CHEMICAL ENGINEERING TRANSACTIONS
VOL. 46, 2015

A publication of AIDIC
The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Peiyu Ren, Yancang Li, Huiping Song

**ISBN** 978-88-95608-37-2; **ISSN** 2283-9216

DOI: 10.3303/CET1546131

# Study on the Failure Surface of Heterogeneous Soil at the Passive State

Fei Song*[a], Rui-Zhi Cheng[a], Li-Qiu Ma[b], Xi-Bin Tang[c], Wen-Zhong Yuan[b]

[a]Institute of Geotechnical Engineering, School of Highway Engineering, Chang'An University, Xi'an, 710064, P.R. China
[b]Guizhou Electricity Engineering Construction Supervise Company, Guiyang, 550005, P.R. China
[c]Guizhou Electric Power Design Institute and Research Institute, Guiyang, 550002, P.R. China
songf1980@163.com

Earth pressure problem is one of the key research subjects in soil mechanics and geotechnical engineering. Heterogeneous soil is always encountered in engineering practices. However, the classical Rankine and Coulomb's earth pressure theories don't take into account of the effect of heterogeneity on the failure surface and the earth pressure. In this paper, the failure surface of heterogeneous soil at the passive state is investigated using the geotechnical FEM software Plaxis. The study results indicate that the failure surface at the passive state is strongly influenced by the strengths of the foundation and the lower layer soil for the backfill consisting of two-layered soils. The failure surface of the two-layered soils approaches the one of the homogeneous soil with the strength of the foundation and lower layer soil.

## 1. Introduction

Earth retaining structures are widely used in engineering practices for the protection of embankments. Evaluation of earth pressures is of practical significance for the design of retaining structures such as retaining walls, sheet pile bulkheads, bridge abutments, and basement walls of buildings. It is one of the key research subjects in soil mechanics and geotechnical engineering. Since Coulomb and Rankine proposed their famous earth pressure theories, a lot of researches have been done in the field of earth pressures. Some researchers modified and improved the classical earth pressure theories. Terzaghi (1943), Morrison and Ebeling (1995), Kumar (2001), Subba and Choudhury (2005) computed the passive earth pressure employing the curved sliding surface and the composite surface as a combination of a logarithmic spiral and a straight line based on the limit equilibrium theory of the soil wedge. The calculation results are more appropriate than the ones got by Coulomb's theory and Mononobe-Okabe method for the big wall friction angle. Sokolovski (1965), Graham (1971), Lee and Herington (1972) computed the earth pressure coefficients using the method of characteristics. Method of slices in slope analysis were employed in solving earth pressure problems by Janbu(1957), Shields and Tolunay (1973), Rahardjo and Frelund (1983), Kumar and Subba (1997), Chen and Li (1998), Zakerzadeh et al. (1999), Zhu and Qian (2000). Chen and Liu (1975 and 1990), Soubra and Kastner (1991), Kumar (2001), Soubra (2000 and 2002) used the technique of limit analysis in solving earth pressure problems. Prakash et al. (1966), Das et al. (1977) considered the effect of cohesion of backfill, cohesion between the backfill and the wall, and the vertical component of inertial force on the earth pressure and modified Mononobe-Okabe's equation. Karh (1960), Wang (2000) took out a horizontal soil slice element from the sliding wedge and set up a differential equation about the earth pressure distribution based on the static equilibrium of the horizontal-soil-stratum. By solving the equation they got the non-linear distribution of earth pressure along the wall. Terzaghi (1934), Ishii et al. (1960), Matsuo et al. (1978), Matsuzawa and Matsumura (1981), Ichihara et al. (1973), Sherif and Fang (1984), Fang et al. (1986, 1994 and 2002), Ishibashi and Fang (1987) conducted experiments and studied the effect of the mode and amount of wall displacement on the earth pressure. However, the above researches don't take into the effect of heterogeneity of the backfill on the failure surface and the earth pressure.

Please cite this article as: Song F., Cheng R.Z., Ma L.Q., Tang X.B., Yuan W.Z., 2015, Study on the failure surface of heterogeneous soil at the passive state, Chemical Engineering Transactions, 46, 781-786 DOI:10.3303/CET1546131

In this paper, the failure process of the two-layered backfill at the passive state is simulated using the geotechnical FEM software Plaxis. Furthermore, the effect of heterogeneity on the failure surface is investigated based on the analysis of the simulation results. The study results can provide theoretical references for the design of the retaining structures such as anchor blocks, laterally loaded pile caps, bride abutments and so on, which depend on the passive resistances for stability.

## 2. Model and parameters of calculation

The model on the computation consists of the rigid retaining wall and the backfill. The heterogeneous backfill consists of two backfill layers with equal thickness. The size of the calculation model is shown in Fig.1. The 15-node triangular element is employed in this analysis to model soil. In the computation, an elastic-plastic stress-strain relationship with Mohr-Coulomb yield criterion is adopted for the backfill.

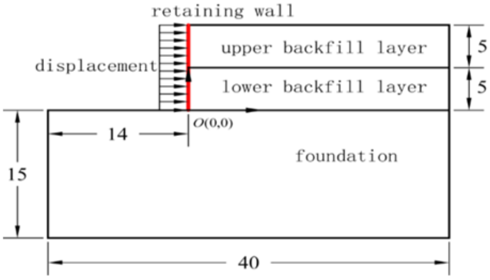

*Fig. (1). Sketch of the calculation model under T mode(Unit: m)*

With references to calculation parameters adopted by Chen et al. (2004), the calculation parameters of the homogeneous soil in this study are selected and listed in table 1. In the following computation and analysis, the physical properties of the foundation are assumed to be the same with those of the lower layer soil.

*Table 1. Calculation Parameters of Soil*

| $\gamma$/(kN/m$^3$) | $c$/kPa | $\varphi$/(°) | $E$/MPa | $v$ | $R_{inter}$ |
|---|---|---|---|---|---|
| 15.6 | 0.1 | 50 | 18 | 0.3 | 0.67 |

Plates in Plaxis are employed to simulate the behavior of the rigid retaining wall and the constitutive law is assumed to be elastic. The most important parameters of the wall are the flexural rigidity (bending stiffness) $EI$ and the axial stiffness $EA$, illustrated in table 2, from which it can be observed that the values of these two parameters are relatively large, ensuring the rigidity of the wall. In addition, the interface element is set between the wall back and backfill to model the interaction between the structure and the soil. The details of constitutive model of the materials and the interface element in Plaxis can be referred to Brinkgreve and Broere (2000), Song et al. (2013). Partitioning of FEM mesh of the model is shown in Fig. 2.

*Table 2. Calculation Parameters of the Wall*

| $EA$/(kN/m) | $EI$/(kN·m$^2$/m) | $w$/(kN/m/m) | $v$ |
|---|---|---|---|
| $2.5\times10^7$ | $2.5\times10^6$ | 10 | 0.15 |

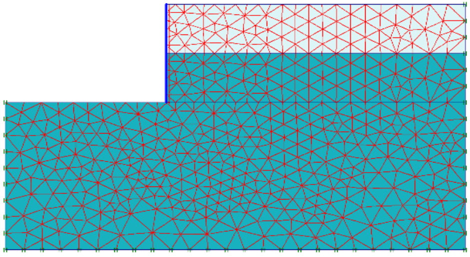

*Fig. (2). Partitioning of FEM mesh of the model*

According to the experimental studies of Fang et al. (1994&2002), the magnitude of wall displacement for loose sand to reach passive state is about 0.17$H$ and that for dense sand is about 0.015$H$. In the calculation, the rigid retaining wall is built in the first step and then the uniform displacements of 0.1m, 0.5m, 1.0m, 1.2m, 1.5m, 1.7m, 2.0m toward the backfill are prescribed on the rigid retaining wall from in the following seven steps in order to simulate the passive failure process. The failure surface of the backfill with the parameters in table 1 is shown in Fig. 3.

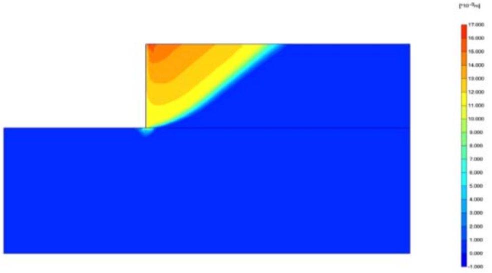

*Fig. (3). Failure surface of the homogeneous backfill*

As is known to all, the strength parameters such as *c* and *φ* have an important effect on the failure surface of the wall. In this study, in order to make it clear that whether the deformation parameters *E* and *v* have influences on the failure surface, the failure surface of the backfill with *E* =50MPa and *v*=0.1 is calculated and compared with the one of the backfill with the *E* =18MPa and *v*=0.3. In the calculation, other parameters are maintained the same as those in table 1. The comparison of the two cases is shown in Fig. 4, from which it can be observed that the sliding surfaces are almost the same, indicating that the influences of the deformation parameters *E* and *v* on the failure mode are very little. Therefore, in the following calculation and analysis, only the strength parameters *c* and *φ* are varied to study their effects on the failure surfaces.

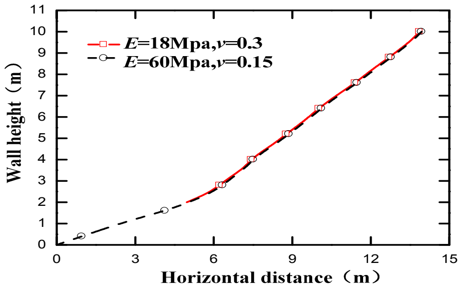

*Fig. (4). Effect of E and v on the failure surface*

## 3. Effect of the internal friction angle

In order to study the effect of the internal friction angle on the heterogeneous soil, the following four cases are calculated and analyzed. Case 1 is the homogeneous soil with *φ*=50°. Case 2 is the homogeneous soil with *φ*=15°. Case 3 is the heterogeneous soil consisting of the upper layer with *φ*=50° and the lower layer with *φ*=15°. Case 4 is also the heterogeneous soil consisting of the upper layer with *φ*=15° and the lower layer with *φ*=50°. The other parameters are the same with those in table 1. The size of the soil layers of both case 3 and 4 are shown in Fig. 1. The sliding surfaces for the four cases at the passive state are illustrated in Fig. 5.

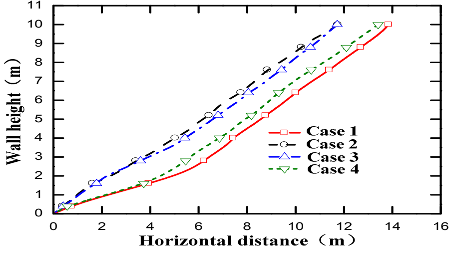

*Fig. (5). Failure surfaces of backfill with different φ values*

It can be observed from Fig. 5 that the size of the sliding wedge of the homogeneous soil with *φ*=50° is obviously larger than that of the homogeneous soil with *φ*=15°. The failure surfaces of the heterogeneous soil consisting of two soil layers lie between those of case 1 and 2. The failure surface of case 3 locates near that of case 2 and the failure surface of case 4 approaches that of case 1, indicating that the internal friction angle of the foundation and the lower soil layer has more important influence on the failure surface than that of the upper soil layer. It can be concluded that the internal friction angle of the foundation and the lower soil layer determines the failure surface of the heterogeneous soil more significantly.

## 4. Effect of cohesion

The following four cases are calculated and analyzed to study the effect of the internal friction angle on the heterogeneous soil. In order to be distinguished with the above previous cases, the numbers of the four cases are 5, 6, 7 and 8 respectively. Case 5 is the homogeneous soil with $c$=70kPa. Case 6 is the homogeneous soil with $c$=23kPa. Case 7 is the heterogeneous soil consisting of the upper layer with $c$=70kPa and the lower layer with $c$=23kPa. Case 8 is also the heterogeneous soil consisting of the upper layer with $c$=23kPa and the lower layer with $c$=70kPa. The internal frictional angle $\varphi$ of these four cases is 0.1° and the other parameters are the same with those in table 1. The size of the soil layers of both case 7 and 8 are also illustrated in Fig. 2.
The sliding surfaces for the four cases at the passive state are illustrated in Fig. 6, from which it can be observed that the effect of the cohesion of the foundation and the two layers on the failure surface of the heterogeneous soil is almost the same with that of the internal friction angle. The size of the sliding wedge of case 8 is much larger than that of case 7, indicating that the effect of cohesion of the foundation and the lower backfill layer affects the failure surface more significantly than that of the upper backfill layer. However, the failure surface of case 8 doesn’t approach that of case 5 so closer in comparison with the case of internal friction angle, showing that the effect of cohesion is not so large than that of internal friction angle.

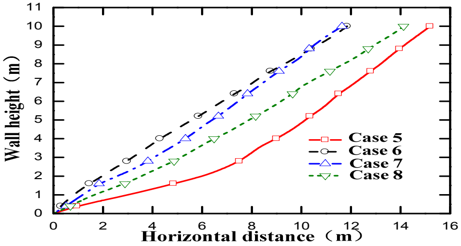

*Fig. (6). Failure surfaces of backfill with different c values*

## 5. Analysis of the effect of strength under rt mode

In the previous analysis, the movement mode of the wall is assumed to be translation, which is denoted as T mode. In order to study the effects of strength parameters of the heterogeneous soil on the failure surface with other wall movement modes, the different cases 9～16 of the wall with the mode of rotation about top, which is known as the RT mode, are calculated and analyzed.
As is illustrated in Fig.7, the maximum displacements of 0.1m, 0.5m, 1.0m, 1.2m, 1.5m, 1.7m, 2.0m toward the backfill are prescribed on the bottom of the wall in order to simulate the passive failure process under RT mode. The strength parameters of backfill of cases 9～16 are the same with those of cases 1～8 in turn respectively. Cases 9～12 are aimed at the study of the effect of internal friction angle and cases 13～16 are aimed at the study on the effect of cohesion. The comparison of the calculation results are shown in Fig. 8, from which it can be observed that the effect of strength parameters on the failure surfaces under RT mode is similar with that under T mode. The strength of the foundation and the lower backfill layer has a more important effect on the location of the failure surface than that of the upper backfill layer.

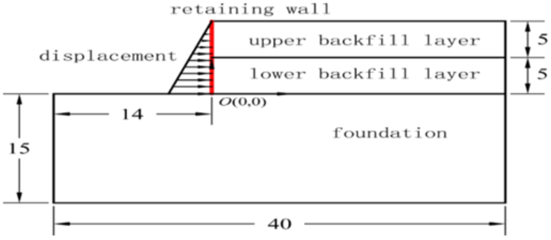

*Fig. (7). Sketch of the calculation model under RT mode(Unit: m)*

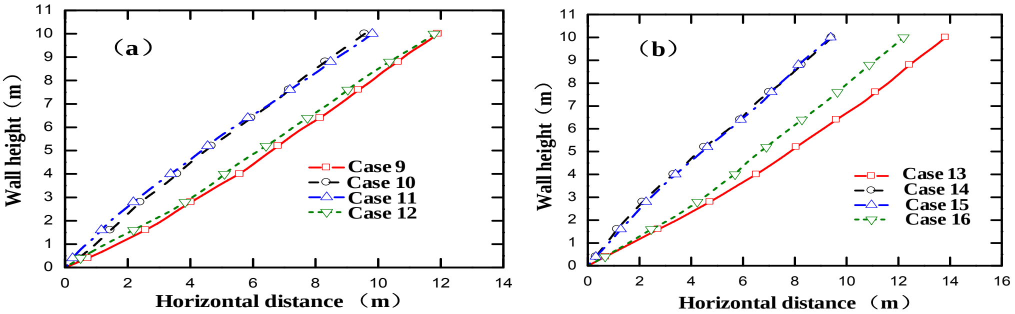

*Fig. (8). Failure surfaces of heterogeneous backfill under RT mode: (a) the effect of φ; (b) the effect of c*

## 6. Conclusions

In this paper, the effect of the strength of the upper and lower layer of the heterogeneous backfill on its failure surface at the passive state is investigated by employing the geotechnical FEM software Plaxis. On the basis of the analysis of the results, it is found out that the failure surface at the passive state is strongly influenced by the strengths of the foundation and the lower layer soil for the backfill consisting of two-layered soils. The failure surface of the two-layered soils approaches the one of the homogeneous soil with the strength of the foundation and the lower layer soil.

### Acknowledgement

The authors wish to acknowledge the Key Industrial Science and Technology Project of Shaanxi Province (No. 2015GY149) and the Scientific Project funded by the Ministry of Housing and Urban-Rural Development of the People’s Republic of China Council (No. 2015-K2-008) for its financial support.

### References

Brinkgreve R. B. J. and Broere W., 2000, PLAXIS 2D Version 9 Reference Manual, PLAXIS bv P.O. Box 572.2600 AN DELFT Netherlands.

Chen Y. K., Wang Y. M., Xu R. Q.and Gong X. N., 2004, Numerical analysis of passive earth pressure on rigid retaining wall, Chinese Journal of Rock Mechanics and Engineering, vol. 23, no. 6, pp: 980-988.

Chen W. F., (1975), Limit analysis and soil plasticity, Developments in geotechnical engineering, Elsevier, Amsterdam, The Netherlands.

Chen W. F. and Liu X. L., 1990, Limit analysis in soil mechanics, Developments in geotechnical engineering, Elsevier, Amsterdam, The Netherlands.

Chen Z. Y. and Li S. M., 1998, Evaluation of active earth pressure by the generalized method of slices, Canadian Geotechnical Journal, vol. 35, no. 2, pp: 591-599, doi: 10.1139/t98-022.

Das B. M. and Puri V. K., 1996, Static and dynamic active earth pressure, Geotechnical and Geological Engineering, vol. 14, pp: 353-366.

Fang Y. S. and Ishibashi I., 1986, Static earth pressures with various wall movements, Journal of Geotechnical Engineering, ASCE, vol. 112, no. 3, pp: 317-333, doi :10.1061/(ASCE)0733-9410(1986)112:3(317).

Fang Y. S., Chen T. J. and Wu B. F., (1994), Passive earth pressures with various wall movements, Journal of Geotechnical Engineering, vol. 120, no.8, pp: 1307-1323, doi: 10.1061/(ASCE)0733-9410(1994)120:8(1307).

Fang Y. S., Ho Y. C. and Chen T. J., 2002, Passive earth pressure with critical state concept, Journal of Geotechnical and Geoenvironmental Engineering, vol. 128, no.8, pp: 651-659, doi: 10.1061/(ASCE)1090-0241(2002)128:8(651).

Graham J., 1971, Calculation of passive pressure in sand, Canadian Geotechnical Journal, vol. 8, no.4, pp: 566-578, doi: 10.1139/t71-058.

Gu W. C., 2001, Calculation of earth pressures acting on retaining walls. Beijing, China Building Industry Press.

Ichihara M., and Matsuzawa H., (1973), Earth pressure during earthquake, Soils and Foundations, vol. 13, no. 4, pp: 75-86.

Ishii Y., Arai H. and Tsuchida H., 1960, Lateral earth pressure in an earthquake, In Proceedings of the 2nd World Conference on Earthquake Engineering, Tokyo, vol. 1, pp: 211-230.

Ishibashi I. and Fang Y. S., 1987, Dynamic earth pressures with different wall movement modes. Soils and Foundations, vol. 27, no. 4, pp: 11-22.

Janbu N., 1957, Earth pressure and bearing capacity calculations by generalized procedure of slice, in Proceedings of the 4th International Conference on Soil Mechanics and Foundation Engineering, London, vol.2, pp: 207-212.

Kumar J. and Subba R. K. S., 1997, Passive pressure determination by method of slices, International Journal for Numerical and Analytical Methods in Geomechanics, vol.21, no.5, pp: 337-345, doi: DOI: 10.1002/(SICI)1096-9853(199705)21:5<337::AID-NAG873>3.0.CO;2-P.

Kumar J., 2001, Seismic passive earth pressure coefficients for sands, Canadian Geotechnical Journal, vol. 38, no. 4, pp: 876-881, doi: 10.1139/t01-004.

Lee I. K. and Herington J. R., 1972, A theoretical study of the pressure acting on a rigid wall by a sloping earth or rockfill, Geotechnique, vol.22, no.1, pp: 1-27, doi: 10.1680/geot.1972.22.1.1.

Matsuo M., Kenmochi S. and Yagi H., (1978), Experimental study on earth pressure of retaining wall by field tests, Soils and Foundations, vol. 18, no. 3, pp: 27-41.

Matsuzawa H., Matsumura A., 1981, Passive earth pressure during earthquakes. Proceedings of the 1st International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, Rolla, Missouri, pp: 715-720.

Morrison E. E. and Ebeling R.M., 1995, Limit equilibrium computation of dynamic passive earth pressure, Canadian Geotechnical Journal, vol. 32, no.3, pp: 481-487, doi: 10.1139/t95-050.

Prakash S. and Saran S., 1966, Static and dynamic earth pressures behind retaining walls, in Proceedings of the 3rd Symposium on Earthquake Engineering, University of Roorkee, India, pp: 277-288.

Rahardjo H. and Ffedlund D. G., 1983, General limit equilibrium method for lateral earth force, Canadian Geotechnical Journal, vol. 21, no. 1, pp: 166-175, doi:10.1139/t84-013.

Sherif M. A. and Fang Y. S., 1984, Dynamic earth pressures on walls rotating about the top, Soils and foundations, vol. 24, no. 4, pp: 109-117.

Shields D. H. and Tolunary A. Z., 1973, Passive pressure coefficients by method of slices, Journal of the Soil Mechanics and Foundations Division, ASCE, vol. 99 no. SM12, pp: 1043-1053.

Sokolovski, 1965, Statics of granular media. Pergamon Press, New York.

Song F., Cao G. R. and Zhang L. Y., Tan X., 2013, Numerical analysis of failure mode of geocell flexible retaining wall, ASCE Geotechnical Special Publication, vol. 232, pp:136-145, doi: 10.1061/9780784413128.017

Soubra A. H. and Kastner R., 1991, Passive earth pressure coefficients in seismic areas by the limit analysis method, in Proceedings of the 5th international conference on soil dynamics and earthquake engineering, pp: 415-426.

Soubra A. H., 2000, Static and seismic passive earth pressure coefficients on rigid retaining structures, Canadian Geotechnical Journal, vol. 37, no. 2, pp: 463-478, doi: 10.1139/t99-117.

Soubra A. H. and Macuh B., 2002, Actice and passive earth pressure coefficients by kinematical approach, in Proceedings of the Institution of Civil Engineers: Geotechnical Engineering, vol. 155, no. 2, pp: 119-131.

Subba R. K. S. and Choudhury D.S., 2005, Seismic passive earth pressures in soils, Journal of Geotechnical and Geoenvironmental Engineering, vol.131, no.1, pp: 131-135, doi: 10.1061/(ASCE)1090-0241(2005)131:

1(131)

Terzaghi K., 1934, Large retaining wall tests, Engineering News Record, vol.112, pp: 136-140.

Terzaghi K., 1943, Theoretical Soil echanics. Wiley, New York.

Wang Y. Z., 2000, Distribution of earth pressure on a retaining wall, Geotechnique, vol. 50, no.1, pp: 83-88, doi: 10.1680/geot.2000.50.1.83.

Zakerzadeh N., Fredlund D. G. and Pufahl D. E., 1999, Interslice force functions for computing active and passive earth force, Canadian Geotechnical Journal, vol. 36, no. 6, pp:1015-1029, doi: 10.1139/t99-065.

Zhu D. Y. and Qian Q. H., 2000, Determination of passive earth pressure coefficients by the method of triangular slices, Canadian Geotechnical Journal, vol. 37, no. 2, pp: 485-491, doi: 10.1139/t99-123.