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Numerical analysis of stability of slope reinforced with piles subjected to combined load

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ABSTRACT: By using elasto-plastic finite element method based on the technique of shear strength reduction, stability of slope reinforced with piles and performance of load-bearing piles in slopes subjected to combined load are numerically analyzed. The iteration non-convergence criterion conventionally used for assessing the instability state of slopes is employed to evaluate the limit-equilibrium state of pile-soil-slope system. Moreover, considering the complexity of pile-soil interaction, the criterion based on the uncontrolled displacement at a certain characteristic nodes on the slope surface is used for evaluate the limit state as an assistant criterion in addition to the iteration non-convergence criterion of solution in order to get more reasonable and reliable solution from numerical results. Finally, the effect of the combinations of vertical load and horizontal load on the stability of pile-soil-slope system is investigated through numerical analyses.

1 INTRODUCTION

The stabilizing piles are widely used in the reinforcement engineering of slopes and mitigation and prevention of natural geological disasters induced by landslides. However, because of its rather sophistication, the working mechanism of stabilizing piles and stability of piles in the slopes are not clarified especially when the piles are subjected to the combined actions of both components of horizontal load and vertical load imposed by the superstructures. Under such a circumstance, the piles in slope will play two functions, one is as reinforcement to induce the instability and another is to bear the loads transferred by structures. In fact, the pile-soil-slope will constitute an interaction system. Therefore, it will be theoretically important and practically significance to examine the mechanism of piles in both stabilizing the slope and carrying the loads and to discover the interaction effect of piles-soil-slope. In this paper, the stability of slopes reinforced with piles against potential sliding and bearing capacity behavior of piles in the slopes subjected to combined loads as well as interaction mechanism of pile-soil-slope are numerically investigated.

2 SHEAR STRENGTH REDUCTION ELASTO-PLASTIC FEM CONSIDERING CONTACT BEHAVIOR

2.1 *Interaction between surfaces*

The interaction of contacting surface between pile and soils consists of two components: one normal to the surfaces and one tangential to the surfaces. The tangential component consists of the relative motion (sliding) of the surfaces and, possibly, frictional shear stresses. Each contact interaction can refer to a contact property that specifies a model for the interaction between the contacting surfaces. There are several contact interaction models available in ABAQUS soft, the friction behavior of interface is adopted here.

2.2 *Contact algorithm*

ABAQUS examines the state of all contact interactions at the start of each increment to establish whether slave nodes are open or closed. In Figure 1, p denotes the contact pressure at a slave node and h represents the penetration of a slave node into the master surface. If a

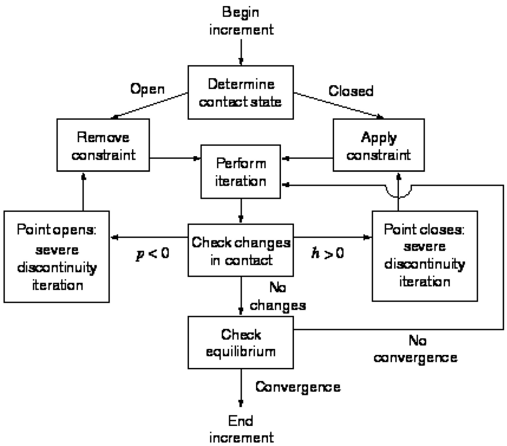


Figure 1. Contact algorithm(from ABAQUS6.3).

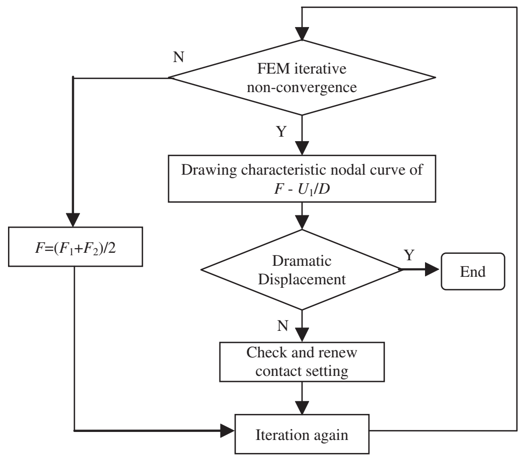


Figure 2. SSR-E-P-FEM procedure considering contact behavior.

node is closed, ABAQUS determines whether it is sliding or sticking. ABAQUS applies a constraint for each closed node and removes constraints from any node where the contact state changes from closed to open. ABAQUS then carries out an iteration and updates the configuration of the model using the calculated corrections. By default, ABAQUS abandons any increment where it needs more than twelve severe discontinuity iterations and tries the increment again with a smaller increment size. If there are no severe discontinuity iterations, the contact state is not changing from increment to increment (see Figure 1).

2.3 *Shear strength reduction elasto-plastic FEM considering contact behavior*

Finite element analysis of slope stability does not provide an explicit factor of safety (FS) but utilizes the so-called shear strength reduction technique (Zienkicwicz,1975; Ugai,1989; Matsui & San,1992). The FS of a slope is defined as the number by which the shear strength parameters must be factored down to bring the slope to failure. Using this technique, the mobilized shear strength parameters, c_m and $\tan\phi_m$, are obtained by dividing c and $\tan\phi$ by the strength reduction factor (SRF) as follows:

$$c_m = \frac{c}{F}, \quad \tan\phi_m = \frac{\tan\phi}{F} \tag{1}$$

where F is defined as shear strength reduction factor.

According to the above ideas, an elasto-plastic FE computation programming using Fortran90 is developed based on ABAQUS software. Python language is used to write a judgement program and evaluate the numerical convergence (see Figure 2). The non-convergence criterion combined with dimensionless displacement increment at some characteristic nodes on slope surface is employed to analyze the stability of slopes with stabilizing piles and load-bearing piles under combined load mode.

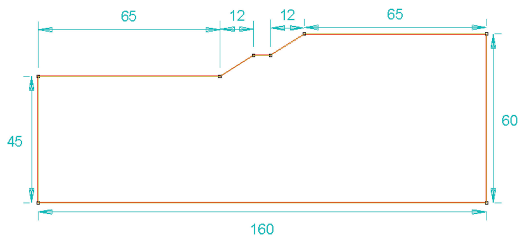
Table 1. Material parameters for FE analysis.

Property	Soil	Pile
Young's modulus, E(MPa)	50.0	26000.0
Poisson's ratio, ν	0.3	0.2
Unit weight, γ(kN/m^3)	1800.0	2400.0
Internal friction angle, ϕ(°)	35.0	–
Effective cohesion, c(kPa)	10.0	–
Dilation angle, ψ(°)	0.0	–

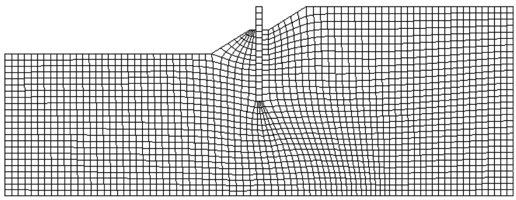
3 NUMERICAL ANALYSIS OF THE SLOPES CONTAINING LOAD-BEARING PILES UNDER COMBINED LOAD

3.1 *Numerical analysis procedure and model parameters*

An example of pile-soil-slope system in an idealized elastic, perfectly plastic soil are investigated using finite element program ABAQUS (Hibbitt, Karlsson & Sorensen, INC. 1978). A single pile is considered in the FEM Model. Materials parameters for finite element analysis are listed in Table 1. Figure 3(a) and (b) show the plan view and FE computational model, respectively. Seen from Figure 3(a), a 15 m high cut slope with an average slope angle of 32° is modeled. The concrete piles are assumed to be 2 m in diameter, 30 m in length, and with 22.5 m penetration. The cut slope is formed by a series of excavation processes



(a) Geometry plan view of slope



(b) FEM model of slope with pile

Figure 3. Slope geometry and FEM computational model.

simulated numerically. Each step excavates 2.5 m of soil and the excavation continues until a slope height of 15 m has been reached. The piles are formed by concrete in the middle of the cut slope. For simplicity, the groundwater table is taken to be far below the pile tip in the analysis (Charles et al., 2001).

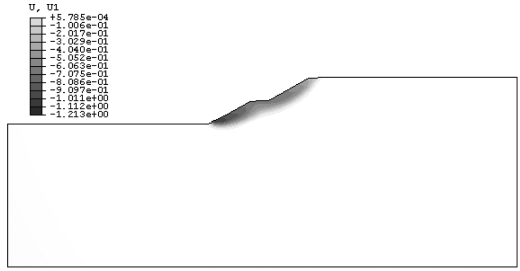
In the numerical analysis, soils adopt idealized ealsto-plastic constitute model based on the Mohr-Coulomb failure criterion utilizing eight-node quadrilateral elements with reduced integration and non-associated flow laws, pile is regarded as elastic body, the interaction between pile and soils abides by the afore-mentioned contact algorithm. The non-convergence option is taken as being a suitable indicator of failure, and the relationships between SRF and the displacements at some characteristic nodes on slope surface are also analyzed to evaluate the global failure of the slope. Slope failure and numerical non-convergence occur simultaneously, and are accompanied by a dramatic increase in the nodal displacements within the mesh.

3.2 *Numerical analysis of slope stability*

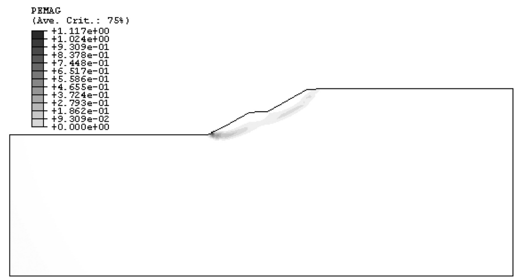
According to the technique of shear strength reduction and the non-convergence criterion of FEA, the distributions on horizontal displacement and equivalent plastic strain representing the global failure of slope are given in Figure 4, the corresponding safety factor of slope is $F_s = 2.13$.

3.3 *Stability of slope with stabilizing piles*

In order to check the effect of reinforcing pile on the stability of slope, a row of stabilizing piles are inserted



(a) Horizontal displacement distribution



(b) Equivalent plastic strain distribution

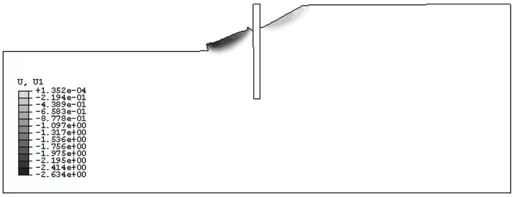
Figure 4. Slope deformation and plastic strain distribution at $F = 2.13$ (global failure).

on the middle platform of multi-stage slope. FEA non-convergence criterion is adopted to evaluate the stability of pile-slope systems, the distribution of horizontal displacement and equivalent plastic strain at the time of non-convergence with $F = 2.20$ are showed in Figure 5. Compared with the figures, the internal displacement in slope remarkably increases at the time of non-convergence than that of before non-convergence.

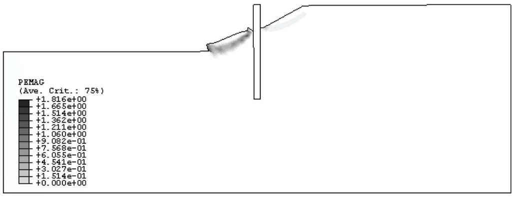
Figure 6 shows the relationships between the dimensionless characteristic nodal displacement on slope surface and strength reduction factor SRF. In the Figure, T_1 indicates adjacent node behind the pile, T_2 indicates adjacent node in front of the pile, B is the node at the toe of the lower slope, M is the node situated on the first-stage slope surface, which displacement is largest. Through analyzing the curves in Figure 6, the four characteristic nodes on the slope surface all show uncontrolled displacement increase before the non-convergence.

3.4 *Stability of slope with load-bearing piles under combined load mode*

In order to investigate the mechanical behavior of load-bearing pile and the stability of pile-slope system, the above-mentioned stabilizing pile is again studied here. A vertical load as $P_v = 1000$ kN, 2000 kN and 4000 kN is respectively applied on the top of the stabilizing pile. The instability criterion of numerical computation



(a) Horizontal displacement distribution



(b) Equivalent plastic strain distribution

Figure 5. Deformation and plastic strain of slope stabilized by piles at $F = 2.20$(at the time of non-convergence).

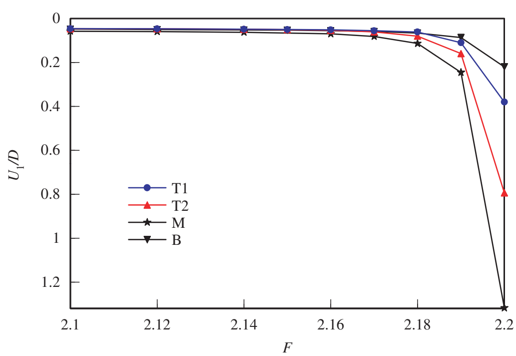


Figure 6. Relationship between SRF and dimensionless nodal displacements.

non-convergence combined with key nodal dramatic displacement on the slope surface is employed to evaluate the global stability. According to the numerical results, the global stability factor is 2.20 as same as that condition of only stabilizing pile. But the maximum horizontal displacement at the characteristic nodes on the slope surface rather increases with increasing vertical load. The above analysis shows that load-bearing pile has no effect on the stability of slope with high safety factor when the vertical load of load-bearing pile is not beyond the admissible value of the standard.

On the other hand, the global stability of pile-slope system is also computed under four different horizontal load mode as $P_h = 500$ kN, 1000 kN, 1500 kN and 2000 kN. According to the numerical results, the corresponding safety factor of pile-slope system is respectively 2.13, 1.65, 1.33 and 1.11 as shown in

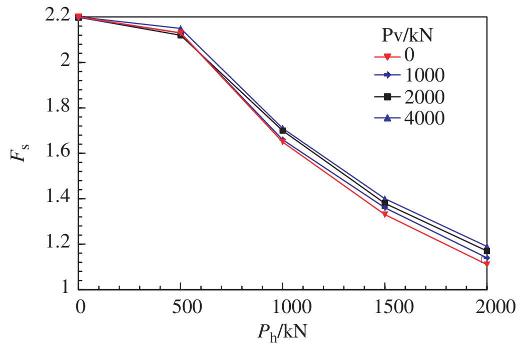


Figure 7. The relationship between safety factor of slope with stabilizing and load-bearing piles and combined loads.

Figure 7, which are far lower than that of the slope only containing stabilizing pile or load-bearing pile, the maximum decreasing degree of the former is more two times than the latter. Thus, the effect of horizontal load on the global stability of pile-slope system can not be ignored.

In addition, the combined load mode including horizontal and vertical load is computed to investigate the global stability of pile-slope system. Under the combined load modes, the horizontal load acting on the top of pile is respectively $P_h = 500$ kN, 1000 kN, 1500 kN and 2000 kN, the vertical load is respectively $P_v = 1000$ kN, 2000 kN and 4000 kN, which are the same as the afore-mentioned. Figure 7 plots the variations of the global safety factor F_s with applied horizontal load P_h on the top of pile under different vertical load P_v. Seen from Figure 7, the global safety factor of pile-slope system obviously decreases with increasing the horizontal load under a given vertical load on the top of pile. A nonlinear relation between the two sides can be drawn by the analysis of curves. Moreover, the global safety factor of pile-slope system will slightly increases with increasing the vertical load under a given horizontal load. In contrast, the key nodal maximum horizontal displacement on the slope surface yet takes on some increase within 10%. It indicates that load-bearing and stabilizing piles cause a vertical load transfer, reducing the horizontal and vertical stresses in the shallow layers of the slope but increasing the stresses in the deeper layers. Due to the reduced stress in the shallow depths in front of pile, the local stability of the shallow layers of the slope will be improved. In addition, due to a very higher global safety factor of the slope without containing stabilizing piles, the impacts of the load-bearing and stabilizing piles on the global stability of the slope are not expected to be significant, but the horizontal loads become a controlled factor on the global stability of slope, and will not be ignored.

4 CONCLUSIONS

(1) By using elasto-plastic finite element method based on shear strength reduction, stability of slope with stabilizing piles and load-bearing piles under combined load are numerically analyzed.
(2) The iteration non-convergence criterion combined with the uncontrolled displacement at a certain characteristic node on the slope surface is reasonable and reliable to evaluate the stability of slope containing piles.
(3) Numerical results show that the impacts of the load-bearing and stabilizing piles on the global stability of the slope are not expected to be significant for a slope with higher safety factor, but the horizontal loads become a controlled factor on the global stability of slope.

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