Study on the Horizontal Subgrade Reaction of Expressway Protective Guard Pillar

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Abstract
It is quite necessary to describe the relationship between the horizontal subgrade reaction and the horizontal displacement with a simple form. This study provides the analysis of the horizontal subgrade reaction of protective guard pillar in the conflict between automobiles and protective guard pillars. Making use of the relationship between soil load and horizontal load, we can build the theory of assessment of the coefficient of horizontal subgrade reaction, and then simulate the relationship between soil and column with spring in the help of the theory. In this paper, we use Mohr-coulomb yield criterion and integrate ABAQUS finite element numerical simulations, to find that it is the difference between the greatest horizontal stress components σ_x and the smallest horizontal stress components σ_y that causes the fact that horizontal load leads to the plastic yielding of protective guard pillar and earth coupling model soil. and also, the paper provides the theoretical formula of coefficient of horizontal subgrade reaction and the ultimate bearing capacity of horizontal subgrade reaction, then build the theoretical model of coefficient of horizontal subgrade reaction when soil is under the action of horizontal force, to offer design and analysis reference for practical projects.
Keywords Protective guard pillar, Level of load, ABAQUS, Level reaction site, Mohr-coulomb yield criterion, Numerical simulation

1 Introduction

The accident that automobiles collide guardrails is one of the main forms of road traffic accidents, and their collision has become main research direction of traffic safety[1-3]. In the analysis of building structures, spring is usually exerted in the foundation to simulate the relationship between soil and structures, so as to predict the coefficient of soil subgrade reaction in the system of building structures, and then we can ascertain spring coefficient. Usually, the prediction method of coefficient of soil subgrade reaction refers only to semi-infinite space soil or beam on elastic foundation[4-5], so it's necessary to revise the existing prediction method of coefficient of soil subgrade reaction, and ascertain its failure mechanism. This research makes use of the relationship between soil load and horizontal load, taking their elastic plastic behavior into consideration[6-7], and builds the prediction method of coefficient of soil subgrade reaction which is applied to buiding structure system, expecting that the research result is helpful for the selection of coefficient of engineering soil subgrade reaction.

Take the columns of semi-rigid guardrail system as object of study, and research each component's characteristics of deformation and energy-absorbing in the impact of shock. Because of the fact that the column is rammed and buried into soil,and the nonlinear characteristics of soil's height, in-depth study of the relationship between surrounding soil and column and also the characteristics of deformation and energy-absorbing of column is of great importance. This paper integrates finite element numerical simulations, providing the analysis of horizontal subgrade reaction and limiting uniform force,and finally simulates the relationship between soil and column with a series of horizontal springs, to build the theoretical model of coefficient of horizontal subgrade reaction when the soil is under the action of horizontal force;offers design and analysis references for practical projects.

2 Previous Research for Coefficient of Subgrade Reaction k_s

Piles' horizontal resistance is represented by coefficient of subgrade reaction k_s. Coefficient of subgrade reaction k_s is proposed by kinds of proposals. Usually, the derived relational expression $k_{h0} = \alpha \cdot E_0 \cdot D^{-3/4}$ acts as the coefficient of subgrade reaction when the benchmark displacement is 10mm,and we can represent the coefficient of subgrade reaction with the nonlinear curve of second order $k_h = k_{h0}/y^{1/2}$ of the relative displacement y between piles and the surrounding subgrade.Among them,:determinate number=80 (for cohesive soil ,when E_0 is derived by N,is 60). Gold proposed that relation curve of horizontal load P_{max} and displacement could be represented approximately by three crease line, among them, y is the relative displacement of piles and surrounding subgrade, $1(y < 0.6mm)$,$1/4(0.6mm < y < 10mm)$, $1/12(y > 10mm)$ acts as the slope of each line[8].

As can be seen from the above, k_h's character is that its value reduces gradually with deformation.

Seed and others analyzed many horizontal subgrade response results, and proposed that stress reduction factor should be decreased with depth, and show bandwidth viriation with depth[9]. The deeper, the wider. Also, they suggested that when analyzing and designing, we could use average curve.

The most important data of pile detail design includes coefficient of subgrade reaction k_s that responses deformation behavior. In existing d Sees the formula (2). esign, k_s's precise value is not as precise as other soil parameters (such as: undrained cohesion, internal friction angle, etc.). Usually, we can estimate the relationship of horizontal subgrade reaction with Young's modulus Es:

Non-sticky soil $k_h = 3 \times E_s/D$, Sticky soil $k_h = 1.6 \times E_s/D$, D is pile diameter.

In evaluating pile's coefficient of horizontal subgrade reaction, its horizontal load's horizontal displacement and the effect of horizontal subgrade reaction are pretty important, only in reasonable way to build appropriate design value, and it's essential to operate the experiment of loading pile load horizontally or conduct the simulation of correct value. The traditional method is to conduct the experiment of pile's destructive load, and it's rather difficult in loading condition or test technology[10-11]. Finite element method is the most appropriate method at this stage, through the material parameters obtained from laboratory testing, the mechanical behavior of making use of simulation analysis to determine the pile-soil interaction is worthy of wide concern.

3 Numerical Simulation Analysis

Analyzing and calculating the factors that affect pile's horizontal subgrade reaction and displacement correctly is of the utmost importance.This study simulates the contact problem of pile-soil interaction with ABAQUS finite element software, and makes use of the one by one contact algorithm in ABAQUS, and then build contact couple between the side of pile and the soil; for pile shaft, we can use elastic plastic model, and for soil, we can simulate with Mohr-Coulomb model; taking the effect of initial earth stress into consideration, we introduce soil lateral pressure coefficient to achive balance in the stage of 'GEOSTATIC', and this is very effective for simulation of geotechnical issues.

3.1 The Establishment of Finite Element Model of Column Soil

In the geometric model, use large body to simulate semi-infinite space, and in the simulate calculation , the radius of the soil is much lager than the radius of the pile's cross-section. As the picture 1 shown. In this model, the soil is built by eight-node entity reduced element, and others are four node shell element. The whole mode system includes 89158 nodes and 76656 elements, and material models are all elastic plastic materials that consider isotropic hardening.
The main parameters that can be revised in desigh are as follows(See Table 1).

3.2 Interpretation of Result

Mohr-Coulomb damage and strength criteria is widely applied to geotechnical engineering. The constitutive model that is used in ABAQUS is the classical expansion of Mohr-Coulomb yield criterion[12]. At some point the role of the shear stress equal to the shear strength, the damage occurred, and the role of shear strength in the face of the linear relationship between normal stress; allow the material isotropic hardening or softening, however, the shape of the flow of the model potential function in the meridional plane is hyperbola, and there is no cusp in the π plane, potential function is therefore completely smooth, ensuring the uniqueness of the plastic flow direction.

Fig.2 is the curve of path and displcement for the soil in front of column at

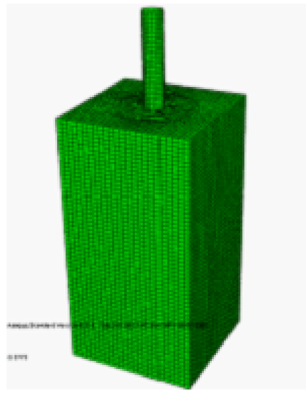

Fig.1 Mesh model

different loading time on the depth of the soil. As can be seen from Figure, the displacement of the soil in front of the column is gradually increasing with the load; and is of inverse relationship with the buried depth. Because of the role of soil bound, the region that column and soil doesn't saperate, has the characteristic that displacement reduces with buried depth; at about 1.05 meters in depth accurs the phenomenon that column saperate from the soil.

k_h is the ratio of the distribution force destiny q and relative displacement y,that is q/y; q is obtained form the distribution stress in the surface of the pile, and here we should firstly study the stress σ_x of the point in front of pillar. Fig.3 is the curve of the relationship between the path in depth and σ_x $(\sigma_x = S11)$, as can be seen, according to the horizontal load, S11 is negative value, and its absolute value is roughly linear and gradually become larger.

Fig.4 is the distribution force of the soil in front of pillar in depth, as can be

Table 1 Model of material parameters

Pile length	2.2 m	pile length Buried in soil	1.5m
Pile diameter	0.14m	elastic modulus of column	2.1E12 Pa
Elastic modulus of soil	5.0E+6Pa	Coefficient of soil lateral pressure	0.538
Soil Poisson's ratio	0.35m	Friction angle	20
Soil cohesion	3000Pa	Expansion angle	0.1

seen, with the development of deformation, the latter phenomenon of spin-off accurs, so we can predict the theoretical starting point of the spin-off, and the following spin-off broadens gradually.

4 Limiting Distribution Force q_{cr}

Based on the study on limiting distribution force q_{cr}, we can draw the qualitative conclusions as follows:

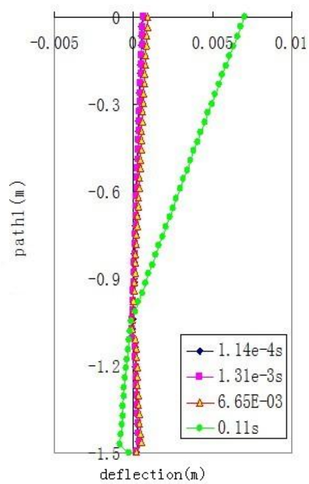

Fig.2 The depth way-deflection curve

(1) the limiting distribution force q_{cr} that varies with the the soil density γ, This function as shown in Fig.5, and the performance is not obvious. Especially in a lot of literatures, q_{cr} is in proportional relationship with proportion γ, here the relationship $q_{cr} \infty rgx$ isn't performed very well. The relationship is as stated above, σ_x is the middle stress, and yield stress is related to σ_y and σ_z. That is to say, usually, when we consider coulomb earth pressure, we take it as plane strain issue, σ_z is middle stress, and coulomb limiting stress is determined by the difference of σ_y and earth pressure $\sigma_x \infty rgx$ and believe that $\sigma_y \infty rgx$. The performance of the relationship is: The movement of the soil pile, is in three-dimensional stress state in soil that in front of the pile. Coulomb limiting stress is determined by the difference of σ_y and earth pressure σ_x. Consequently, the function $q_{cr} \infty rgx$ can't exist.

(2) About the relationship with cohesion C, according to the research and analysis into numerical simulations, we can gain a deeper knowledge: no matter big or small the depth x is, q_{cr} will become bigger with the cohesion C. Consequently, the expression of q_{cr} is:

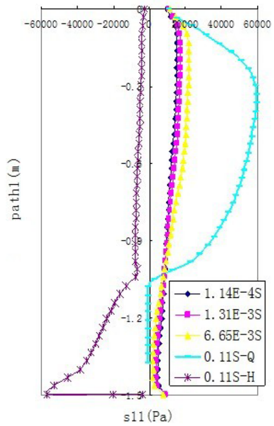

Fig.3 Depth way-load direction curve of pressure and resistance

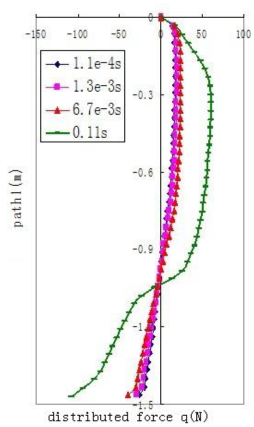

Fig.4 Depth way-distributed force relational graph

$$q_{cr} = q_{cro} + C_c \times x \tag{1}$$

q_{cr} can be ascertained from the following expression

$$q_{cro} \cong 2\frac{\cos\phi}{1-\sin\phi}cB \tag{2}$$

Meanwhile, the relationship between coefficient C_c and cohesion C is ascertained.For previous research on the construction of pile, coefficient C_c is not dependent on cohesion, but has founction relationship with friction angle ϕ in $3k_p rg$ form and density γ.

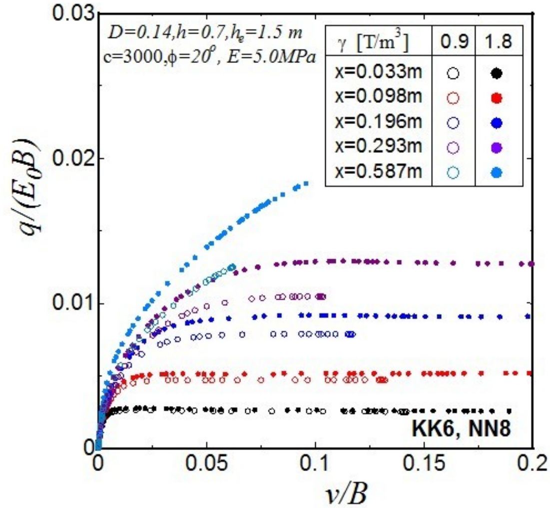

Fig.5 $r=$ 1800 and $r=$ 900situation q/E_0B and v/B relations

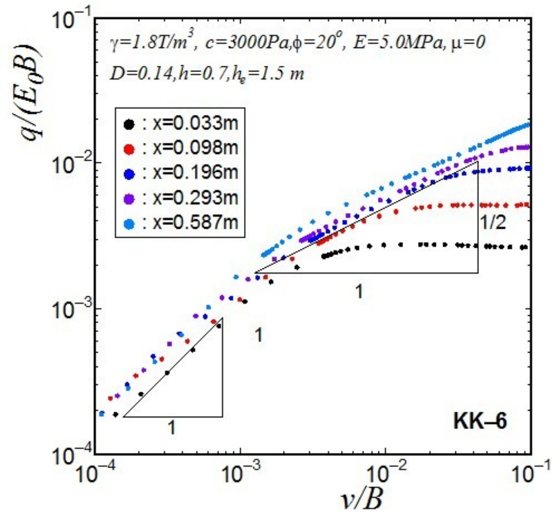

Fig.6 In logarithm graph q/E_0B and v/B relations

Based on the research above, the approximate expression of limiting force q_{cr} is:

$$q_{cr} \cong 2\frac{\cos\phi}{1-\sin\phi}B(c+0.24k_1k_2rg\frac{1+\sin\phi}{1-\sin\phi}\frac{x}{B}) \tag{3}$$

k_1 and k_2 are the modified coefficient of soil proportion γ and cohesion C.

$$k_1 = 0.3 + 0.8 \times \frac{r_0}{r}, r_0 = 1800kg/m^3 \tag{4}$$

$$k_2 = 0.5 + 0.5 \times \frac{c}{c_0}, c_0 = 3000P_a \tag{5}$$

5 The Proposal of the Relationship of Horizontal Subgrade Distribution Force q and Horizontal Displacement v

The purpose of this study is to propose the analysis of the simple model of horizontal subgrade reaction in the conflict between automotives and protective guard pillars. Therefore, based on the statement above, it's quite essential to describe the relationship between the horizontal subgrade distribution force q and the horizontal displacement v with a simple form. This paper researched the logarithmic chart that is shown in Fig.6, and express the relationship between q and q approximately in the chart with three lines. In the logarithmic chart, firstly, for initial elastic deformation, can be expressed approximately as the line whose slope $\lambda = 1$; secondly, the latter non-elastic deformation can be expressed approximately as the line whose slope $\lambda = 1/2$; at last, if horizontal subgrade distribution force q reaches limiting force q_{cr}, then it can be expressed approximately as the line whose slope $\lambda = 0$.

From the Fig.6 we can see: In the early stages of non-elastic deformation, horizontal subgrade distribution force q's limiting resistance is q_{cro} in the place where $x = 0$, Sees the formula (2).

However, we can see from the chart, when the depth X is big, the starting point transit form the line whose slop $\lambda = 1$ to the line whose slope $\lambda = 1/2$, when we calculate horizontal subgrade reaction q_{cr}, we can use the following expression :

$$q_{re} = P_2 \times [q_{cro} + 0.1(q_{cr} - q_{cro})] \tag{6}$$

q_{cr} can be ascertained by it. Therefore, q can be ascertained by the following expression :

$$q = \begin{cases} P_1 \times C_1 E_0 v & (v \le v_{re}) \\ C_x E_0 \sqrt{vB} & (v_{re} \le v \le v_{cr}) \\ P_2 \times q_{cr} & (v_{cr} \le v) \end{cases} \tag{7}$$

P_1 and P_2 in equation (6) and (7) modified coefficients when considering the friction between soil and pillar. When the friction coefficients $\mu = 0$, $P_1 = P_2 = 1$; when $\mu \neq 0$, the calculation of P_1 and P_2 will be stated later.

The unknown quantities v_{re}, C_x and v_{cr} in equation (7) can be ascertained as follows:

Firstly, when v reaches v_{re}, q reaches q_{re} from the first expression in equation

(7) we can obtain:

$$v_{re} = \frac{q_{re}}{P_1 C_1 E_0} \tag{8}$$

And also, when $v = v_{re}$ from the first and second expressions in equation (7)we can obtain:

$$C_x = \frac{q_{re}}{E_0 \sqrt{B v_{re}}} \tag{9}$$

So when $v = v_{cr}$, from the second and third expression in equation (7)we can obtain:

$$v_{cr} = \frac{(\frac{p_2 q_{cr}}{C_x E_0})^2}{B} \tag{10}$$

The predicting value according to the expression (3) is quite closed to the ABAQUS numerical simulations, therefore, the theoretical model of the horizontal resistance of the protective guard pillar in subgrade is feasible.

6 Conclusion

As is shown in the research result, with the help of the ABAQUS software, we built the coupling model of pillar and soil under the action of horizontal load, and analyzed soil's mechanical behavior when pillar is under the action of horizontal load, and also, proposed theoretical expression about the coefficient of horizontal subgrade reaction. The simulation results fit the trend of the literature[13] experimental data very well, indicating that ABAQUS has a great ability in dealing with highly nonlinear issues of the interaction between pillar and soil.

(1) Along the depth of the pillar, the coefficient of horizontal subgrade reaction is not certain, in the region more nearer to the surface, the value is relatively smaller, and this is the result that the horizontal resistance is small for the region near the surface .

(2) In pillar's slewing deformation, the coefficient of horizontal subgrade reaction is not certain too. It will become smaller with the development of the deformation. This is because the effects of plastic deformation become greater gradually.

(3) According to the argument above, using Mohr-coulomb yield criterion, we can find that soil plastic yielding damage is caused by the difference between σ_x and σ_y. Because of the action of horizontal load, σ_x that is S11) is negative value, and its absolute value is roughly linear and gradually become larger, and σ_y (that is S22)'s absolute value gradually become smaller. The greatest stress component is σ_x, and the smallest stress component is not σ_z (that is S33) which in gravity direction ,but is σ_y nd the cause of the entire yielding is the difference between σ_x and σ_y.

(4) Proposed the theoretical expressions of the limiting distribution force q_{cr}

and horizontal subgrade reaction q and horizontal displacement v .

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