Memoirs of the Faculty of Engineering, Kyushu University, Vol.75, No.1, July 2015

Numerical Study on Soil Arching Effects of Stabilizing Piles

by

Fusong FAN*, Guangqi CHEN**, Xinli HU*** and Wei WANG†

(Received January 26, 2015)

Abstract

The Soil arching effect, the transfer of soil pressure from the yielding soil to the piles support, is a phenomena commonly encountered in geotechnical engineering for stabilizing landslides. In this paper, the (finite element method) FEM and (discontinuous deformation analysis) DDA were used to study on the soil arching effects of stabilizing piles in landslides. This paper proposes a method for two dimensional numerical simulation to perform three dimensional soil-pile interaction so that the slope angle can be considered even using a two dimensional numerical method. And then, a FEM model is built based on the FEM to investigate the soil arching effect on stress and deformation distribution in detail for different pile intervals and pile width. The results shown that the soil arching effects do exist and the height of soil arching becomes larger when the pile interval is larger; the soil arching height does not change when the pile width increases, while the shape of soil arching changes. Finally, in order to investigate the failure condition of a stabilizing pile enforced slope, DDA is applied. The results comparison between the example of FEM model and DDA model is conducted to verify the DDA application of solving the continuity problem. Then the failure of model is also analyzed by the simulation of DDA. The results show that the DDA has accordant results with FEM for the small deformation problems, and the DDA can be applied to simulate the large deformation and failure problems of soil arching which cannot be done by FEM.

Keywords: Landslide, Soil arching, Stabilizing pile, FEM, DDA

1. Introduction

Soil arching is a phenomenon commonly observed in geotechnical engineering[1]. It can transfer soil pressure from a yielding support to its adjacent non-yielding support. The relative movement in the different part of soil mass generates a shear resistance in the opposite direction of the movement, reducing the stresses on the yielding support and increasing the pressures in the

* Graduate Student, Department of Civil and Structural Engineering
** Professor, Department of Civil and Structural Engineering
*** Professor, Department of China University of Geosciences (Wuhan)
† Graduate Student, Department of Civil and Structural Engineering

stationary region[2]. Since soil arching effects existing in the soil mass[3, 4, 5, 6, 7] were found in a larger number of engineering projects and laboratory experiments, this phenomenon has been widely studied by many researchers with experiments, limit equilibrium analysis and numerical simulation.

In the study with experiments, the pioneer work about soil arching phenomenon was performed by Terzaghi[2]. The arching in sand mass was formed by a trapdoor test, which reproduces the effect by imposing a localized deformation of a horizontal support. The similar trapdoor tests have also been carried out by some other authors with different experimental designs and devices[8, 9, 10]. These studies majorly focused on the following aspects: the shape of an arch, the relation between soil arching and the soil mass failure mechanism, the influence of different confinements and different experimental materials, the bearing capacity of soil arching.

In the study with limit equilibrium analysis methods, Ito et al.[6] developed a soil arching analytical equation to estimate the lateral pressure on stabilizing piles and Matsui[11] presented a series of model tests for various conditions of the piles and soil to verify the analytical equations used in the early stage. The results show that the ultimate lateral pressure can be approximately estimated as larger as 1.6 times the analytical lateral pressure. Low[12] proposed the equilibrium of semicylindrical sand arches model in the embankment, which was modified and used in the engineering by Yang[13]. Li[14] has built the control equation of maximum pile spacing in view of the stress condition of limiting equilibrium of soil at the arching crown based on the Mohr-Coulomb failure criterion of shearing strength.

In the study with numerical simulation, two types of numerical methods are available. One is for continuous media with small deformation. The widely used methods are finite element method (FEM)[15, 16, 17, 18] and finite difference method (FDM)[19, 20]. They have been applied to analysis of the soil arching effect [21, 19, 20, 22] in order to explain the generation mechanism of soil arching effect as well as to explain the relationship between the soil arching effect and the piles failure types, soil property, piles length. The other is for discontinuous media with large deformation, the so-called discrete element methods. For example, Smoothed particle hydrodynamics (SPH) method was used to simulate the frictional contact between soils and rigid structure with two algorithms for contact behavior in the soil arching by Bui[12]. Yeung[24] used the Discontinuous Deformation Analysis (DDA) to analyze the failure of soil arching.

The soil arching effect is attracting researchers' attention more and more in disaster prevention. Stabilizing piles are widely used for preventing landslide. A soil arching can be formed between two piles and it could make the deformation and stress in the soil mass inhomogeneous. The arching can also enforce a slope. Thus, it is important and necessary to clarify the soil arching formation conditions including fixed arch foot (stabilizing piles) which bear the pressure, arch ring (soil mass) which has strength and the pressure distribution (landslide thrust)[1] so that a optional design plan of stabilizing piles can be made.

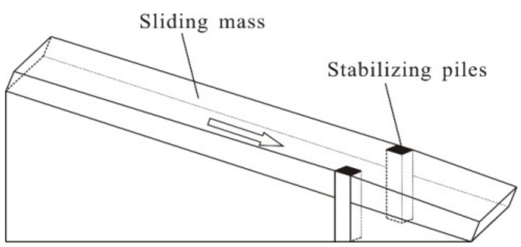
The soil arching effect on the anti-sliding effect was reported in many engineering practices [5, 20, 26]. In the stabilizing pile structure, the driving force on the soil mass between the piles is transmitted to piles by the soil arching[26]. Kahyaoglu[21] conducted an experiment for the investigation of the effects of pile spacing and pile head fixity on the lateral soil pressure. Bosscher and Gray[5] carried out an experiment composed of gates and load-deformation measuring system in a sloping sand bed. The results show that the discrete piles embedded into a firm, non-yielding base in a slope can provide significant additional stability to a slope if conditions for soil arching are met. Yang and Yao[27] studied the phenomenon of soil arching effect when stabilizing piles are used to reinforce the landslide using the centrifuge model tests and reproduced the soil arching in space of piles and its failure mode. They proved that the load of soil arching changes with the increasing of pile space nonlinearly. Besides, when pile space increases to a certain extent, the load of soil arching will decrease sharply.

Although sustained efforts have been made and great progress has been achieved in the study on the arching effect of a stabilizing pile system, it is still far from practical requirements of optional design since many assumptions are needed for slope model, loading and boundary conditions in experimental and analytical methods. Especially, how to consider pile-soil interaction in a three dimensional a complicated anti-sliding system with stabilizing piles is one of the most difficult problems.

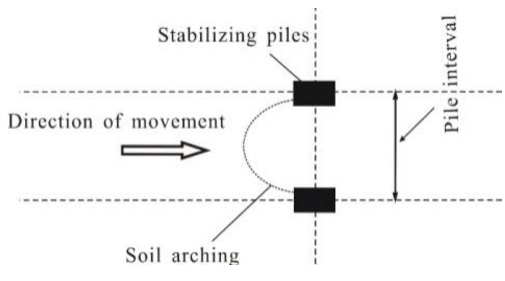
In this paper, we use numerical simulation methods to analyze the mechanism of pile-soil interaction and soil arching effects. Firstly, a two dimensional model is proposed to simulate a three dimensional stabilizing pile enforced slope so that the slope angle can be considered even using a 2D numerical method. And then, a FEM model is built based on the FEM to investigate the soil arching effect on stress and deformation distribution in detail for different pile intervals and pile width. Finally, in order to investigate the failure condition of a stabilizing pile enforced slope, DDA (Discontinuous deformation analysis) is applied. The results comparison between the example of FEM model and DDA model is conducted to verify the DDA application of solving the continuity problem. Then the failure of model is also analyzed by the simulation of DDA.

2. A simplified 2D numerical model for a 3D slope with stabilizing piles

A slope model with stabilizing piles is shown in Fig. 1(a). A 3D numerical simulation is necessary for this problem. However, it is difficult for many engineers to perform a 3D numerical simulation under considering soil-pile interaction using FEM and DDA. For this reason, a 2D model is proposed in this paper. The driving force from gravity is projected to the normal and tangent directions of the slope surface. The 2D model is shown in Fig. 1(b). The driving force is the tangential component subtracted by the friction assistance calculated from the normal component and internal friction angle of the soil. It is assumed here that soil movement will keep in a plane movement and the stabilizing piles are fixed in the horizontal direction[28)].



(a)



(b)

Fig.1 (a) The 3D slope with stabilizing piles and (b) the simplified 2D numerical model.

3. Numerical Simulation of Soil Arching Effect using FEM

3.1 FEM Model

In order to clarify the relationship between stabilizing piles and soil arching, a FEM numerical simulation model was built. The triangle meshes are used in the FEM model. The model with boundary conditions is shown in **Fig.2**. In this model, the pile section size was 2 m × 3 m, the length of model was 43 m. According to computational method of simplification model, the soil mass of unit thickness is assumed for analyzing this model and the driving force from gravity is projected to the normal and tangent directions of the slope surface. The force of tangent directions are $F`=mg\sin\theta$ and the normal directions are $F_N=mg\cos\theta$. The friction assistance calculated from the normal component and internal friction angle $\varphi$ of the soil. So the driving force $F=F`-F_N\tan\varphi$. In this model, the slope inclined angle is 37° and the simulated slope length is 75m. So the applied uniform load which point to y-axis reverse direction was 50 kN/m^2.

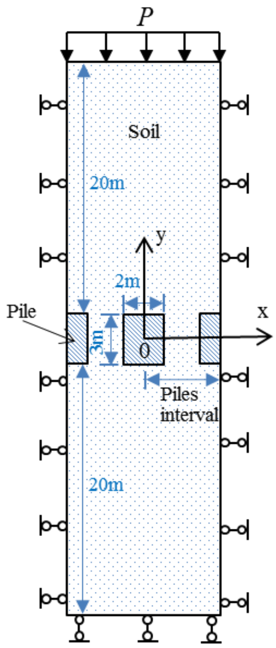


Fig.2 The model for numerical simulation.

The width of basic model was twice the pile interval for avoiding the influence of left and right boundary conditions. The left and right boundaries of model were fixed in the x-direction and the bottom boundary was fixed in the y-direction. The bottom of piles was fixed in x-, y- and z-direction.

The soil behavior is assumed to be the material of elastic-plastic using Mohr-Coulomb failure criterion. Besides, the coordinates are updated in each step in the numerical simulation process. An isotropic elastic model was used for the stabilizing pile, and elastic-plastic model was applied to the surrounding soil. In addition, the interface element was used to simulate the friction between the soil mass and the piles. The interface element has two contact types in the normal and tangent directions. The friction contact is used in the tangent direction by the friction coefficient 0.5 and the hard contact is used in the normal direction.

The soil with an elastic modulus 1000 kPa, a unit weight 20 kN/m^3, a Poisson ratio 0.35, a cohesion 30kPa, and an internal friction angle 32°. The elastic pile with an elastic modulus 28 GPa, a poisson ratio 0.2, and a unit weight 23 kN/m^3.

3.2 Mechanism Analysis of Soil Arching Effect

The model of pile interval 12 m was taken as the example to clarify soil effects. Then, according the numerical simulation, the soil strain of y-direction ε_y at the center of two adjacent piles is shown in **Fig.3**. The changes of soil arching effect can be divided into five parts from the front of the piles to the back according the ε_y at the center of two adjacent piles. 1. A-B: The ε_y near driving force is very large because of the driving force action in y-direction. 2. B-C: The gradually decreases because the piles begin to exert anti-slide effect. The soil arching effect is obvious when ε_y is minimum. 3. C-D: As the effect of soil arching cannot work on this part, ε_y increases slightly. 4. D-E: The effect of soil arching disappears on this part, but the ε_y decreases because of the action of friction between piles and soil. 5. E-F: The ε_y is uniformitarian in this part because the soil movement was stopped by the resistance in the front of landslide.

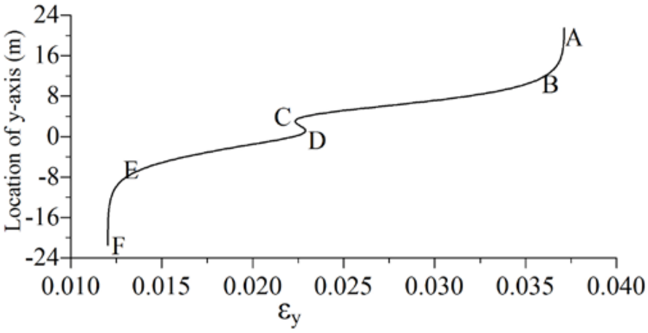


Fig.3 ε_y of soil at the center of two adjacent piles.

The contour of maximum principal stress of the model is shown in **Fig.4**. It reveals that the rotation of the principal stress directions. As shown in the **Fig.4**, the directions of the principal stresses change in the two principal directions because of the constraint of piles, and the contour of maximum principal stress like an arch. A significant stress arching was formed in the soil. And a small reverse stress arching was also formed at the center of two adjacent piles when the soil deformation space decreased in the process of soil deformation because of the action of friction between piles and soil.

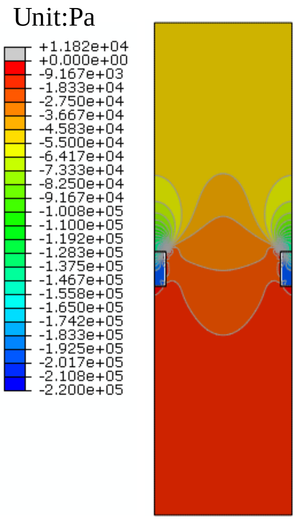


Fig.4 Contour of maximum principal stress.

The stress of y-direction σ_y of different planes horizontal to the x-axis is shown in **Fig.5**. The distribution of σ_y was uniform when the plane was far from the piles and looked like an arch when near the piles. It can be obtained the value of load in the front of the piles from the curves of the σ_y which parallel to the y-axis. The load sharing ratio of soil and piles can be got from the area which surrounded by the stress curves in y-direction and horizontal axis.

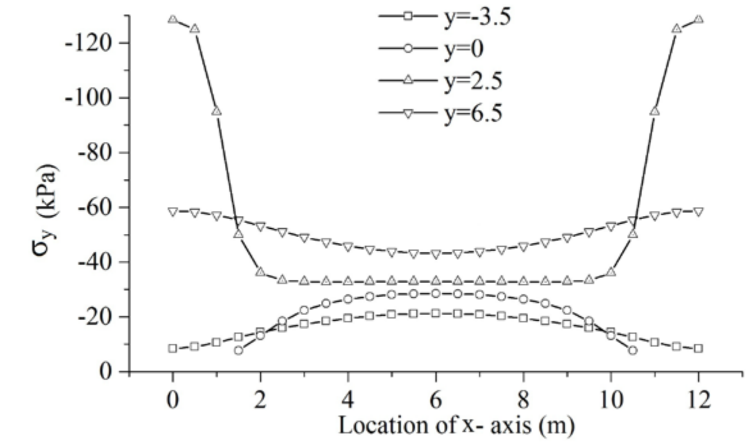


Fig.5 σ_y of soil in different planes horizontal to x-axis.

3.3 Soil Arching Effect of Different Pile Intervals

For the purpose of comparison, different numerical simulation models of the pile intervals 4 m, 6 m, 8 m, 10 m and 12 m were designed. According to the numerical simulation of different pile intervals, the stress of x-direction σ_x at the center of two adjacent piles is shown in **Fig.6**.

As the **Fig.6** shows that σ_x increased firstly, and decreases afterwards from the back of piles to the piles. When the pile intervals were 4 m, 6 m, 8 m, 10 m and 12 m, the coordinate position that soil σ_x reaches the maximum were x = 2.5 m, 3.5 m, 4 m, 4.5 m and 4.6 m, respectively. The soil arching height was the coordinate position which the σ_x reaches the maximum according to the theory about the rotation of principal stress directions. Besides, the soil arching height stopped increasing when the pile interval reaches certain value.

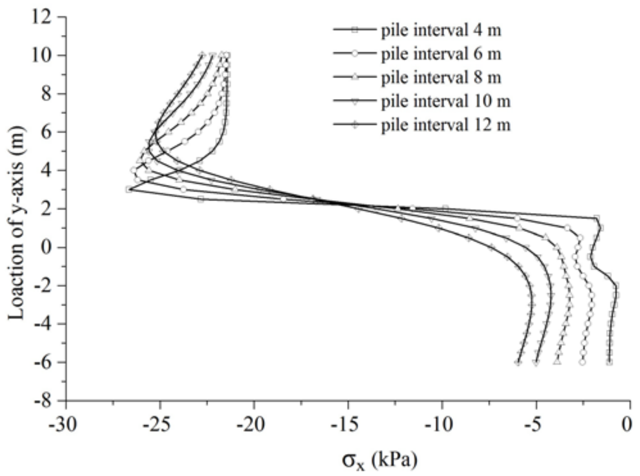


Fig.6 σ_x at the center of two adjacent piles.

The load sharing ratio of soil or pile is the proportion of soil or pile load to the total load. It is an important study object as the main standard of the anti-slide effect. So a plane was chosen for which parallels to the y-axis and in the front of piles 0.5m. Then the value of load in the front of the piles could be obtained. For explaining this computational method, the model of **Fig.2** and the σ_y of different planes of **Fig.5** were used as the analysis example. Seven representative profiles are chosen to show the stress distribution (see **Fig.5**). A lot of quantitative data can be obtained from this figure, whose horizontal ordinate is the x-direction horizontal distance, and the vertical ordinate is the normal stress. Therefore, the closed area between the stress curve (kPa/m) and the x-axis (m) is the total stress (kPa), i.e., the integral of the element stress multiplied by the width of the element. For example, the closed area of the normal stress curve in the y-direction profile is the load applied to the profile. The total load at the upper boundary is the normal stress. According to this method, the load sharing ratio of soil was the ratio of the value of soil load to the total. The soil load sharing ratio in the front of piles were 5.2%, 12.3%, 19.6%, 26.4% and 32% when the pile interval 4 m, 6 m, 8 m, 10 m and 12 m. When the pile interval becomes larger, the load sharing ratio of soil became larger and the load sharing ratio of piles becomes smaller.

3.4 Soil Arching Effect of Different Pile Width

The numerical simulation basic model was adopted and the pile interval was 6 m. Different numerical simulation models of the pile width 0.5 m, 1 m, 2 m and 3 m were designed and the contour of maximum principal stress these models are shown in **Fig.7**.

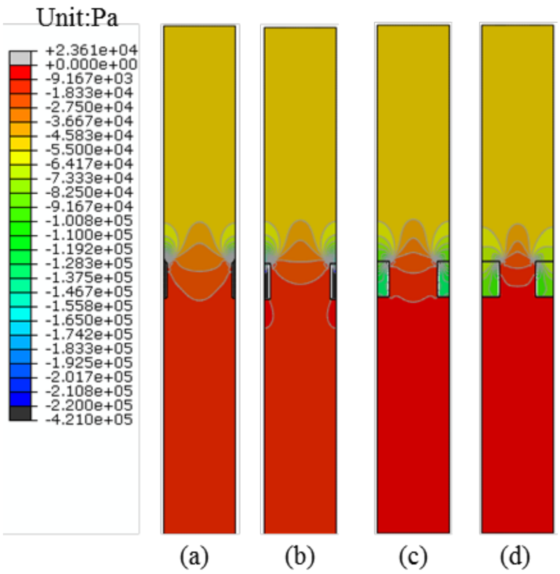


Fig.7 Contour of maximum principal stress of different pile width (a) pile width= 0.5 m; (b) pile width= 1 m; (c) pile width= 2 m; (d) pile width= 3 m.

The soil arching height did not change as pile width increased, but the shape of soil arching changed with the increase of pile width. The soil arching height is only related to the supported parts (fixed arch foot)[1)] and the soil arching height is confirmed by the distance between two fixed arch foots. So the soil arching height did not change as pile width increased. The shapes of soil arching were parabolic with pile width 2m and 3m and triangle with pile width 1 m and 0.5 m. Besides, the influence area of soil arching increased when the pile width decreased.

The same computational method of the load sharing ratio was used. The soil load sharing ratio in the front of piles were 30%, 21%, 12% and 7.5% when the pile width 0.5 m, 1 m, 2 m and 3 m. It increased as the pile width increased, but the change of the soil load sharing ratio was very small when pile width was larger than 2 m.

4. Numerical Simulation of Soil Arching Effect using DDA

Discontinues Deformation Analysis (DDA)[29] is one of the discontinuous based numerical models, which is formularized in the same way as FEM. DDA generally uses isolated blocks generated from discontinuities[30] such as faults, joints and cracks instead of the elements in FEM. One of the major advantages is that it can be applied to simulation of large deformation and failure problems which cannot be done by FEM. The DDA used a penalty method in which the contact is assumed to be rigid. No overlapping or interpenetration of the blocks is allowed as the same as real physical cases. In this study, we firstly use artificial mesh to forming DDA block like FEM elements so as to verify the possibility of applying DDA to investigate soil arching effects. And then, large deformation and failure behavior problems are simulated to clarify the function of stabilizing piles in preventing landslides.

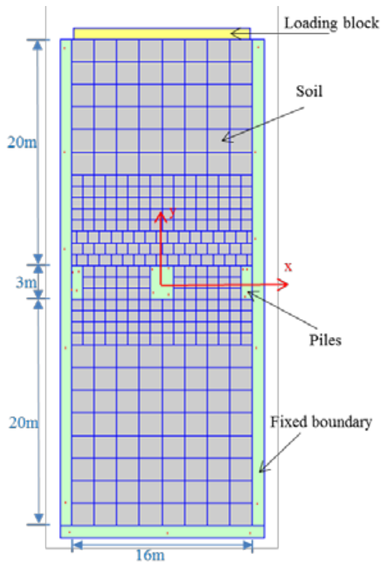


Fig.8 The numerical simulation model of DDA.

The DDA model of pile interval 8 m was taken as the example to clarify soil arching effects (**Fig.8**). In this model, the pile section size was 2 m × 3 m, the length of the model was 43 m, the loading block thickness was 1m. The green parts of the model were the fixed block as the boundaries. The yellow loading block was used to simulate the driving force. The boundary conditions and the size of DDA are same to the FEM model which is shown in the **Fig. 2**. The soil with an elastic modulus 1000 kPa, a unit weight 20 kN/m^3, a Poisson ratio 0.35, a cohesion 30kPa, and an internal friction angle 32°. The elastic pile with an elastic modulus 28 GPa, a poisson ratio 0.2, and a unit weight 23 kN/m^3. The parameter of DDA model is also same to the FEM model. The calculation results of DDA and FEM which have same model size and boundary are contrasted in the **Fig.9**. The calculation result shows that the error is small and DDA and FEM are all suitable for solving the soil arching problem. DDA uses isolated blocks generated from discontinuities such as faults, joints and cracks instead of the elements in FEM. This method offers an effective approach for solving the continuity problem.

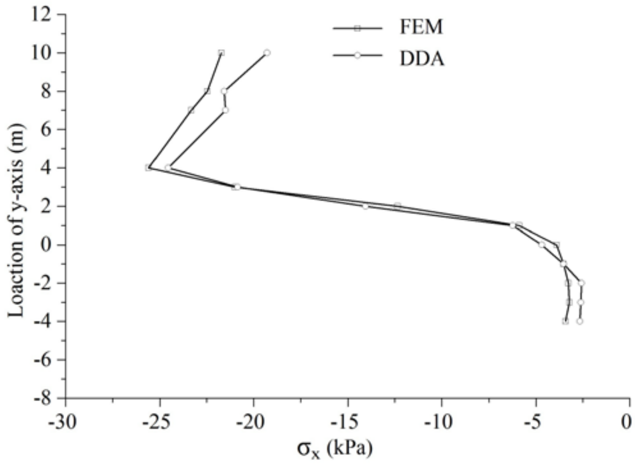


Fig.9 The calculation results of DDA and FEM.

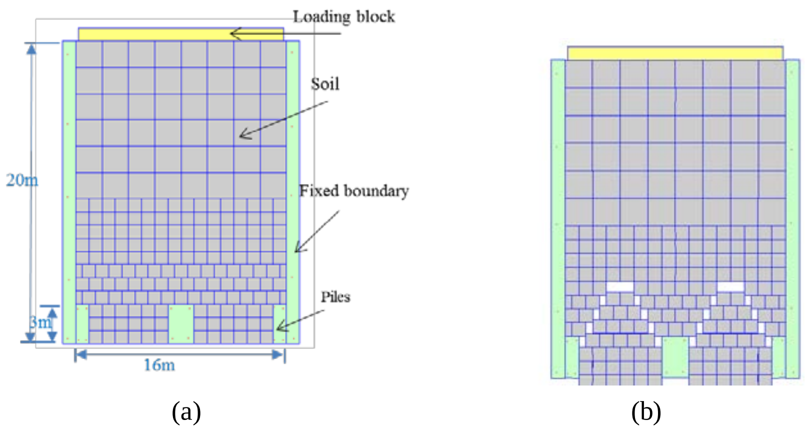


Fig.10 (a) DDA model of free bounary and (b) soil arching in faiure soil mass.

Although the FEM and DDA could solve the continuity problem, the failure of soil mass in the landslide is common when the front of landslide has no enough frictional resistance. So the DDA is used to simulate the failure problem of soil arching. If the frictional resistance is small and it cannot support the stability of the landslide, the bottom boundary of the model is needed to modify. So the bottom fixed boundary should be withdrawn. Then a DDA model which has no fixed boundary on the bottom of model is built which is shown in the **Fig.10**(a). The simulate results is shown in the **Fig.10**(b). It is obvious that the soil has destroyed and the soil arching is clear. The soil arching effect when the soil mass is failure could be simulated well.

5. Conclusion

This study uses numerical simulation methods to analyze the mechanism of pile-soil interaction and soil arching effects. The two dimensional model is proposed to simulate a three dimensional stabilizing pile enforced slope so that the slope angle can be considered even using a 2D numerical method. This method of simulating offers an effective approach for solving the three dimension problem. A FEM model is built based on the FEM to investigate the soil arching effect on stress and deformation distribution in detail for different pile intervals and pile width. The results shown that the soil arching effects do exist and the height of soil arching becomes larger when the pile interval is larger; the soil arching height does not change when the pile width increases, while the shape of soil arching changes. Finally, DDA is applied for investigating the failure condition of a stabilizing pile enforced landslide. The results comparison between the example of FEM model and DDA model is conducted to verify the DDA application of solving the continuity problem. Then the failure of model is also analyzed by the simulation of DDA. The results show that the DDA has accordant results with FEM for the small deformation problems, and the DDA can be applied to simulate the large deformation and failure problems of soil arching which cannot be done by FEM.

Acknowledgements

This study have received financial support from Grant-in-Aid for challenging Exploratory Research, 15K12483, G. Chen) from Japan Society for the Promotion of Science. Also, this work was supported by Kyushu University Interdisciplinary Programs in Education and Projects in Research Development. The financial support is gratefully acknowledged.

References

1) F. Fan, G. Chen, L. Zheng, Y. Zhang, and Y. Li, Study on soil arching effects of stabilizing piles using numerical methods, Frontiers of Discontinuous Numerical Methods and Practical Simulations in Engineering and Disaster Prevention, pp. 295-302(2013).
2) K. Terzaghi, C. Engineer, A. Czechoslowakia, I. Civil, A. Tchécoslovaquie, and E. Unis, Theoretical soil mechanics: Wiley New York, pp. 45-53(1943).
3) K. Terzaghi, The shearing resistance of saturated soils and the angle between the planes of shear. Proceedings of the 1st international conference on soil mechanics and foundation engineering, Vol. 1, pp. 54-56 (1936).
4) W. L. Wang, and B. C. Yen, Soil arching in slopes, Journal of Geotechnical Engineering, Vol. 100, No. 1(1974).
5) P. J. Bosscher, and D. H. Gray, Soil arching in sandy slopes, Journal of Geotechnical Engineering, Vol. 112, No. 6, pp. 626-645(1986).
6) T. Ito, and T. Matsui, Methods to estimate lateral force acting on stabilizing piles, Soil and Foundations, Vol. 15, No. 4, pp. 43-59(1975).
7) S. Van Eekelen, A. Bezuijen, and A. Van Tol, An analytical model for arching in piled embankments, Geotextiles and Geomembranes, Vol. 39, pp. 78-102(2013).
8) T. Adachi, M. Kimura, T. Nishimura, N. Koya, and K. Kosaka, Trap door experiment under centrifugal conditions, Deformation and Progressive Failure in Geomechanics, Vol. 21, No. 11, pp. 725-730(1997).
9) B. Chevalier, G. Combe, and P. Villard, Experimental and discrete element modeling studies of the trapdoor problem: influence of the macro-mechanical frictional parameters, Acta Geotechnica, Vol. 7, No. 1, pp. 15-39(2012).
10) G. R. Iglesia, H. H. Einstein, and R. V. Whitman, Investigation of soil arching with centrifuge tests, Journal of Geotechnical and Geoenvironmental engineering, Vol. 140, No. 2(2013).
11) T. Ito, T. Matsui, and W. Hong, Extended design method for multi-row stabilizing piles against landslide, Soil and Foundations, Vol. 22, No. 1, pp. 1-13(1982).
12) B. Low, S. Tang, and V. Choa, Arching in piled embankments, Journal of Geotechnical Engineering, Vol. 120, No. 11, pp. 1917-1938(1994).
13) S. Yang, X. Ren, and J. Zhang, Study on embedded length of piles for slope reinforced with one row of piles, J Rock Mech Geotech Eng, Vol. 3, No. 2, pp. 167-178(2011).

14) S.J. Li, J. Chen, and C. Lian, Mechanical model of soil arch for interaction of piles and slope and problem of pile spacing (J), Rock and Soil Mechanics, Vol. 5, pp. 004(2010).
15) R. Kourkoulis, F. Gelagoti, I. Anastasopoulos, and G. Gazetas, Hybrid method for analysis and design of slope stabilizing piles, Journal of Geotechnical and Geoenvironmental Engineering, Vol. 138, No. 1, pp. 1-14(2011).
16) M. R. Kahyaoglu, G. Imancli, A. U. Ozturk, and A. S. Kayalar, Computational 3D finite element analyses of model passive piles, Computational Materials Science, Vol. 46, No. 1, pp. 193-202(2009).
17) J. Won, K. You, S. Jeong, and S. Kim, Coupled effects in stability analysis of pile–slope systems, Computers and Geotechnics, Vol. 32, No. 4, pp. 304-315(2005).
18) J. Pan, A. Goh, K. Wong, and A. Selby, Three ‐ dimensional analysis of single pile response to lateral soil movements, International Journal for Numerical and Analytical Methods in Geomechanics, Vol. 26, No. 8, pp. 747-758(2002).
19) G. Martin, and C.Y. Chen, Response of piles due to lateral slope movement, Computers & structures, Vol. 83, No. 8, pp. 588-598(2005).
20) C. Li, H. Tang, X. Hu, and L. Wang, Numerical modelling study of the load sharing law of anti-sliding piles based on the soil arching effect for Erliban landslide, China, KSCE Journal of Civil Engineering, Vol. 17, No. 6, pp. 1251-1262(2013).
21) M. R. Kahyaoğlu, O. Onal, G. Imançlı, G. Ozden, and A. Ş. Kayalar, Soil arching and load transfer mechanism for slope stabilized with piles, Journal of Civil Engineering and Management, Vol. 18, No. 5, pp. 701-708(2012).
22) L. Robert, and Z. Sanping, Numerical study of soil arching mechanism in drilled shafts for slope stabilization, Soil and Foundations, Vol. 42, No. 2, pp. 83-92(2002).
23) S.J. LI, J. CHEN, and C. LIAN, Mechanical model of soil arch for interaction of piles and slope and problem of pile spacing (J), Rock and Soil Mechanics, Vol. 5, pp. 004(2010).
24) M. Yeung, "Analysis of a mine roof using the DDA method." pp. 1411-1417(1993).
25) L. Xiong, and T. Li, Application of soil arching effect on the anti-sliding pile engineering, Journal of Disaster Prevention and Mitigation Engineering, Vol. 25, No. 3, pp. 275-277(2005).
26) S. Lirer, Landslide stabilizing piles: Experimental evidences and numerical interpretation, Engineering Geology, Vol. 149, pp. 70-77(2012).
28) J. Zhang, X. Qiang, and Z. Zhang, Arching effect of anti-slide pile structure and its numerical simulation, Chinese Journal of Rock Mechanics and Engineering, Vol. 23, No. 4, pp. 699-703(2004).
29) G. Shi, Discontinuous deformation analysis, a new numerical model for the statics and dynamics of block system. PhD thesis, Univ. of California, Berkeley, America (1988).
30) W. Wang, DDA method and its application in engineering. PhD thesis, Univ. of Nan Jing, Hohai, China (2001).