Estimation of Ultimate Soil Resistance for Laterally Loaded Piles Using a Coupled Eulerian-Lagrangian Model

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Abstract: In the numerical analysis of laterally loaded pile-soil interaction, the classical Lagrangian model under the large soil deformation or rough pile-soil interface will cause convergence problems due to soil plastic damage and great mesh distortion, which leads to a large discrepancy between the calculation results and the actual situation. In this paper, a numerical model based on the coupled Eulerian-Lagrangian (CEL) method was proposed to investigate the laterally loaded pile-soil interaction and the variation of ultimate soil resistance (USR) acting on the pile side. The results show that the USR calculated by the CEL model was consistent with the theoretical values and the Lagrangian model results in the literature, which indicates that it is appropriate to study the laterally loaded pile-soil interaction behavior using the CEL model. In pile-soil interaction problems involving large deformations, the CEL model describes well the soil flow behavior around the pile and has significant advantages in the application.

1 INTRODUCTION

For laterally loaded piles (see Figure 1), the deformation behavior of piles is mainly affected by the distribution of ultimate soil resistance (USR) on the pile side (Guo, 2006). Different assessment results are inevitably obtained by using different USR distributions. Therefore, accurate determination of the USR on the pile side is essential for the accurate design of the pile foundation.

To obtain the real USR, Abdrabbo et al. (2012) and Kim et al. (2004) carried out a large number of laboratory or field tests to investigate the relationship between pile displacement and soil resistance. Furthermore, Randolph and Houlsby (1984) derived an upper-limit solution for the USR of circular piles by considering the friction at the pile-soil interface. Based on this theory, the USR can be determined to be approximately $9.14c_uD$ and $11.94c_uD$ (where c_u is the undrained shear strength of the soil and D is the pile diameter) for smooth and rough conditions at the pile-soil interface, respectively.

Numerical simulation can be used to quantitatively analyze the variation of the USR under different conditions. Georgiadis et al. 0 adopted a finite element model to analyze the USR in clay considering the effect of side-by-side piles. Yang et al. (2002) developed an LPILE model to study the deformation behavior of piles in homogeneous sands and clays and obtained the pile displacement-soil resistance curves. Zhao et al. (2019) established an Abaqus 3D finite element model to study the interaction characteristics between laterally loaded piles and soil.

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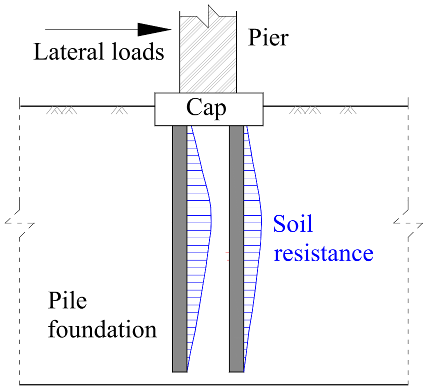

Figure 1: Schematic diagram of laterally loaded piles.

However, the numerical models adopted in the above literature are quite different from the actual situation when the soil deformation is large or the pile-soil interface is rough. The reason is that the Lagrangian model used in the above literature has convergence problems due to the extreme plastic damage of the soil and the great distortion of the mesh (Sheng et al., 2005). Therefore, to further reveal the laterally loaded pile-soil interaction mechanism and estimate the USR acting on the pile side, this study aims to investigate this issue by using a coupled Eulerian-Lagrangian (CEL) finite element method considering large deformation characteristics and to provide new ideas for the research and engineering design of laterally loaded piles.

2 COUPLED EULERIAN-LAGRANGIAN METHOD CONSIDERING LARGE DEFORMATIONS

The methods of describing material motion are classified as Lagrangian or Eulerian, as shown in Figure 2. In the Lagrangian method, the material is tightly connected to the mesh and moves only with the deformation of the mesh, whereas in the Eulerian method, the material can flow freely in the Eulerian domain mesh but the mesh always remains motionless. Since there is no need to consider mesh quality issues (e.g. mesh distortion), the Eulerian method has significant advantages for analyzing problems involving large deformations and material damage.

Combining Eulerian and Lagrangian methods to form an advanced numerical analysis technique, i.e., the CEL method (Luke et al., 2021), which is particularly suitable for the analysis of the interaction between materials with large relative stiffness and easy to yield by establishing the Eulerian and Lagrangian bodies and allowing the two to come into contact. For the pile-soil interaction problem involved in this paper, the CEL analysis will have a significant advantage due to the large difference in pile-soil stiffness and the ease of destruction of the soil.

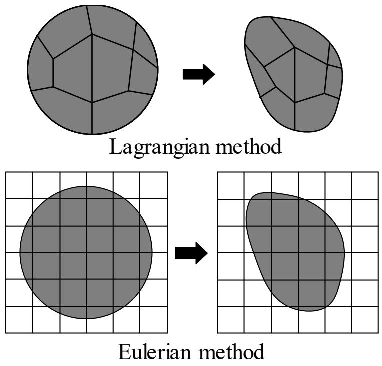

Figure 2: Methods for describing the motion of materials.

3 ANALYSIS OF ULTIMATE SOIL RESISTANCE FOR LATERALLY LOADED PILES

3.1 Laterally Loaded Pile Model Based on the CEL Method

Considering the side-by-side effect, the unit-length laterally loaded pile-soil interaction model was established, see Figure 3, where the pile diameter D was 1.0 m, the s was the pile spacing, and the boundary distance was $s/2$ from the pile axis. Concerning the Lagrangian model adopted by Chen and Martin (2002), the distance of the right boundary from the pile axis was 12.0 m and the distance of the left boundary from the pile axis was 8.0 m.

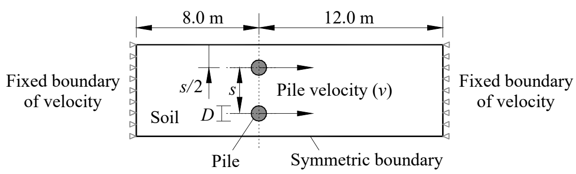

Figure 3: Numerical conceptual model for laterally loaded piles.

The established CEL finite element model is shown in Figure 4. The soil region was modeled by Eulerian material and the reserved pile region was set as a void. The soil was described by the Mohr-

Coulomb material model, with a density of 1642 kg/m^3, and an elastic modulus of 6.0 MPa, and the pile-soil interaction process was regarded as an undrained process under rapid loading, then Poisson's ratio was set to be the value of 0.495 (Georgiadis et al., 2013; Tho et al., 2014). The friction angle was 0.1°, and the undrained shear strength c_u was 15.6 kPa. The unit-length pile was modeled by Lagrangian material, which was regarded as a linear material, with an elastic modulus of 33.6 GPa, and a Poisson's ratio of 0.17. The Eulerian-Lagrangian coupled contact was established, and the friction factor at the pile-soil interface was set to be f (the interface is represented to be smooth when f=0, and the interface is represented to be rough when f=1.0). The pile was moved horizontally laterally at a speed of 0.001 m/s for a calculation time of 100 s, and the variation in pile reaction force (whose magnitude is equal to the soil resistance p) was recorded through a reference point.

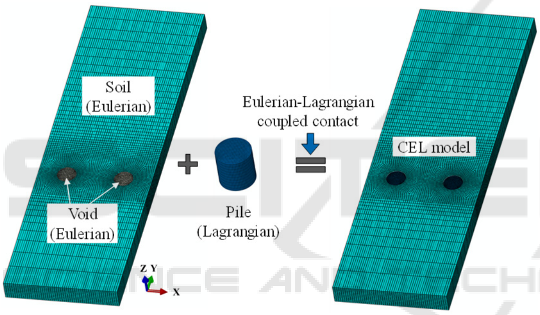

Figure 4: The establishment process of the CEL model.

3.2 Variation in the USR

Figure 5 shows the development of soil resistance of a monopile for friction factors of 0 and 1.0, respectively. The soil resistance is normalized in the figure in the following way

$$N_p = \frac{p}{c_u D} \tag{1}$$

where N_p is the soil resistance factor.

As can be seen from the figure, with the increase of pile horizontal displacement, the soil resistance gradually increases and tends to stabilize after reaching the limit. The whole development process can be divided into three stages: (i) the soil is in the elastic stage, the pile displacement is from 0 to 6.0 mm, and the soil resistance increases linearly; (ii) the soil is in the elastic-plastic stage, the pile displacement is from 6 to 60.0 mm, the soil resistance increases to the limiting value, and the increase decreases gradually; (iii) the soil is in the plastic stage, the pile displacement is larger than 60.0 mm, the soil resistance reaches the limiting value and then tends to stabilize.

In addition, the USR was 8.87 $c_u D$ and 11.86 $c_u D$ under f=0 and f=1.0, respectively, which were in good agreement with the theoretical results of Randolph and Houlsby (1984), with a difference of 3.0% and 0.7%, respectively, indicating that it is appropriate to study the laterally loaded pile-soil interaction behavior using the CEL model.

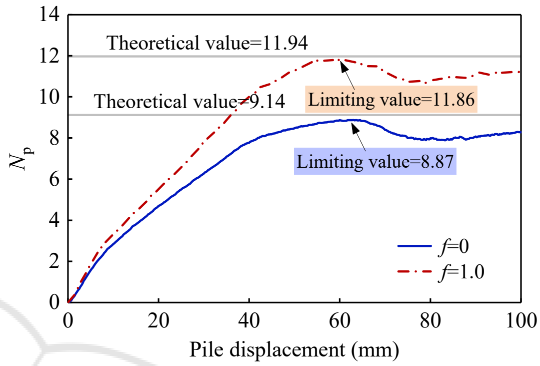

Figure 5: Comparison of CEL model calculated results with theoretical results from the literature.

Figure 6 shows the equivalent plastic strain distribution when the soil resistance reaches the limit value. When f=0, the pile-soil interface is smooth, the soil undergoes bypassing along the pile surface, the soil equivalent plastic strain region is overall narrow, the maximum equivalent plastic strain is small, and the distribution area of the triangular wedge elastic zone is small. When f=1.0, the soil cannot produce relative sliding along the pile surface, resulting in the soil providing a greater resistance, and the triangular wedge elastic zone distribution area is larger.

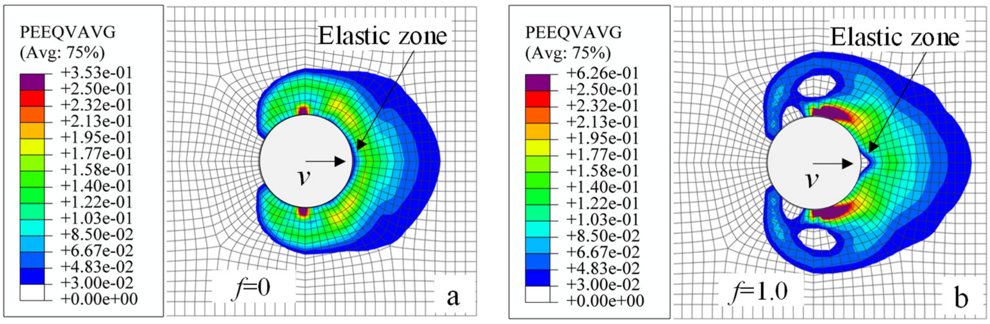

Figure 6: Equivalent plastic strain distribution of soil on the pile side.

Figure 7 shows the development of soil resistance for different pile spacings at f=1.0. As the pile spacing increases, the 'stiffness' of the soil resistance development curve increases, and the USR also increases, and gradually converges to the USR under a single pile. Comparing these results with those of Georgiadis et al. (2013), it can be seen that the results of the CEL model are very close to those of the literature, but the results of this paper are overall small. The reason is that the CEL method fully considers the large deformation effect of soil flow around the pile, resulting in a relatively weaker resistance given by the soil.

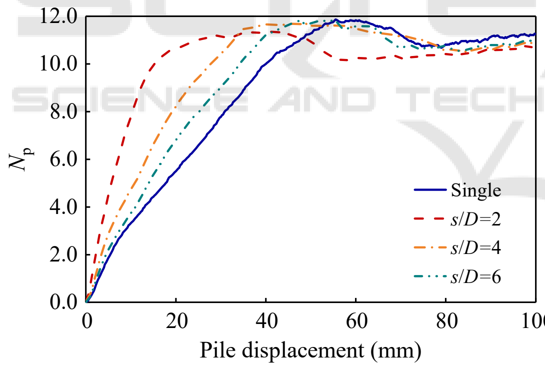

Figure 7: Development of soil resistance at different pile spacings (f=1.0).

4 CONCLUSIONS

A CEL model was proposed to investigate the mechanism of laterally loaded pile-soil interaction and the variation of USR, and the following conclusions were obtained:

(1) The USR calculated by the CEL model was very close to the theoretical results and the Lagrangian model results in the literature, which indicated that it is reliable to analyze the laterally loaded pile-soil interaction using the CEL method.

(2) The CEL method can overcome the convergence problems caused by plastic yielding and mesh twisting in the Lagrangian model and is more applicable in pile-soil interaction problems involving large deformation. Compared with the Lagrangian model, the CEL model can well describe the soil flow behavior around the pile.

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REFERENCES

Guo, W. D. 2006. On limiting force profile, slip depth and response of lateral piles. *Computers & Geotechnics,* 33(1): 47-67.

Abdrabbo, F. M., Gaaver, K. E. 2012. Simplified analysis of laterally loaded pile groups. *Alexandria Engineering Journal,* 51(2): 121-127.

Tak Kim, B., Kim, N. K., Jin Lee, W., Su Kim, Y. 2004. Experimental load-transfer curves of laterally loaded piles in nak-dong river sand. *Journal of Geotechnical & Geoenvironmental Engineering,* 130(4): 416-425.

Randolph, M. F., Houlsby, G. T. 1984. The limiting pressure on a circular pile loaded laterally in cohesive soil. *Geotechnique,* 34(4): 613-623.

Georgiadis, K., Sloan, S. W., Lyamin, A. V. 2013. Ultimate lateral pressure of two side-by-side piles in clay. *Geotechnique,* 63(13): 1170-1175.

Yang, Z., Jeremic, B. 2002. Numerical analysis of pile behavior under lateral loads in layered elastic-plastic soils. *International Journal for Numerical and Analytical Methods in Geomechanics,* 26: 1385-1406.

Zhao, M., Peng, W., Yang, C., Xiao, Y. 2019. Analysis of strain wedge for laterally loaded pile based on ABAQUS. *Journal of Railway Science and Engineering,* 16(09): 2199-2206.

Sheng, D., Eigenbrod, K. D., Wriggers, P. 2005. Finite element analysis of pile installation using large-slip frictional contact. *Computers and Geotechnics,* 32(1): 17-26.

Luke, T., Ashley, P., Ali, T. 2021. Coupled Eulerian-Lagrangian simulation of a modified direct shear apparatus for the measurement of residual shear strengths. *Journal of Rock Mechanics and Geotechnical Engineering,* 13(05): 1113-1123.

Chen, C. Y., Martin, G. R. 2002. Soil–structure interaction for landslide stabilizing piles. *Computers & Geotechnics,* 29(5): 363-386.

Tho, K. K., Chen, Z., Leung, C. F., Chow, Y. 2014. Enhanced analysis of pile flexural behavior due to installation of adjacent pile. *Canadian Geotechnical Journal,* 51(6): 705-711.