



IMPROVEMENT OF PUSHOVER ANALYSIS TAKING ACCOUNT OF PIER-PILE-SOIL INTERACTION

Limin SUN¹ and Chennan ZHANG²

SUMMARY

The pushover analysis is becoming popular as a simple method for seismic performance evaluation of structures. This paper presented a pushover analysis model, which can take account of soil-pile-structure interaction. As load pattern for pushover analysis, monotonic increasing inertial forces was applied to a superstructure and shear deformation was applied to soil respectively. A bridge pier-pile-soil system was analyzed by using the presented model, and the results were compared with those of nonlinear dynamic time history analysis, it was showed that the improved pushover method and its parameters determination were proper for providing a reasonable estimate of the structural maximum response. In order to embody the nonlinearity of soil, nonlinear soil springs contacting piles and soil should be adopted in the model instead of equivalent linear ones. A static experiment of multi-pile foundation in a shear deformation soil box was carried out to study the effect of soil movement on a multi-pile foundation, the relationship of soil-pile interaction force and relative deformation, and the determination method of the nonlinear interaction spring.

Keywords: pushover analysis, pier-pile-soil interaction, bridge, experiment

INTRODUCTION

Piles foundations, which are appropriate for various kinds of geologic conditions, are mostly applied for various bridge structures. According to the reports of the seismic disasters, the destruction of bridge structures that are supported by piles foundations shows that piles are one of the most vulnerable components. The study of pile-soil interaction is a hot research topic in the field of earthquake engineering and geotechnical engineering, and there are many seismic analyses have been performed. The main

¹ Professor, State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China. Email: lmsun@pop07.odn.ne.jp

² Engineer, Lin Tung-Yen & Li Guo-Hao Consultants Shanghai Ltd., Shanghai, China. Email: chennanzhang@hotmail.com

purpose of these seismic analyses is to study where the destruction locates, and how the status and degree of the destruction is. Pushover analysis, as a simplified computer method for seismic performance evaluation of structures, is becoming popular and is widely applied in the seismic analysis. It can estimate the structure behavior under the seismic load, confirm the weakness location of the structures, and describe the destruction status exactly. And because of its simplicity of operation, many scholars began to study the theory and the method of the pushover analysis taking account of the pier-pile-soil interactions.

Lumped mass model is often adopted in the seismic response analysis of bridge pier-pile-soil system. A well-known lumped mass model for describing pile-soil interaction is Penzien model [1]. Authors have proposed a modified Penzien model [2]. In this study, based on the modified Penzien model, authors presented an improved pushover analysis method, which can take account of soil-pile-structure interaction.

PUSHOVER ANALYSIS MODEL FOR PILE-PIER SYSTEM

As shown in Fig 1, a lumped mass model based on the modified Penzien model is used for modeling a bridge pier-pile-soil system. It is assumed that the additional mass of in the original Penzien model can be regard as the real mass of soil around piles, and in addition, the free field is also included in the calculation model. And it is also assumed that all the piles have the same horizontal deformation and the top of each pile is rigidly fixed in the footing and the pile tip is fixed on bedrock with a hinge. Piles were connected to the site with horizontal pile-soil springs, whose stiffness value can be determined by Mindlin equation:

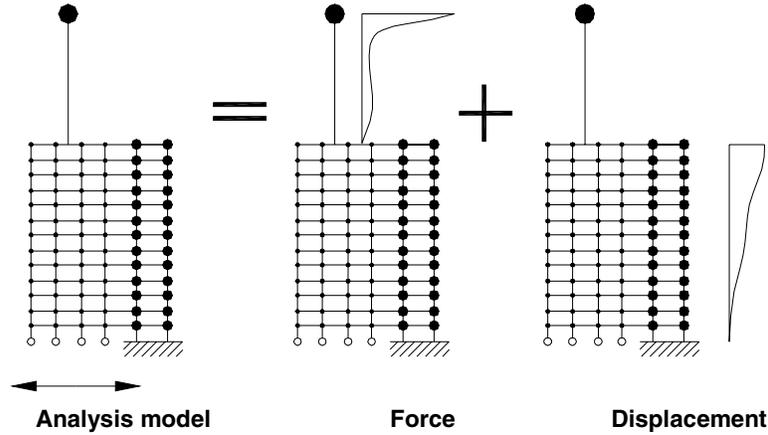


Fig.1 Analysis model and load pattern

$$K_{Hi} = \frac{8\pi E_i}{3} \left\{ \sinh^{-1} \frac{h_i - z_i}{B} + \sinh^{-1} \frac{h_i + z_i}{B} + \frac{2}{3B^2} \left[\frac{B^2 h_i - 2B^2 z_i + h_i z_i^2 + z_i^3}{[B^2 + (h_i + z_i)^2]^{1/2}} - \frac{z_i^3 - 2B^2 z_i}{(B^2 + z_i^2)^{1/2}} \right] \right. \\ \left. - \frac{2}{3} \left[\frac{z_i - h_i}{[B^2 + (h_i - z_i)^2]^{1/2}} - \frac{z_i}{(B^2 + z_i^2)^{1/2}} \right] + \frac{4}{3} \left[\frac{B^2 z_i + h_i z_i^2 + z_i^3}{[B^2 + (h_i + z_i)^2]^{3/2}} - \frac{B^2 z_i + z_i^3}{(B^2 + z_i^2)^{3/2}} \right] \right\}^{-1} \quad (1)$$

where, K_{Hi} -- stiffness of the spring between piles and the i th soil layer.

E_i -- Elastic module of the i th soil layer.

h_i -- the thickness of the i th soil layer.

z_i -- center depth of the i th soil layer.
 B -- radius of the pile.

Although pushover analysis is a procedure of static analysis, the additional mass and the mass of free field can not be ignored, because the deformation of the soil, i.e., the load pattern, lies on how the modes are. According to reference [3], the mass of free field can be regarded as 200 times the additional mass. While the coefficients of the pile-soil interaction springs do not need to be taken into account.

The effect of the earthquake on the piles foundation can be regard as the combination of horizontal inertial force and the movement of the soil layers. The load patterns of monotonic load can be composed of lateral horizontal force applied to the superstructures and the horizontal displacement to the free field (shown in Fig1.).

The horizontal force applied to the superstructures can be calculate as:

$$F_i = \frac{m_i \phi_{1i}}{\sum_{j=1}^n m_j \phi_{1j}} V_b \quad (2)$$

where, F_i -- horizontal force applied to the i th node.

m_i, m_j -- mass of the i th, j th node.

ϕ_{1i}, ϕ_{1j} -- amplitude of first mode at the i th, j th node.

n -- total number of the node on the structure beyond the ground, ,

V_b --total horizontal force applied to the structures, the value of V_b is the product of the total mass and the response spectrum of pseudo acceleration.

The displacement applied to the each layer of soil can be analyzed by SHAKE [4] program, which is usually used for analyzing the response of layered soil. The program can get the absolute displacement of each layer. The deformation can be transferred to the relative displacement to the bedrock, and then be applied to the free field, which was connected to the pile with the horizontal soil-pile interaction springs.

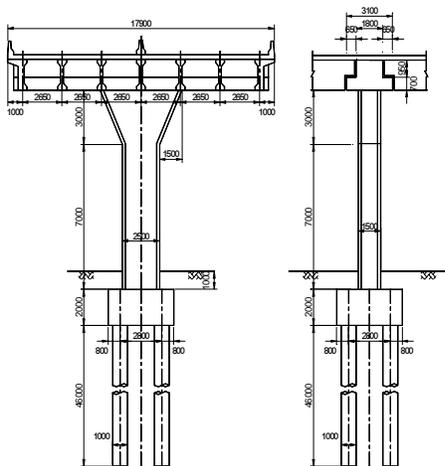


Fig.2 Single column pier

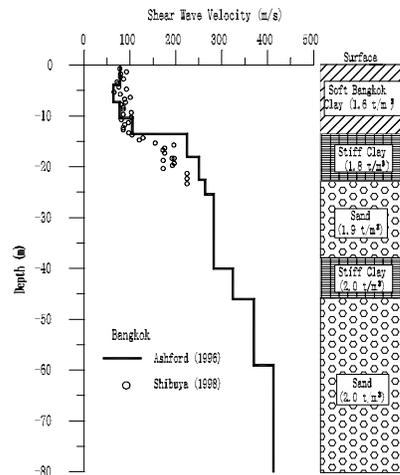


Fig.3 Soil profile

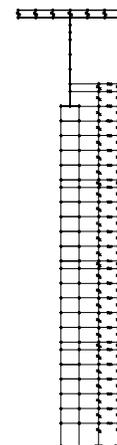


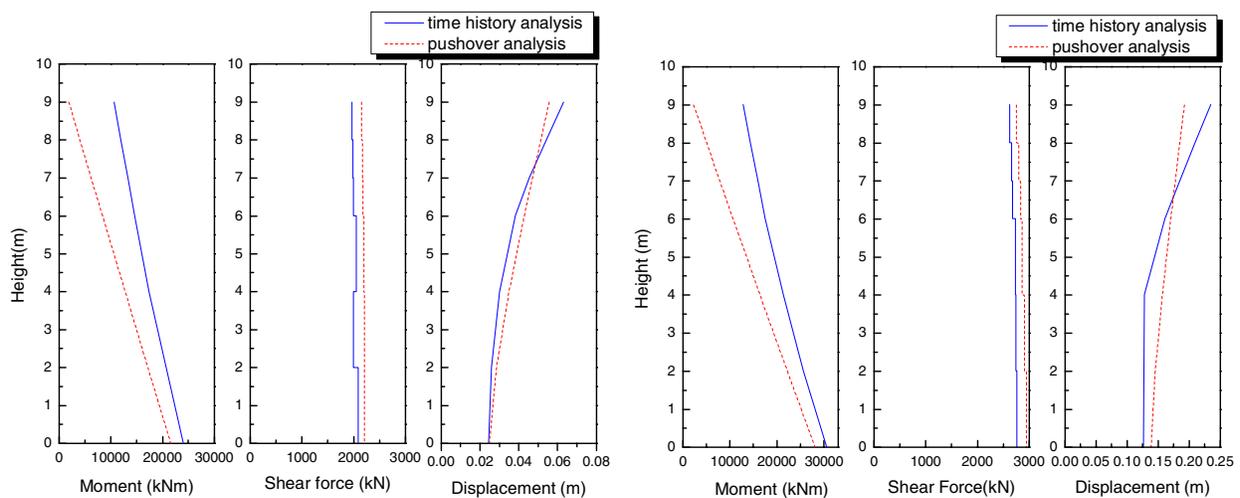
Fig.4 analysis model

A bridge single column pier was analyzed by pushover analysis. The bridge system under studied is a typical reinforced viaduct with a single column pier and pile foundation as shown in Fig.2. The bridge pier is about 11m in height and has a rectangular cross section of 1.5m×2.5m. The foundation consists of 4

piles, which are 46m in length. A generalized soil profile, shown in Fig.3, which was predicted from geotechnical investigation, is adopted for the bridges. The analysis is in transversal direction of bridge.

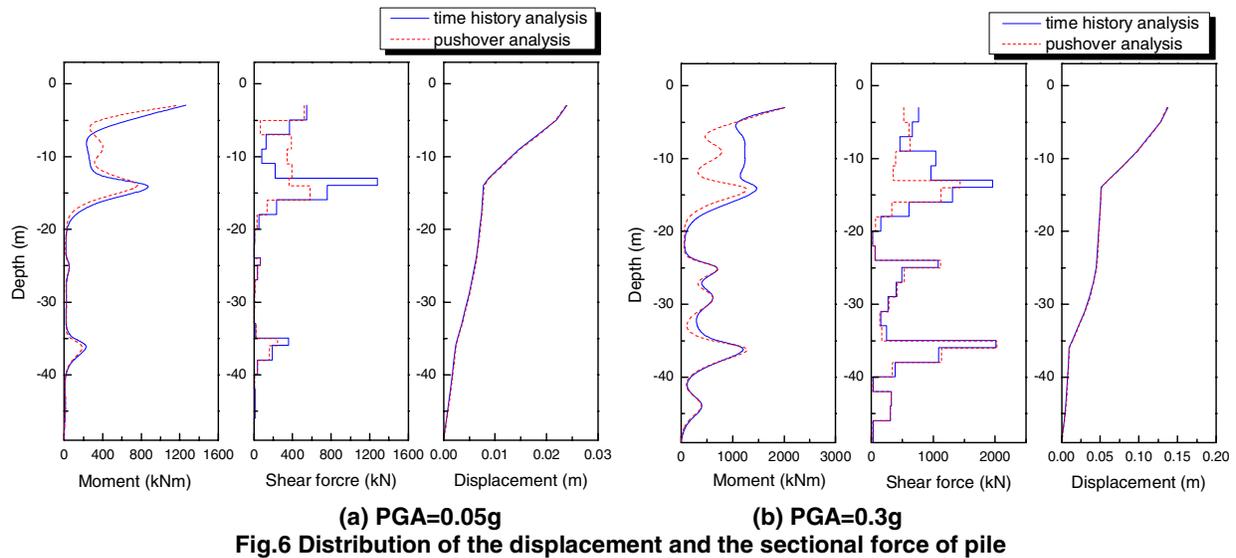
In order to certify the validity of pushover analysis, a time history analysis is also carried out to compare the results with that got from pushover analysis. In the study, Elcentro NS (1940) waves scaled with PGA=0.05g and PGA=0.3g (refer to Case 0.05g and Case 0.3g) are used as the input wave at bedrock in transversal direction of the viaduct.

Fig.5 shows the distribution of the maximum displacement and the maximum internal forces, i.e., the sectional moments and the sectional shear forces, of pier and piles analyzed by pushover analysis. The curves denoting the result from time history analysis are also plotted in Fig.5. Compared the results, the distribution of the sectional shear forces got from two various analysis method accord with each other, while there is some difference in the displacement of the pier and the sectional moment, the result got from time history analysis are a little greater than that from pushover analysis. In this model, the beam over the pier has a long cantilever in later direction, and the beam possesses great moment of inertia. Under the seismic load, if the beam vibrates in a rotation form, there will be great moment at the top of the pier, while in pushover analysis, only lateral forces are applied to the structure, and the moment at the pier top is zero. This is where the difference lies in. Whether the beam's rotation has a great effect on the pier or not, about which researchers has various viewpoints, is not the main topic in this paper, and since the distributions of the inertial force and displacement are relative similar, a conclusion can be drawn that the pushover analysis can provide a reasonable estimate of the response of the pier.

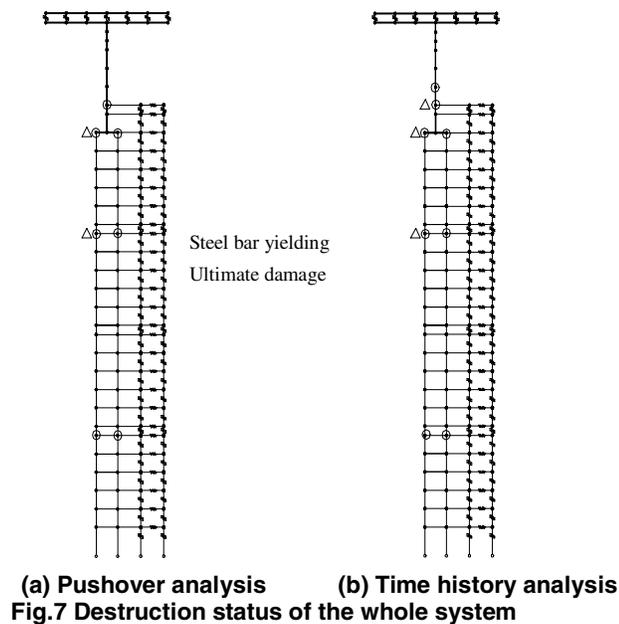


(a) PGA=0.05g (b) PGA=0.3g
Fig.5 Distribution of the displacement and the sectional force of pier

The distribution of the maximum displacement and the maximum internal forces of pile foundation are shown in Fig.6. The curves show that the results of horizontal displacement of the pile from pushover analysis are coincident with that from time history analysis. While for internal forces, there is something different at the range of 0~14m, which is composed with soft clay. The results from pushover analysis is a little less, and the distribution is relative similar. Because of the great difference of soil properties between the first two layers, there is large deformation at the boundary of the first layer and the second layer, and the sectional moments and sectional shear forces changed a lot. A pile may be damaged at such locations.



In this analysis, for case 0.05g, the behavior of whole system is in elastic. Neither the pier nor the pile is there any damage. For case 0.3g, the behavior of the system is get into plastic stage. Plastic hinge formed and the reinforcement steel bar began to yield. The destruction status of the pier and the piles are shown in Fig.7. At the bottom of the pier, the result from the pushover analysis shows that the steel bar begin to yield, while in time history analysis, the result shows that the pier come to its capacity limit at the bottom of the pier, and at the section beyond the bottom, the steel bar in the pier begin to yield. This is because of the difference between the analysis results of pier sectional internal force from two analysis methods. For piles, the results of damage information are coincident with each other. Steel bars yields at the pile top and the boundary of the stiff soil layer and soft soil layer.



According to the analysis, a conclusion can be drawn that the presented pushover analysis is proper for providing a reasonable estimate of the structural maximum response and the status of destruction.

In this analysis, nonlinearity of soil is evaluated with an equivalent linear method, and the precision can meet the engineering expectation. While, for various degree of the earthquake stimulation, the shear module of the soil will vary as well as the stiffness of the interaction spring, and the analysis models must be set up individually. That will greatly increase the work of the analysis, and it will make against the generalization of the pushover analysis. Some discussions were performed in order to overcome this disadvantage,

Fig. 8 shows the pushover curves of the two cases. Although the frequency of the first mode varied, the vector of mode shape did not change a lot. And there is no great difference between the applied lateral forces vectors of two cases. Two pushover curves almost superposed. The capacity of the system can be expressed by the pier's pushover curves. The only difference of two cases is the stiffness of the interaction spring. If a nonlinear interaction spring were applied, the disadvantage will be overcome.

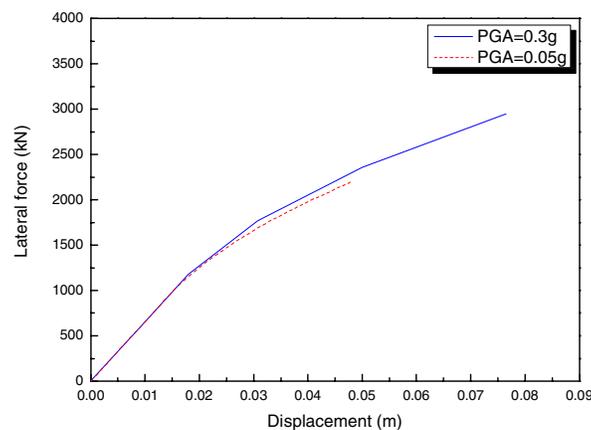


Fig.8 Pushover curves of the two cases

STATIC EXPERIMENT OF MULTI-PILE FOUNDATION IN SHEAR DEFORMATION SOIL BOX

In order to study the effect of soil movement on the multi-pile foundation, the relationship of soil-pile interaction force and relative deformation, and the determination method of the nonlinear interaction spring, a static experiment of multi-pile foundation in a shear deformation soil box was carried out. The experiment equipment—shear deformation soil box, which was designed for shaking table experiment [5], is shown in Fig.9. In this study, it is used for pseudo static experiment. The soil box can simulate the shear deformation of soil boundary in one direction. In order to simplify the experiment, a 2×2 piles foundation is adopted as the studied object. Four piles, each 80 centimeters in diameter, were fixed under a pier footing. In order to simplify the experiment, no piers and superstructures were included in the model, and only sands are adopted for the site soil.

The experiment is composed with two tests. In Test I, the main effect of the soil deformation on the piles foundation was studied. The equipments and the sensors for measurement are shown in Fig.10. A trigonometry form of the soil displacement was assumed to simulate the movement of the site. The soil box was stimulated by a cyclic force at the end side with a height of 1.6m, and the load rule was increasing amplitude and displacement loading (shown in Fig.11). According to the preliminary analysis, 5mm was adopted as the control value of the displacement where the force applied, and 1, 2, 4, 6, 8 times the control value was used as maximum displacement of the each level of the load. The load will repeat three times at each level. For the last load level, the box was pushed in one direction till the displacement where the force applied to reach 70mm. In order to avoid violent variation of the velocity, each level of the

load was applied in a form of sinusoidal wave. One period of the loading is 200 sec, which is far from the period of the system, and the whole procedure could be regarded as a static one.



Fig.9 Shear deformation soil box

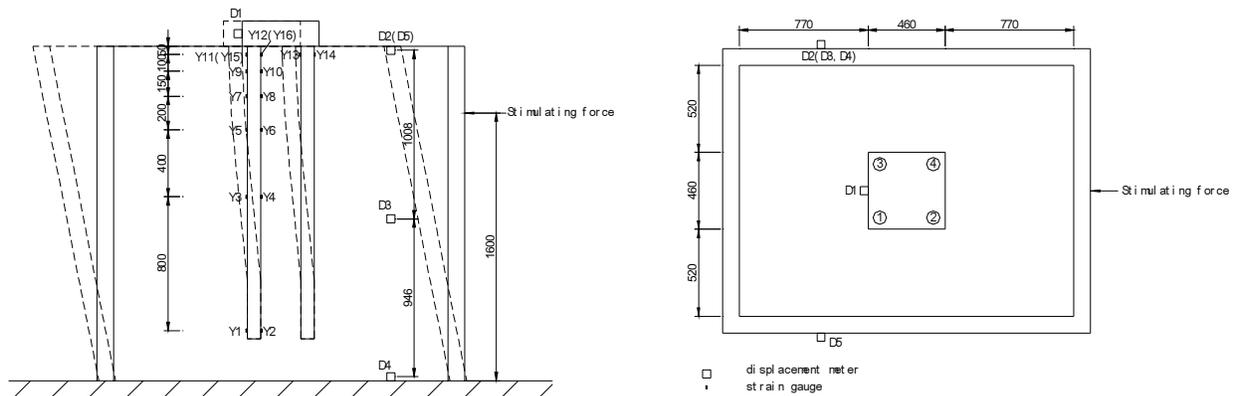


Fig.10 Experiment set-up (Test I: pushing soil box)

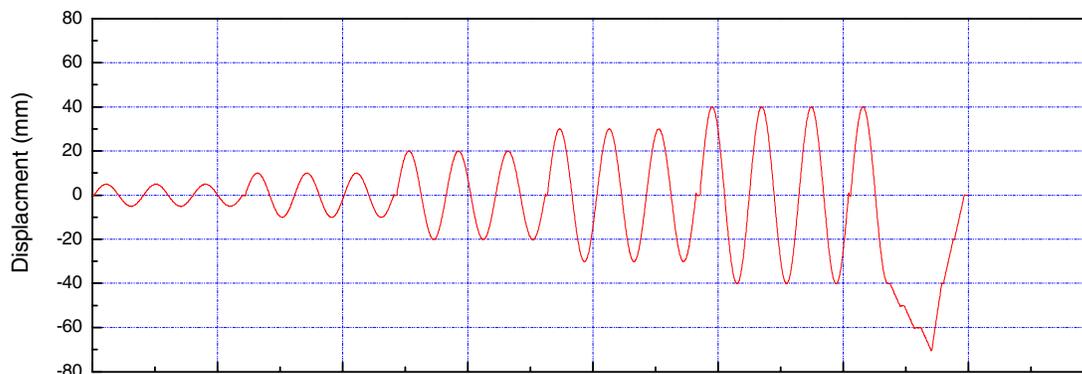


Fig.11 Loading rule

Fig.12 shows the load-horizontal displacement relation of the soil box at the location of stimulation. The shape of the hysteresis curves was like a shuttle, and the characteristic of nonlinearity of the soil is obvious. Because the stimulation is a long period sinusoidal wave, the displacement and the applied force reach the maximum contemporarily, and the viscous hysteresis character was not represented.

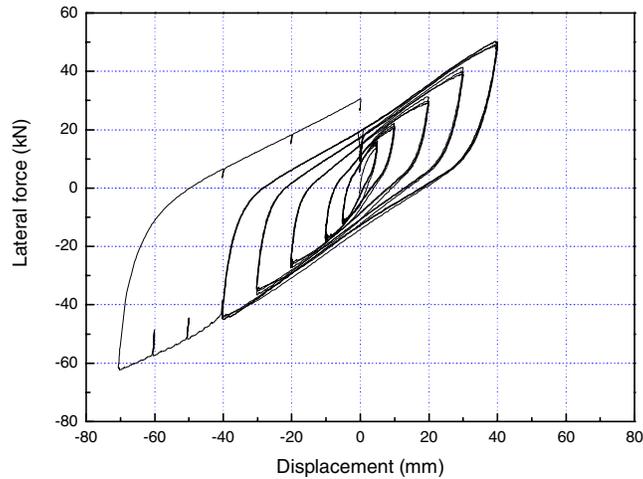


Fig.12 Hysteresis character of the soil

In Test II, the main effect of the inertial force of superstructures on the piles foundation was studied. The equipments and the sensors for measurement are similar to that of Test one (shown in Fig.13). The piles foundation was stimulated by a cyclic force applied to the footing, and the soil box was fixed by assistant structures. Since the size of the model was not large enough, a jack was used as the loading equipment. The load was controlled by the displacement of the footing. At each load level, when the displacement reached the control value, the force was unload to zero and the load would not be repeated because of the difficulty of loading equipment. 1mm was adopted as the control value of the first level, and 2mm was adopted as the increment to each level. When the displacement of the footing reached 35mm, the force was increased till the structure was destroyed.

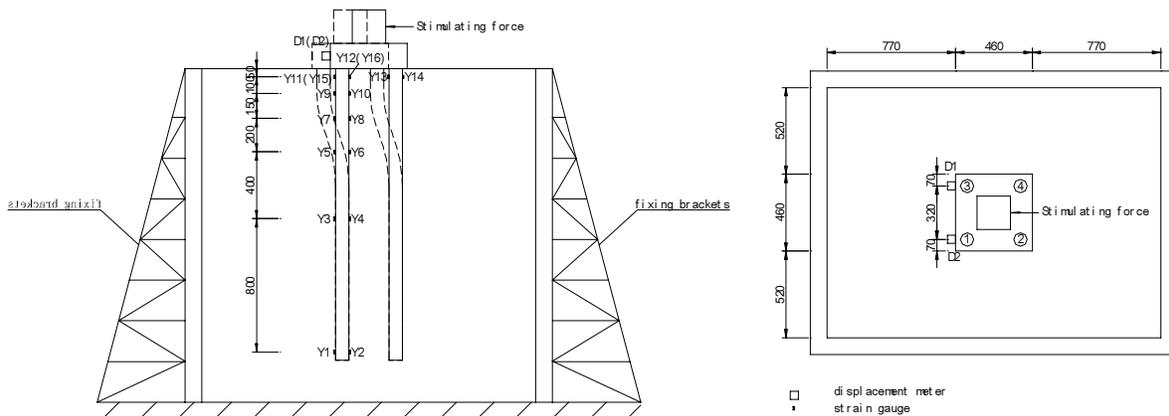


Fig.13 Experiment set-up (Test II: pushing foundation)

Theoretic analysis

Theoretic analysis was carried out to study the relationship of soil-pile interaction force and relative deformation, and the determination method of the nonlinear interaction spring. Fig.14 shows the analysis model. Since the displacement form has been confirmed, the additional mass and the mass of free field were ignored to simplify the calculation. The $G/G_0 \sim \gamma$ and $\beta \sim \gamma$ curves of the sands are plotted in Fig.15.

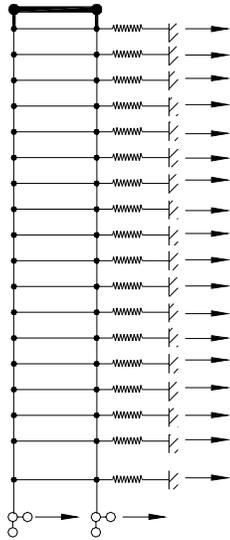


Fig.14 Analysis model for Test I

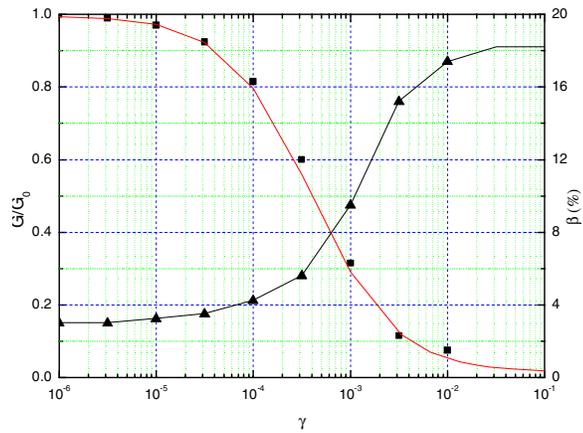


Fig.15 G/G_0 - γ β - γ curves of the sands

The theoretic analysis of sectional moment distribution of the pile was compared with that got from experiment as shown in Fig.16. For the first three cases, in which the loading amplitude was relative small, the theoretic analysis fit the experiment very well. Except for the top of the pile, the measurements of the moments are coincident with the analysis result at the depth of 0.15m. As the load increasing, the difference between the measurement and the analysis increased respectively. The results of pushover analysis were a little less at the depth below -0.5m (6 times the radius of the pile) than that from the experiment, while greater at the depth beyond -0.5m. Although there is difference between the theoretic analysis and the experiment, the distributions are almost the same. If the shear moduli of the soil could be chose reasonably, the analysis method is proper to estimate the effect of soil movement on the piles foundation.

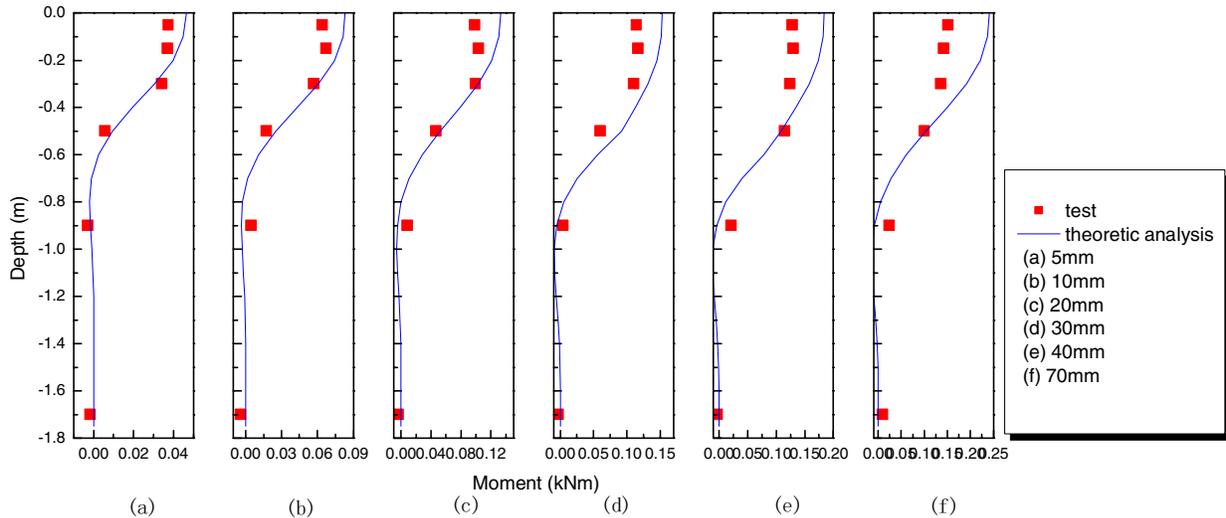


Fig.16 Sectional moment distribution of the pile

The force-displacement relation between the soil and piles at the depths from 0 to 0.3m were shown in Fig.17. For all the load case, the maximum relative displacement of the pile to the soil locates at the surface of the soil, and the curves could be described as bilinear ones. As the depth increased, the degree of the nonlinearity decreased and the curves inclined to linear ones. According to the experiment, the

secant of the curves get from the test regarded as the initial stiffness, the relative horizontal displacement between the soil and pile at the first load level regarded as the yielding displacement, and 20% taken as the post-yielding stiffness factor, the soil-pile interaction springs could be described as bilinear ones, the model of interaction springs would be adopted for the next analysis.

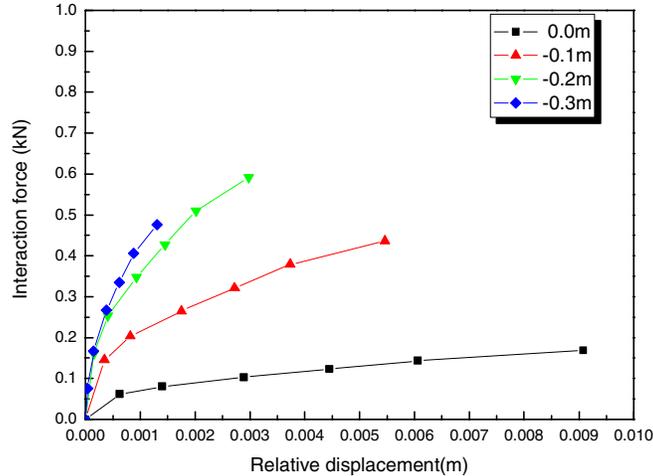


Fig.17 The force-displacement relation between the soil and piles at various depths

The presented model of bilinear soil-pile interaction spring was applied in the theoretic analysis of Test II. The curves of force applied at the footing versus the displacement of the footing are plotted in Fig.18. The softening of the soil, the cracking of the piles and the yielding of the steel bar in the piles could be expressed on the line. Compared to that got from experiment, the curves meet the envelope line of the loading history very well, that indicates the bilinear spring model is proper for estimating the nonlinearity of the soil.

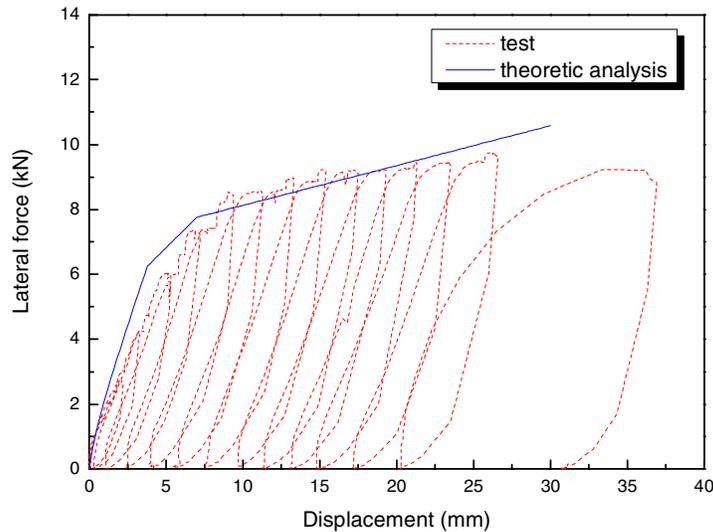


Fig.18 Relationship of force—displacement of the footing

According to the theoretic analysis, the failure mode of the piles is shown in Fig.19. The analysis indicates that the plastic hinge will form at the top of the piles and at the depth of 0.5m (about 6 times the radius of the pile), and the concrete of the pile will crack at the range of 0~-0.5m. Compared to the model of experiment, the results of the analysis were basically coincident with that of experiment.

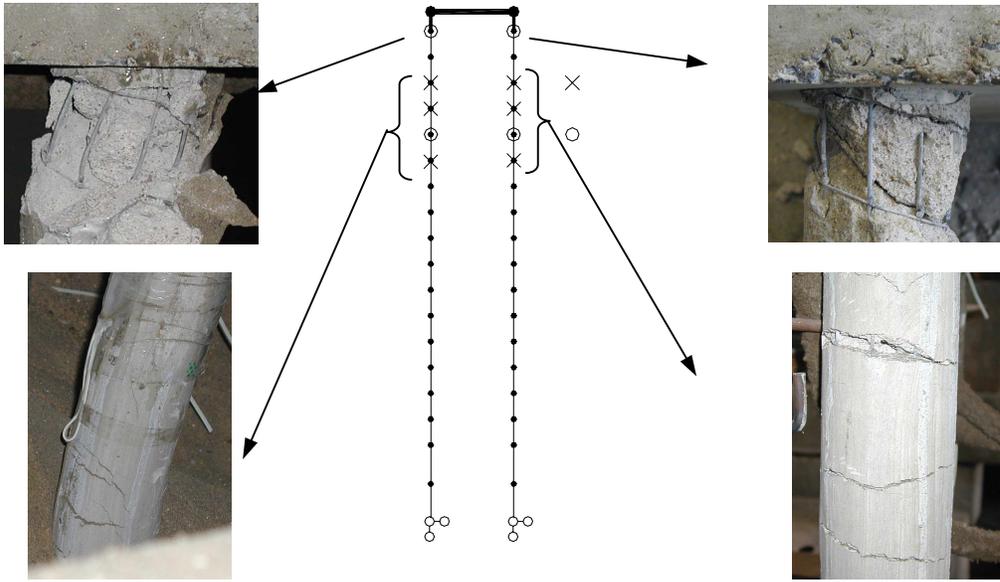


Fig.19 Failure mode of the piles

CONCLUSIONS

A pushover analysis model, which can take account of soil-pile-structure interaction, is presented. A bridge pier-pile-soil system was analyzed by using the presented model, and the results were compared with those of nonlinear dynamic time history analysis. A static experiment of multi-pile foundation in a shear deformation soil box was carried out to study the effect of soil movement on the multi-pile foundation, the relationship of soil-pile interaction force and relative deformation, and the determination method of the nonlinear interaction spring. Based on the analysis results, conclusions could be drawn that:

1. The results of the distributions of the inertial force and displacement got from two various method are relative similar. The presented pushover analysis is proper for providing a reasonable estimate of the structural maximum response and the status of destruction.
2. For various degree of the earthquake stimulation, the shear module of the soil will vary as well as the stiffness of the interaction spring, and the analysis models must be set up individually. A nonlinear interaction spring should be applied to overcome the disadvantage.
3. Although there is difference between the theoretic analysis and the experiment, the distributions are almost the same. If the shear module of the soil could be chose reasonably, the analysis method is proper to estimate the effect of soil movement on the piles foundation.
4. The secant of the curves get from the test regarded as the initial stiffness, the relative horizontal displacement between the soil and pile at the first load level regarded as the yielding displacement, and 20% of taken as the post-yielding stiffness factor, the soil-pile interaction springs could be described as bilinear ones, the curves meet the envelope line of the loading history very well, that indicates the bilinear spring model is proper for estimating the nonlinearity of the soil.
5. In this study, the determination of the soil-pile interaction springs was based on the experiment data; more research should be done to achieve a general model of nonlinear soil-pile interaction of springs.

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