Dynamic Interaction of Soil-Pile-Structure under Seismic Action

Zhiming QU and Sanyuan SHI

Associate Professor, School of Civil Engineering , Hebei University of Engineering, Handan City, Hebei Province, 056038, China
chinaqzm@163.com

ABSTRACT :

Due to randomness of seismic load, it is difficult to predict the complexity of the soil, pile, structures and their system. Presently, there isn't a better way to explain and simulate the dynamic interaction of soil-pile-structure completely and precisely. Based on the stiffness expressions of interaction, the improved physical and mathematical models are setup to reflect the basic mass, stiffness and damping factors in the dynamic action analysis. In the meantime, the main problems of dynamic interaction are revealed. Through theoretical analysis, experiment and observation results, the dynamic interaction of soil-pile-structure is reappeared qualitatively and quantitatively. The physical action mechanism, variation, characteristic laws and the catastrophic results are explained, inferred, summarized and analyzed respectively. It is concluded that the numerical process reflecting actual interaction is expressed and verified by model experiment and observation results. The interaction parameters are deduced theoretically in the mathematical model. Through observation and experiment, the geometric non-linearity of slip and disjoint of soil-pile is checked and tested during seismic action.

KEYWORDS: dynamic interaction, soil-pile-structure, seismic action, geometric non-linearity

1. INTROCUTION

Seismic soil-pile-structure interaction is a popular and important topic in the fields of construction engineering, bridge engineering, earthquake engineering and geotechnical engineering. Before the 1960s, it is confined to the scope of static or approximate static law, in which the pile is usually resolved as flexible foundation beam. In the 1960s, dynamic analysis such as Penzien model began to appear. Form the 1970s, FEM, BEM and other simulation methods were used. Over the last 10 years, further studies were mainly deepened, refined and précised from single pile to pile group, from two-dimensional to three-dimensional and so on. At the same time, some scholars studied the simplified analysis of which the dynamic Winkler foundation beam was the most widely applied. It was based on the Winkler foundation assumption in which the response of each soil layer had nothing to do with the adjacent layer and ignored the soil shear transferring. The representative models are Penzien, Matlock, El Naggar and Novak, Nogami, Boulanger, Kagawa models and so forth. The precise methods of present study are BEM, FEM and their combination. High coupling of each part in soil-pile-structure interaction makes the problem very complicated. The study showed that interaction included the impact of foundation on the dynamic characteristics of superstructure, the feedback input by superstructure on the ground surface.

Simplified analysis is on the basis of most extensive dynamic Winkler foundation beam model, which is easy to be accepted by engineering designer and concerned with the researchers. In China, Penzien model and a variety of simplified Penzien model has been extensively developed. Simplified analysis methods can be roughly divided into flexible dynamics and practical experience. The former considers the inertia effect, damping and stiffness characteristics of soil and non-linearity using the equivalent linear method, but it is difficult to consider local non-linearity. The latter can appropriately consider the local non-linearity. However, it is more difficult to simulate soil inertia and damping effect. Non-linearity in Novak model is not considered, but the model can reasonably simulate the flexibility. Nogami model, conceptually, can be seen as the combination of Matlock and Novak model. The precise analysis method, FEM may consider more factors. Though it plays an important role in studying the mechanism of seismic soil-pile-structure interaction and analyzing various parameters, the current research remains difficulty to be directly applied to engineering practice. Based on the study mentioned above, the dynamic interaction of soil-pile-structure is overall analyzed in order to establish numerical models reflecting actual dynamic interaction rationally, which is verified through trial model and prototype observations in earthquake.

2 SIMPLIFIED ANALYSIS OF DYNAMIC INTERACTION OF PILE GROUP

2.1 Model and Governing Equations

The main principle of Penzien model is that the mass of pile and foundation are concentrated along the depth to be points of particle and DOF, which is dynamically analyzed through the superstructure and the upper part of the whole structure. Free fields are analyzed, and then the response of the natural foundation will pass through equivalent springs to the equivalent soil system.

As to natural foundation, it is assumed that the soil is laminated horizontally. Its seismic response is not influenced by existing structures, so soil-pile element can be analyzed. Through analyzing free fields, the distributions of displacement, velocity and acceleration are settled as $\{d_f\}$, $\{\dot{d}_f\}$ and $\{\ddot{d}_f\}$ respectively. Equivalent soil-pile-structure includes the equivalent soil, piles and upper structure. Assuming that the vibration is the same as that in the soil around the piles and piles in earthquake, and there exist shearing and damping effect among soil layers, the upper structure and piles are simplified to the concentration mass system.

The bending and shear deformation are taken into account. The response of free fields is through equivalent spring and damper system acting on equivalent systems, which can simulate the energy dissipation of dynamic interaction. The upper structure will be dispersed as *n* particles string and *m* particles in the lower part. The division of piles discretion is the same as that of soil layers and the spring effect reflecting soil horizontal stiffness is on the junction of the soil surface. Φ^S, Υ^S and Ψ^S are the quality, stiffness and damping matrixes of superstructure respectively. Successively, Φ^p, Υ^p, Ψ^p and Φ^e, Υ^e, Ψ^e are the matrixes of piles and equivalent soil, where superscript *p* and *e* represents pile and equivalent soil respectively. Using free fields input, the equation of equivalent soil (XIAO2003) can be written as follow.

$$[\Phi]\{\ddot{d}\}+[\Psi]\{\dot{d}\}+[\Upsilon]\{u\}=[\Phi']\{\ddot{d}'_f\}+[\Psi']\{\dot{d}'_f\}+[\Upsilon']\{d'_f\} \tag{2.1}$$

Where, $[\Phi]$, $[\Upsilon]$ and $[\Psi]$ are the mass, stiffness and damping matrix respectively.

2.2 Parameters of Dynamic Interaction

In equation (2.1), Φ^S, Φ^p, Υ^S and Υ^p can be obtained by conventional methods, but Υ^p of pile group is that the sum of single pile stiffness is divided by $\sqrt{N}$, where *N* is the number of piles. Ψ^S and Ψ^p are calculated in the light of Rayleigh damping (XIAO2003).

$$\Psi^S=\alpha\Phi^S+\beta\Upsilon^S,\Psi^p=\alpha\Phi^p+\beta\Upsilon^p \tag{2.2}$$

In equation (2.2), $\alpha=\xi\omega_1, \beta=\xi/\omega_1$, where ξ is damping ratio of material, ω_1 the basic structure frequency. Therefore, the key is how to solve the dynamic interaction parameters, Φ^e, Υ^e and Ψ^e. The calculation of Φ^p, Υ^p, Ψ^p, Φ^e, Υ^e and Ψ^e is referred.

2.3 Comparative Analysis of Different Models

Pile group model can also be simplified to apply in the degradation of single pile. Compared with the latter, the former considers the impact of soil around the pile and the interaction of parameters is set in different ways. The top time history of displacement, the base time history of shear force and moment should be compared with different models. Comparative analysis shows that whether the characteristic nodes or the time curve of cross-section are maximal or not, the results of two models are well agreed. The soil around pile group model is considered, which equivalently increases the pile stiffness and results in slightly shortening the basic cycle, decreasing the structure top displacement and increasing the bottom moment and shear force. It also shows that no consideration of the soil around the pile is feasible in the simplified single pile model. Although the simplified pile group model can be used to analyze the single pile, the single model should be reliable when the test data are plentiful.

3 FEM OF DYNAMIC SOIL-PILE-STRUCTURE INTERACTION

Theoretically, FEM considers the nonlinearity, time effect of soil consolidation, dynamic effect and the restrictive conditions of special pile boundary. Compatible elements through the same way are used to represent piles and soil, which can additionally better describe the stress wave propagation in the soil and provide flexibility for dealing with changes of soil characteristics and seismic movement in the space. FEM takes into account the actual three-dimensional effects and calculate the stress and deformation in different parts of the pile.

3.1 Models and Equations

The horizontal force is strong of pile in seismic action and horizontal bending is the main feature of pile deformation. In FEM model, the pile will be dispersed as hexahedron elements and the soil as ordinary three-dimensional elements with equivalent parameters. Both of the elements are integrated in the light of eight (2×2×2) Gauss integral points. The model was constrained nodes at the bottom while the viscous boundary is used on the surrounding. To facilitate the grid of circular cross-section will be equivalent to the square with the same area. Since strong plasticity is shown in the earthquake, it is necessary to analyze the dynamic elasto-plasticity. Using the implicit time integration, the balance of system in time step is considered. Te incremental format (XIAO2003) in dynamic equation is used.

$$\Phi^{t+\Delta t}\ddot{D}^{(i)} + {}^{t}\Psi^{t+\Delta t}\dot{D}^{(i)} + {}^{t}\Upsilon\Delta D^{(i)} = {}^{t+\Delta t}\Lambda - {}^{t+\Delta t}\Omega^{(i-1)} \tag{3.1}$$

Where Φ, ${}^{t}\Psi$ and ${}^{t}K$ are the mass matrix, damping matrix at time t and stiffness matrix respectively. $\ddot{D}$, $\dot{D}$ and D are the acceleration vector, velocity vector and displacement vector respectively. The left superscript means the time step, the right upper superscript the iterative step. ${}^{t+\Delta t}\Lambda$, the nodal load vector with external action, includes the dynamic loads such as the volume force, the surface force and the inertia earthquake force. ${}^{t+\Delta t}\Omega^{(i-1)}$, after *i-1th* iteration at time $t+\Delta t$, is the nodal load vector which is equivalent to the stress state of system element.

3.2 Boundary Conditions and Interface of Pile-soil

Using FEM to analyze the dynamic interaction of structure-foundation, because of the calculate conditions, the finite media region is cut from the semi-infinite simulating region. To the seismic action, the power action is necessary to be simulated to spread along the distance. The boundary conditions of pile-soil interaction are in the scope of far-field study, in which the physical elements' characteristics will be described on the basis of complex stiffness.

Because the stiffness of pile-soil support system is decided by the sub-layer interaction of piles and piles and soil, so dynamic features of the contact surface of soil-structure being reasonably simulated directly influences the accuracy and reasonableness of dynamic interaction analysis. In this paper, dynamic contact element is used.

3.3 Incompatible Element in FEM of Pile-soil Interaction

In earthquake, the pile foundation will be loaded by greater horizontal shearing and lateral bending is the main feature of pile deformation. In order to better simulate the deformation, incompatible H_{11} element is used, which is divided as hexahedron element with eight nodes adding three non-nodal internal DOF. The displacement interpolation function (XIAO2003) can be written as follow.

$$\begin{Bmatrix} d \\ v \\ w \end{Bmatrix} = d_q + d_\lambda = \sum_{i=1}^{8} N_i(\xi,\eta,\varsigma) \begin{Bmatrix} d_i \\ v_i \\ w_i \end{Bmatrix} + \sum_{i=1}^{3} P_i(\xi,\eta,\varsigma) \begin{Bmatrix} \alpha_i \\ \beta_i \\ \gamma_i \end{Bmatrix} \tag{3.2}$$

Where $N_i = \frac{1}{8}(1+\xi\xi_i)(1+\eta\eta_i)(1+\varsigma\varsigma_i)$, $P_1 = 1-\xi^2, P_2 = 1-\eta^2, P_3 = 1-\varsigma^2$, $i = 1,2,\cdots,8$, $\xi_i,\eta_i,\varsigma_i = \pm 1$. d_q and d_λ are the compatible and incompatible displacement respectively. In order to make elements well tested to ensure convergence, the equivalent conditions are

$$\int_{V^e} \begin{Bmatrix} P_{i,x} \\ P_{i,y} \\ P_{i,z} \end{Bmatrix} dV = \int_{-1}^{1}\int_{-1}^{1}\int_{-1}^{1} \left[J^* \right] \begin{Bmatrix} P_{i,\xi} \\ P_{i,\eta} \\ P_{i,\varsigma} \end{Bmatrix} d\xi d\eta d\varsigma = 0 \tag{3.3}$$

Where J^* is the Jacobian.

4 PILE GROUP ANALYSES

In the pile foundation, the pile group is commonly used. The working conditions of pile group foundation under horizontal loading are different from that of single pile. While the pile space in pile group is less than the critical pile space, the pile-group-effect is appeared through the soil interaction among piles, which is more complicated under dynamic loading. The effect is mainly related to the pile space, modulus of pile and soil, constraints of pile top, activating frequency by external loading shown in fig.1. S and D are the centerline space of adjacent piles and pile diameter respectively. The load distribution on each pile is decided by pile space and its position in pile group.

Calculation conditions are as follows. Piles are designed as 4×4 and the pile is 20 meters long. The sizes of cap are 16×16×1m. The cap is contacted with the ground and the soil is considered as the linear elasticity and Elasto-plasticity. The horizontal acceleration of ground motion is 0.2g. The time history of acceleration and horizontal displacement at cap top are shown in fig.2. The pink line represents the elasticity and the deep blue line the elasto-plasticity.

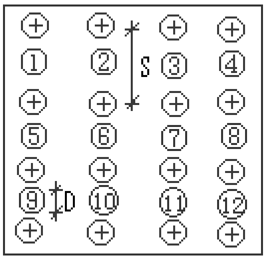

Fig.1 Placing of pile group

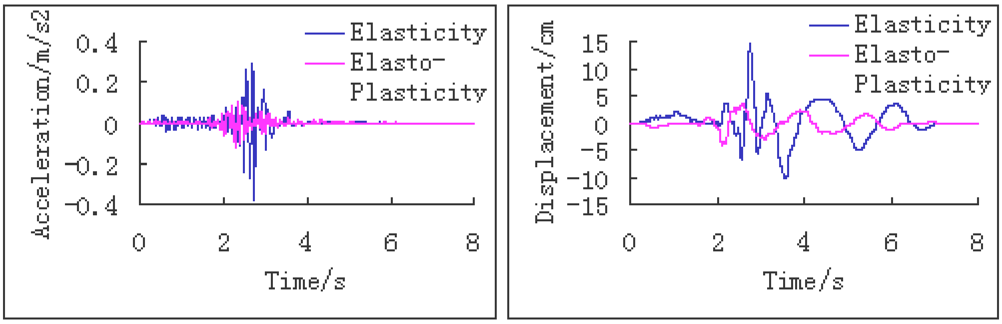

Fig.2 Displacement and acceleration time history at pile cap top under elasticity and elasto-plasticity

Amplification coefficient of horizontal peak acceleration and displacement in different pile locations are shown in fig.3. The bold line means the elasticity and the thin one the elasto-plasticity. AAC means the acceleration amplification coefficient and RHD the related horizontal displacement.

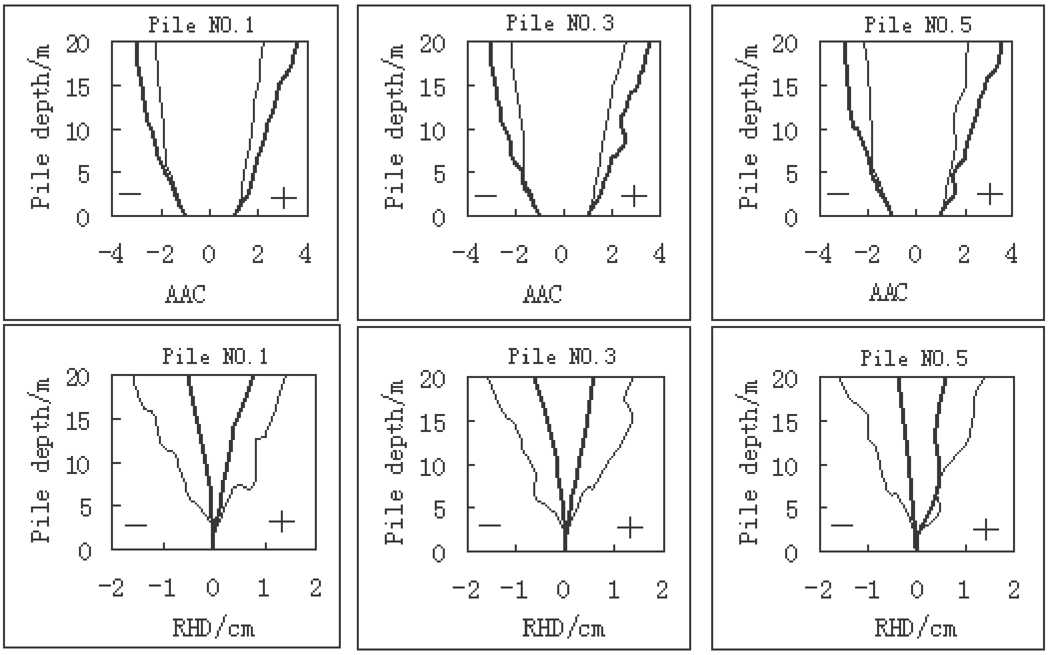

Fig.3 RHD and AAC under elastic and elastic-plastic soil conditions

Calculated by the soil plasticity, the acceleration frequency and displacement time history at cap top are decreased significantly, so is the peak acceleration but the peak displacement is increased. Along pile depth, the amplification coefficient of peak acceleration is well-distributed. Horizontal displacement distribution is significantly decreased. The moment at pile top is reduced about 12 percent and its distribution in different piles in pile group is the same as that of static conditions. Soil characteristics have greater impact on the seismic response of pile group foundation.

4.1 Impact of Constraint Conditions at Pile Cap

The calculation conditions are the same as mentioned above. The time history of acceleration and horizontal displacement at cap top are shown in fig.4. PTC means the pile top constraint and PTF the pile top free.

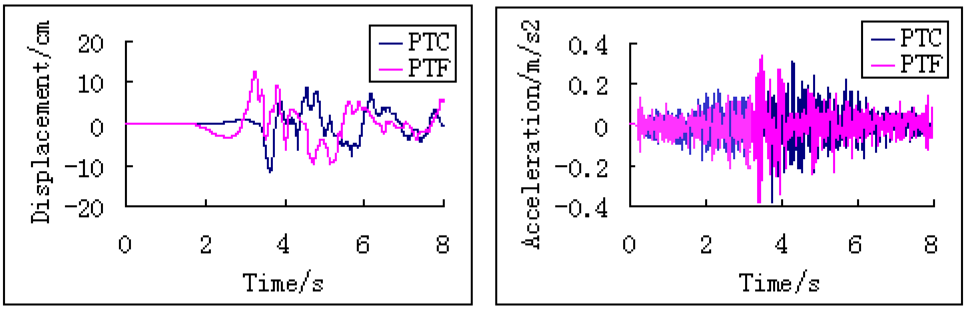

Fig.4 Horizontal acceleration and displacement time history under different constraints

Amplification coefficient of horizontal peak acceleration and displacement in different pile locations are shown in fig.5.

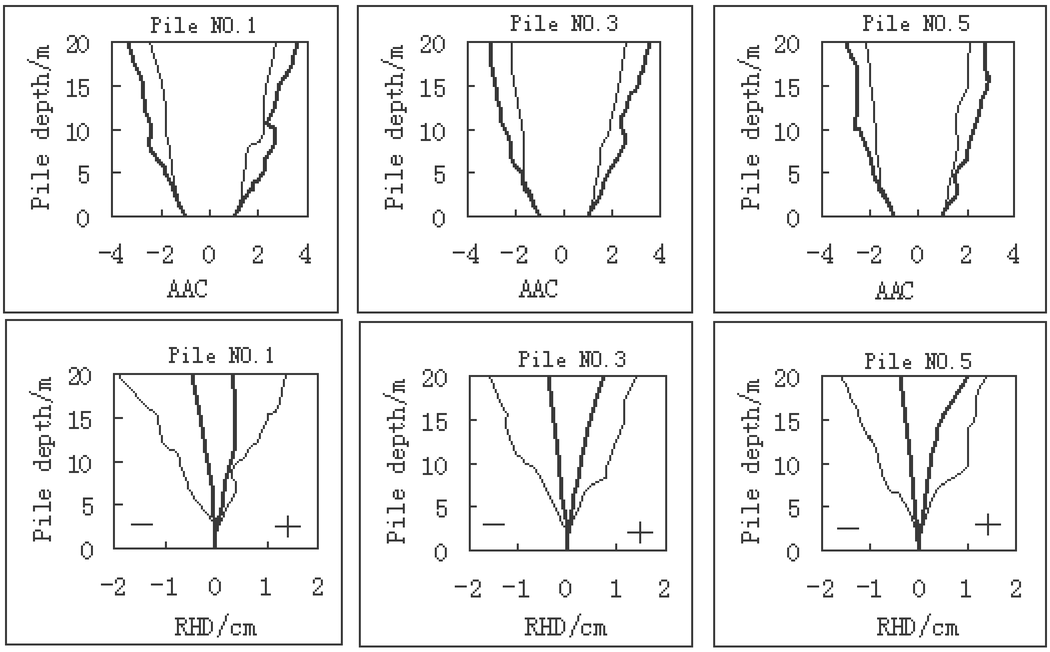

Fig.5 Acceleration amplification coefficients and peak displacements under different constraints

The results show that the acceleration and the displacement time history curves by the constraints at pile top are basically the same but the peak values are slightly reduced. The distribution of peak acceleration and displacement along pile depth is basically identical. The pile constraint conditions at pile top have a certain impact on moment which is, sometimes, slightly increased.

4.2 Impact of Pile Space

The conditions is the same as mentioned above, the pile space in pile group is considered while S/D=4, 6 and 8 respectively. Time history curve of acceleration and displacement is shown in fig.6 in different S/D ratios. Changes pile space has significant impact on the acceleration and displacement time history at cap top. The high-frequency situation in S/D=4 is obviously more than the other two, but the time history is lagged while S/D=6 and 8. The time history curves are similar within two seconds and then there is significant difference.

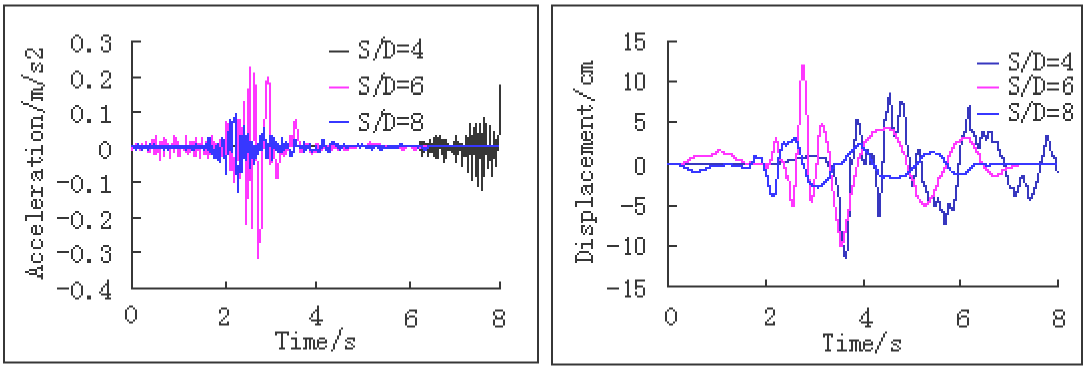

Fig.6 Acceleration and displacement time history at pile cap top under different S/D and pile space

Amplification coefficient of horizontal peak acceleration and displacement in central pile locations are shown in fig.7. Comparing three situations of pile foundation, the basic cycle are 0.4, 0.42 and 0.417 seconds respectively. The extending illustrates that different values of S/D will change the foundation stiffness, which affects the seismic response of foundation.

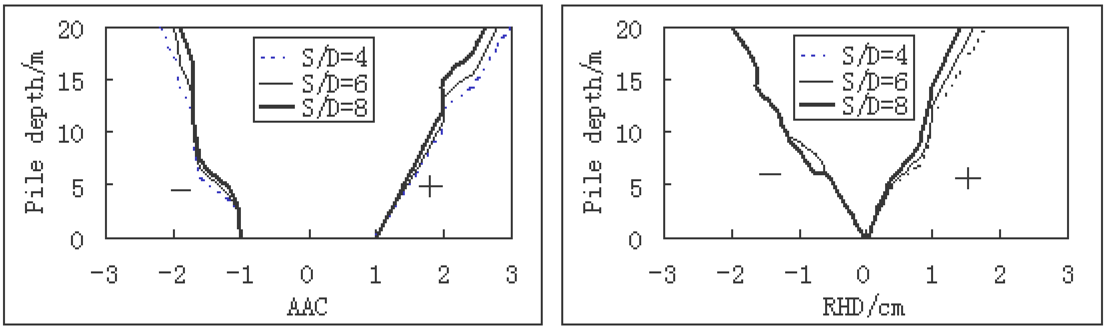

Fig.7 Acceleration amplification coefficients and peak displacements distribution under different S/D

5 CONCLUSIONS

Combining with non-linear finite element analysis, the pile group foundation is comprehensively analyzed under seismic action. The results show that soil characteristics of pile group have greater impact on the seismic response of structure. As to plastic soil, the amplification coefficient of acceleration is decreased and tends to be well-distributed along pile depth. The displacement of structure is slightly increased and the internal forces at pile cap are reduced. Thus, the soil plasticity is considered to be necessary in analyzing seismic response of soil-structure.

In the dynamic response of actual earthquake, the deformation is controlled by vertical vibration and the internal forces by the horizontal vibration. The free length in horizontal or vertical vibration will greatly influence the seismic response. With the increasing of free length, the system stiffness is reduced. With the extension of intrinsic cycle, the acceleration is decreased, the displacement increased and the internal system forces reduced. Therefore, these effects should be considered comprehensively and the free length chosen reasonably during optimal design.

The constraints at pile top have little impact on the distribution of acceleration and displacement and a slight change in the internal forces. As to pile group, while the number of pile and its layout scheme are settled, S/D is an important indicator whose change has certain impact on the acceleration and time-frequency characteristics of the displacement at pile top. With the increasing of S/D, the internal forces are slightly reduced.

Through comparison of the finite element model and simplified model, while the acceleration is 0.lg, the calculation results by two models are well coincided with each other. Because the elastic-plasticity of soil is considered, the finite element model can better simulate actual conditions in strong earthquake and the simplified models are more simple and practical in weak ground motion.

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