***The 2018 Structures Congress (Structures18)***
*Songdo Convensia, Incheon, Korea, August 27 - 31, 2018*

# Deformation analysis of subway foundation pit with different parameters of soil-structure contact

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## ABSTRACT

Through the indoor model experiment, the nonlinear relationship between stress and strain of the contact surface is obtained when the soil and structure interacted. Based on the hyperbolic relationship between Clough and the Duncan tangential model, the tangential nonlinear parameters in the Goodman contact unit are obtained. A FRIC subroutine that satisfies the hyperbolic relationship between Clough and the Duncan tangential model was developed. The mechanical properties of soil-structure contact under different contact parameters and the soil were studied. The variation of the pile wall displacement, the soil displacement behind the wall, and the axial force of the support are analyzed with the friction coefficient of the penalty function model and the Clough and Duncan hyperbola parameters ($K$, $\delta$, $n$, $R_f$) of the nonlinear model.

## 1. INTRODUCTION

In the finite element numerical calculation of foundation pit engineering, the penalty function method is commonly used to simulate the interface between the diaphragm wall or the pile wall and the soil. Chen (2010) analyzed the influence of internal forces and deformations of the foundation pits with and without contact surfaces. Lu (2017) proposed a soft/hardening constitutive model of the soil-structure interface through isotropic compression tests and conventional triaxial compression tests. Wu (2014) used three-axis simulation experimental instrument to achieve the complex stress conditions of the pile-soil interface interaction characteristics. Zhang (1998) obtained the relationship between the shear stress and the strain hyperbola of the "shear-moving belt". Wang (2014) used the contact mechanics method and contact surface element method to simulate the contact between piles and soils, and analyzed the advantages and disadvantages of using Coulomb friction model and Goodman contact element model to calculate the bearing capacity of deep-water drilling pipes. Zhang (2016) introduced the Goodman element and the damage constitutive equation

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into the contact interface between the soil and the structure to analyze the stress transfer between the layers of the asphalt pavement.

## 2. INFLUENCE OF NONLINEAR MODEL PARAMETERS ON INTERNAL FORCE AND DEFORMATION OF FOUNDATION PIT

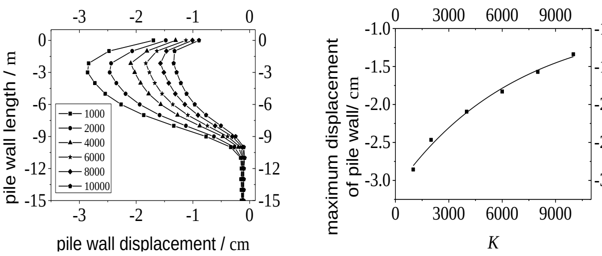
The range of non-linear parameters is shown in Table 1.

Table 1 The list of the range of nonlinear parameters

| $K$ | $\delta$ | $n$ | $R_f$ | $K$ | $\delta$ | $n$ | $R_f$ |
|---|---|---|---|---|---|---|---|
| 1000 | 15 | 0.3 | 0.2 | 6000 | 30 | 0.6 | 0.8 |
| 2000 | 20 | 0.4 | 0.4 | 8000 | 35 | 0.7 | — |
| 4000 | 25 | 0.5 | 0.6 | 10000 | 40 | 0.8 | — |

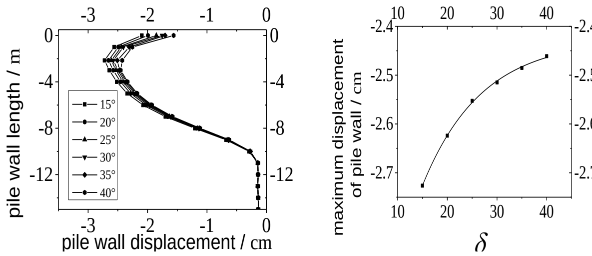
*2.1 Analysis of Influence of Nonlinear Parameters on Displacement of Pile Wall*

The FRIC subroutine of ABAQUS is embedded in the finite element software. The contact parameters of Clough and Duncan hyperbola model are determined according to laboratory tests. Single factor method is used to analyze the influence of four parameters $K$, $\delta$, $n$, $R_f$ on the displacement of the pile wall.



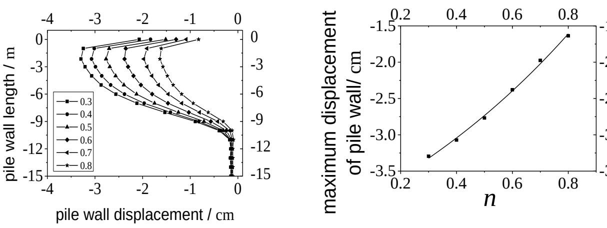

(a) (b)

Fig. 1 Influence of $K$ on the displacement of pile wall



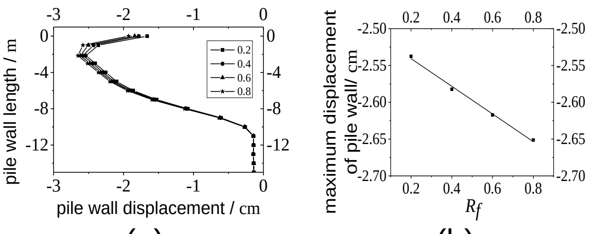

(a) (b)

Fig. 2 Influence of $\delta$ on the displacement of pile wall




(a) (b)

Fig. 3 Influence of $n$ on the displacement of pile wall




(a) (b)

Fig. 4 Influence of $R_f$ on the displacement of pile wall

Fig. 1(a), the horizontal displacement curve along the length of the pile wall presents an “upward convex” shape distribution. The pile wall displacement along the length of the pile wall increases first and then decreases. With the increase of the parameter $K$, the maximum horizontal displacement of the pile wall decreases. Fig. 1(b) shows the relationship between the parameter $K$ and the maximum displacement of the pile wall, indicating that the parameter $K$ has a nonlinear change relationship with the maximum displacement value of the pile wall. With the increase of the parameter $K$, the maximum horizontal displacement value of the pile wall gradually decreases.

Fig. 2(a) shows that the horizontal displacement curve along the length of the pile wall presents an “upward convex” shape distribution. The length displacement along the pile wall increases first and then decreases. In Fig. 2(b), the parameter $\delta$ changes nonlinearly. As the parameter $\delta$ increases, the maximum displacement change rate of the pile wall gradually decreases, and the maximum horizontal displacement of the pile wall varies from 24.6 to 27.2mm, the range of change is small, so the parameter $\delta$ is not the main factor affecting the deformation of the pile wall.

Fig. 3(a) shows that the horizontal displacement curve along the length of the pile wall presents an “upward convex” shape distribution, indicating that the displacement along the length of the pile wall increases first and then decreases. Fig. 3(b) shows the relationship between the parameter $n$ and the maximum displacement of the pile wall. With the increase of the parameter $n$, the maximum horizontal displacement value of the pile wall increases exponentially, and the maximum horizontal displacement of the pile wall ranges from 16.4 to 33.0 mm.

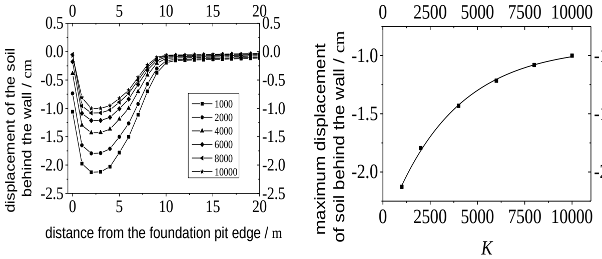
Fig. 4(a), the horizontal displacement curve along the length of the pile wall shows an “upward convex” shape distribution, indicating that the displacement along the length of the pile wall increases first and then decreases. Fig. 4(b), the parameter $R_f$, changes linearly. With the change of parameter $R_f$, the maximum horizontal displacement of the pile wall varies from 25.4 to 26.5mm, and the range of change is small. The change of parameter $R_f$, does not significantly affect the horizontal displacement of the pile wall.

### *2.2 Influence of Nonlinear Parameters on Displacement of Soil behind a Wall*

Fig.5 (a) shows that the vertical displacement curve of the soil behind the wall shows a “groove” shape distribution, indicating that as the distance along the edge of the foundation pit increases, the displacement of the soil behind the wall increases first and then decreases. Fig.5 (b) shows the relationship between the parameter $K$ and the maximum displacement of the soil behind the wall. With the increase of $K$, the maximum displacement value behind the wall gradually decreases. The maximum displacement value behind the wall ranged from 10.0 to 21.3 mm, and the amplitude of its change and the friction coefficient were the same as the amplitude of the maximum displacement value behind the wall.

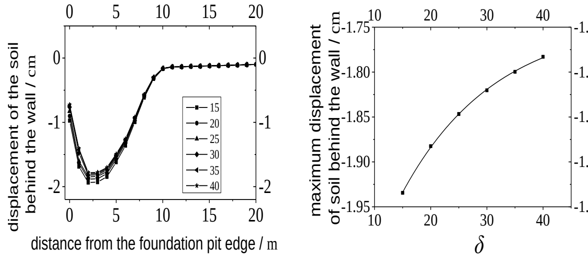
Fig.6 (a) shows that the vertical displacement curve of the soil behind the wall shows a “groove” shape distribution, indicating that as the distance along the edge of the foundation pit increases, the displacement of the soil behind the wall increases first and then decreases, with no effect at infinity. Fig. 6 (b) shows the relationship between the parameter $\delta$ and the maximum displacement of the soil behind the wall. The maximum displacement of the soil behind the wall is 2.4mm, and it changes nonlinearly. The influence of the parameter $\delta$ on the displacement of the soil behind the wall is similar to that on the displacement of the pile wall.

Fig.7 (a) shows that the vertical displacement curve of the soil behind the wall shows a “groove” shape distribution. Fig. 7 (b) shows the relationship between the parameter *n* and the maximum displacement of the soil behind the wall. With the increase of the parameter *n*, the maximum displacement value of the soil behind the wall increases exponentially. The parameter *n* has a great influence on the displacement of the soil behind the wall.



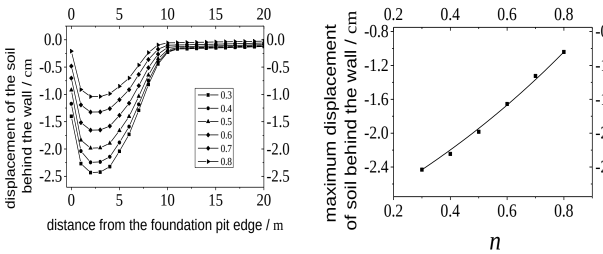

(a) (b)

Fig. 5 Influence of *K* on displacement of soil behind wall



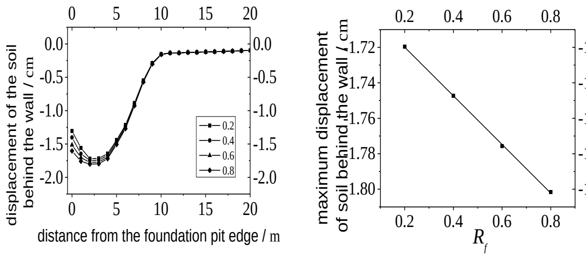

(a) (b)

Fig. 6 Influence of $\delta$ on displacement of soil behind wall




(a) (b)

Fig. 7 Influence of *n* on displacement of soil behind wall




(a) (b)

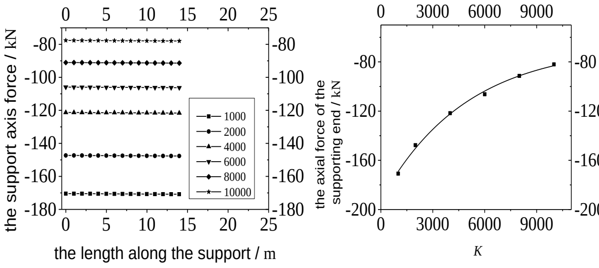
Fig. 8 Influence of $R_f$ on displacement of soil behind wall

Fig.8 (a) shows that the vertical displacement curve of the soil behind the wall shows a “groove” shape distribution. As the distance along the edge of the foundation pit increases, the displacement of the soil behind the wall increases first and then decreases. Fig.8 (b) shows the relationship between the parameter $R_f$ and the maximum displacement of the soil behind the wall. With the increase of the parameter $R_f$, the maximum displacement value of the soil behind the wall is linearly decreasing. The amplitude of the maximum displacement value of the soil behind the wall is less than 1mm, and its effect on the deformation of the pile wall is not obvious.

### *2.3 Influence of Nonlinear Parameters on Support Axial Force*

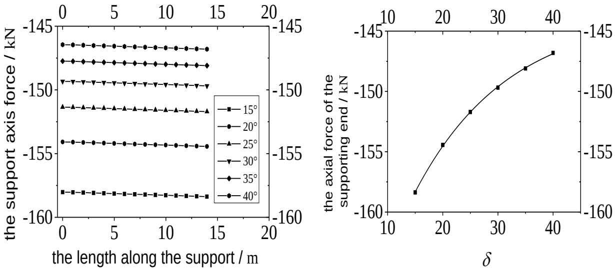
Fig. 9(a) shows that the supporting axial force does not change substantially along the length of the support, which is similar to the case of using the penalty function method for the contact. Fig.9 (b) reflects the relationship between the parameter *K* and the axial force of the supporting end. With the uniform change of the parameter *K*, the axial force at the end of the support decreases continuously and changes nonlinearly. Therefore, the change of the parameter *K* significantly affects the supporting axial force and affects the overall stability of the foundation pit.

Fig. 10(a) shows that there is essentially no significant change in support axial force along the length of the support. Fig. 10(b) reflects the relationship between the parameter $\delta$ and the axial force at the end of the support. When the parameter $\delta$ is 15, the axial force at the end of the support is 158.4 kN. When the parameter $\delta$ is 40, the axial force at the end of the support is 146.8 kN. With the uniform variation of the parameter $\delta$, the axial force at the end of the support decreases continuously and changes nonlinearly, and the rate of change of the axial force gradually decreases. Therefore, the parameter $\delta$ has little effect on the axial force of the support.



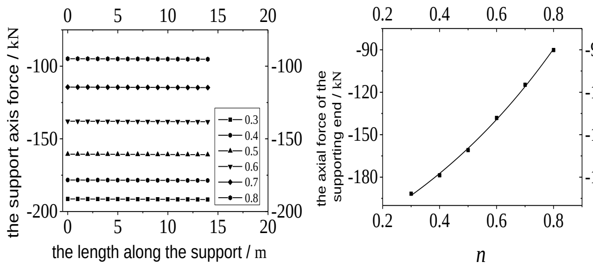

(a) (b)

Fig. 9 Influence of *K* on the supporting axial force



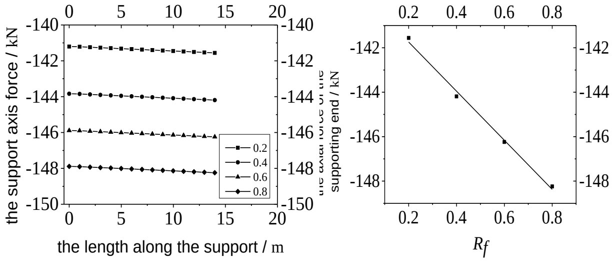

(a) (b)

Fig. 10 Influence of $\delta$ on the supporting axial force




(a) (b)

Fig. 11 Influence of *n* on the supporting axial force




(a) (b)

Fig. 12 Influence of $R_f$ on the supporting axial force

In Fig. 11(a), the axial force of the support and the length along the support are similar to other parameters. Fig. 11(b) reflects the relationship between the parameter *n* and the axial force of the support end. When the parameter *n* is 0.3, the axial force at the support end is 191.7 kN. When the parameter *n* is 0.8, the axial force at the support end is 90.2 kN. With the uniform change of parameter *n*, the axial force at the end of the support decreases continuously and changes exponentially, and the rate of change of the axial force gradually increases. Therefore, the influence of the parameter *n* on the axial force of the support is obvious and it is one of the main factors.

In Fig. 12(a), as the parameter $R_f$ increases, the axial force of the support gradually increases. Fig. 12(b) shows the relationship between the parameter $R_f$ and the axial force of the supporting end. As the parameter $R_f$ increases, the axial force at the end of the support increases linearly. The maximum displacement of the soil behind the wall ranged from 141.6 to 148.2 kN. The difference between the maximum and minimum values was 6.6 kN and the range of variation was small. So the parameter $R_f$ is not the main influencing factor on the deformation of the pile wall.

## 3. CONCLUSIONS

Based on the finite element software ABAQUS, the mechanical properties of soil-structure contact and the elasto-plastic deformation characteristics of soil under different contact parameters were simulated. The following conclusions are obtained:

(1) Based on the non-linear contact model, the horizontal displacement along the length of the pile wall presents an "upward convex" shape distribution, indicating that the displacement along the length of the pile wall increases first and then decreases. Parameter $n$ and $K$ are the parameters that mainly affect the displacement of the pile wall, while the parameter $\delta$ and $R_f$ have no significant effect on that.

(2) The vertical displacement curve of the soil behind the wall shows a “groove” shape distribution. The displacement of the soil behind the wall increases first and then decreases. The range of variation of nonlinear parameters ($K$, $\delta$, $n$, $R_f$) on the vertical displacement of the soil behind the wall is 10.0~21.3mm, 7.3~9.7mm, 10.4~24.3mm, and 17.2~18.0mm.

(3) The supporting axial force does not change substantially along the support length, and the two ends of the support are within 0.5 kN. The range of influence of the nonlinear parameters (($K$, $\delta$, $n$, $R_f$) on the supporting axial force is 82.0 to 170.8 kN, 146.8 to 158.4 kN, 90.2 to 191.7 kN, and 141.6 to 148.2 kN.

(4) The influence of nonlinear parameters on the maximum horizontal displacement value of the pile wall, the maximum displacement of the soil behind the wall and the axial force of the support are nonlinear. In a comprehensive analysis, the nonlinear parameter $n$ has the greatest influence on the internal forces and deformation of the foundation pit, followed by the nonlinear parameter $K$, and finally the nonlinear parameter $\delta$ and the parameter $R_f$.

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