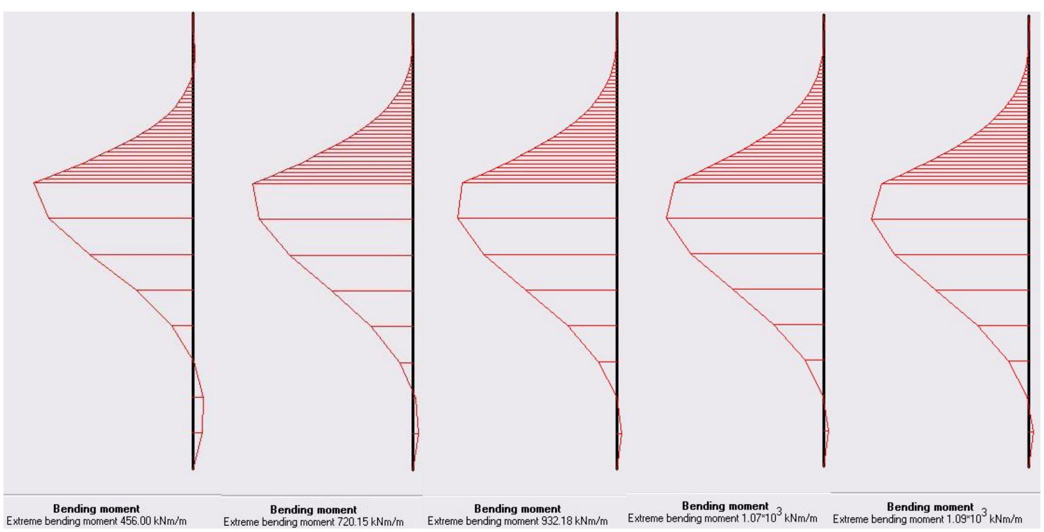


Figure 6: Distribution of bending moment of each phase

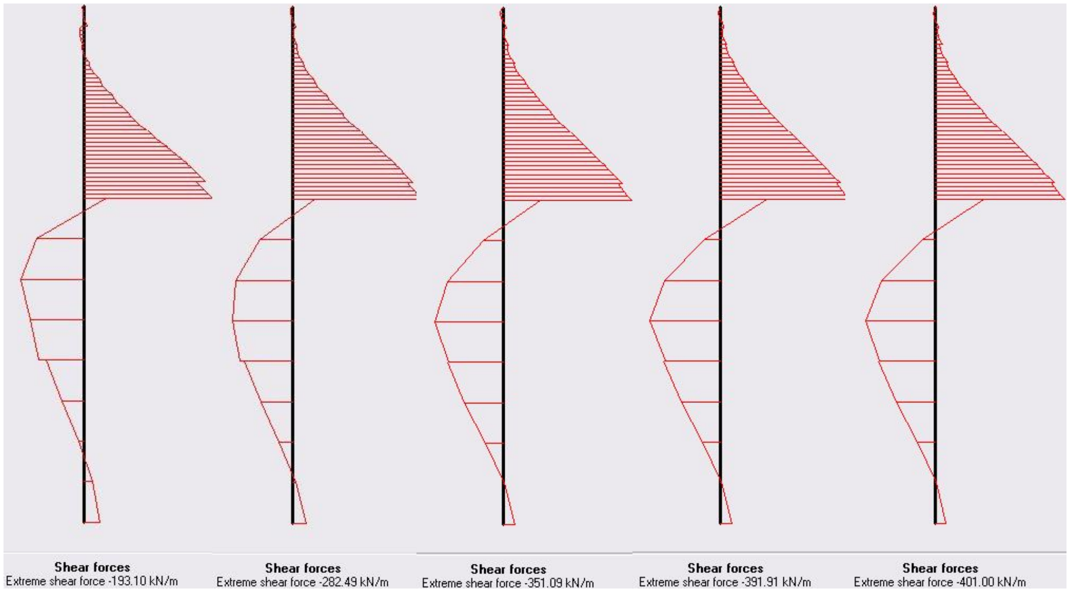


Figure 7: Distribution of shear force of each phase

Max value of bending moment and shear force of anti-slide pile and FOS of each phase listed in Table 4, calculated by FEM.

Table 4: Results of FEM

	No.	Phase1	Phase 2	Phase 3	Phase 4	Phase 5
	FOS	1.944	1.671	1.464	1.382	1.355
Pile	M_{max} (kN.m/m)	456.00	720.15	932.18	1072.32	1095.71
	V_{max} (kN/m)	193.10	282.49	351.09	391.91	401.06

Table 5: FOS comparison of FEM VS slice method

Slice method	Bishop simplified	Morgenstern-Prince	Janbu simplified	Fellenius	Spencer
	1.497	1.503	1.326	1.362	1.531
Deviation	10.47%	10.92%	-2.14%	0.52%	12.99%

Remark: results in Table 5 are at the working condition of set uniformly distributed loads on the whole cross section, which is Phase 5 in FEM calculation.

From results listed in Table 4 and 5, Figure 4 to 7, it can be seen that FEM suitable for analyze the stability of that composite retaining structure, at same time FEM can be used to find the rules of stress distribution of support pile, etc.

CONCLUSIONS

Based on summarize existed researches and engineering applications, this paper separately uses five different traditional slice methods and shear strength reduction method by FEM performs analysis of composite retaining structure's engineering properties.

(1) Two different type methods all fit for analyze the stability of that composite retaining structure, and has its own feature. Traditional slice method can analyze the stability of designated area. FEM can simulate the sequence of construction and find the real potential failure surface.

(2) Location of potential failure surface and FOS calculated by FEM similar to slice method, FOS get by Fellenius slice method is closest to FEM. It means that calculated results are reasonable, two different type methods can be referenced each other.

(3) For the difference of simplified conditions, FOS and location of potential failure surface exists diversity between five slice methods. It suggests that should choice suitable slice method in design and calculation.

(4) With the filling height increase, FOS of composite retaining structure decreased, company with the location change of potential failure surface. The location of potential failure surface cross the bottom of anti-slide pile when the filling height is low, with the increase of filling height the potential failure surface change to the area of pure reinforced soil which above the pile.

(5) Pre-stressed anchor cable anti-slide pile can apparently increase the FOS of composite retaining structure. In this project, by slice method the min value of FOS is 1.362, by FEM the min value of FOS is 1.355, without above anchor cable and pile the FOS dropped to 1.184.

(6) With the filling height increase, the max value of shear strength and bending moment of anti-slide pile increase too. By FEM not only calculate the max value of shear strength and bending moment of anti-slide pile at each phase, but also give rules of distribution along pile shaft.

(7) FOS of pure reinforced soil area is higher than the whole cross section in general.

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