FORCED VIBRATION TESTS ON PILE FOUNDATIONS

C H CHEN[1], C S HUANG[2], C H YEH[3], M H WANG[4], J J BIAN[5], H C LIN[6], Y J LEE[7] And S H YANG[8]

SUMMARY

of Taiwan, a series of forced vibration tests were conducted on full scale large-diameter piles to investigate their dynamic characteristics. Tests were performed on two single piles and two group piles located at Chiayi, Taiwan. For single pile tests, sinusoidal forces were applied at the top of piles in the vertical and horizontal directions, respectively. For group pile tests, sinusoidal forces were applied at various locations of the pile cap top to investigate the response functions corresponding to three translational and three rotational degrees-of-freedom of the pile cap. For each set of tests, responses in the frequency range from 1 to 20 Hz were measured. In this paper, the results of in-situ tests as well as the analytical predictions made by using the hybrid modeling were presented

INTRODUCTION

Speed Rail (HSR) along the West Corridor of Taiwan. The total length of the route is 345km. The southern section which passes through the South-Western plain of the island will be built on elevated viaducts in order to minimize the use of lands and the potential obstacles in east-west transportation. However, this area is well known to have poor soil conditions and active seismicities. Under these circumstances, pile foundation will be the major type of foundations to be used to support the elevated structures. This section has a total length of 150km approximately. With a typical span of 30m, about 5000 piers are needed. By estimation, more than one million meters of large diameter, long piles are going to be constructed for this project. From the viewpoints of quality and quantity of piles needed, it is very worthy to perform a proto-type pilot test for the pile foundations to be used for the planned HSR project. The whole test program will include both the static and dynamic tests (Chen, 1997). Due to the page limit, only the dynamic parts will be reported herein.

To investigate the dynamic behavior of soil-pile interaction, a lot of tests have been conducted, including small scale tests in the laboratory and full scale tests in the field (Novak and Grigg, 1976; Hakulinen, 1991; Janes et al., 1991; El-Marsafawi et al., 1992; and Imamura et al., 1996). The pile tests conducted for the planned High Speed Rail will be the proto-type large diameter piles including the bored piles and the pre-cast concrete piles (designated as PC piles, thereafter

LAYOUT OF PILES

and 13 PC piles of diameter 0.8m. The spacing between piles (center to center) is three times of the pile diameter. All piles are of a length of 34m. To utilize the constructed piles for multiple tests, single pile tests (dynamic tests and vertical load tests) were conducted first. Afterwards, two pile caps were then constructed for group-pile tests. One group consists of 6 bored piles connected by a massive concrete cap of dimension

[1] *Department of Civil Engineering, National Taiwan University, Taipei, Taiwan*
[2] *National Center for Research on Earthquake Engineering, Taipei, Taiwan*
[3] *National Center for Research on Earthquake Engineering, Taipei, Taiwan*
[4] *National Center for Research on Earthquake Engineering, Taipei, Taiwan*
[5] *National Center for Research on Earthquake Engineering, Taipei, Taiwan*
[6] *National Center for Research on Earthquake Engineering, Taipei, Taiwan*
[7] *Depart. of Civil Engrg., National I-Lan Institute of Agriculture and Engrg., Ilan, Taiwan*
[8] *Department of Civil Engineering, National Taiwan University, Taipei, Taiwan*

12m×8.5m×2m, another group consists of 12 PC piles connected by a massive concrete cap of dimension 9m×8m×2m. Two groups are 12m apart.

The bored piles were constructed by two different methods. The B2, B10 and B13 piles were constructed by using the temporarily full-casing method, in which the whole depth of the excavated pile hole was protected by continuously rotating steel casing during the excavation stage of the pile construction. The others were constructed by conventional slurry method of reverse-circulation type. The designed compressive strength of concrete of the bored piles is 2.8MPa. The main reinforcements used were 78-, 52- and 26-D32mm rebars in the upper, middle and lower parts, respectively of the pile. The PC piles used in this test are hollow-typed precast pre-stressed concrete piles made by method of centrifugal spinning. The thickness of the pile tube is 120mm. The compressive strength of concrete is 8MPa. The pile section has 38-9mm• high strength steel wires and the effective pre-stress transferred to concrete is equal to 800kPa. The spiral reinforcement has a nominal diameter of D5.5 (diameter in mm), with a typical pitch of 100mm at the middle portion of the pile length. At both ends, the pitches are reduced to 75mm and 50mm within a range of 1000mm and 800mm, respectively. In addition, the top 2 meters of the pile head are strengthened with longitudinal bars of 19-D19 and hoop reinforcement of D9@500mm. Each precast segment has a length of 17m. During the constructions, the pile was driven by DELMEG D100-13 driving machine with a hammer weight of 100kN. To form a complete pile of length 34m, two segments were connected by site welding. After the complete pile was driven into the ground, the inner hole of the pile was refilled with non-shrinkage concrete with longitudinal reinforcements of 8-D22mm and hoop reinforcements of D10mm@75mm. The compressive strength of the in-filled concrete is 2.1MPa.

Forced vibration tests were performed on two single piles and two group piles. The single piles tested consist of a pre-cast concrete pile (P6) and a bored pile (B10). For group pile tests, both the bored pile group and the PC pile group along with their caps are used for forced vibration tests

GEOLOGICAL CONDITIONS

the ground surface are generally inter-bedded layers of silty clays and clayey sands. By summering the explorations conducted at site, the soil profile from the ground surface down to the depth of 40m is shown in Fig. 2. It consists of yellow clays with some organic materials (0m~3m), gray silty sands (3m~8m), soft clays (8m~12m), medium dense sands (12m~21m), clay layer inter-bedded with thin layers of fine sands (20m~32m), and medium to dense sands (32m~40m). At deeper depths, the deposits are still inter-bedded layers of clay and sand distributed down to a very deep depth. The ground water level is very high at the site, just about 1m below the ground surface. The shear wave velocities measured from the cross-hole seismic surveys are summarized as shown in Fig. 2

LAYOUT OF TEST

tests. Both shakers have a maximum eccentricity ratio of 10:1. The larger shaker (MK-12.8-4600) has a weight of 7.54kN and a maximum eccentric moment of 520N-m, which can be run to a maximum frequency of 10 Hz.

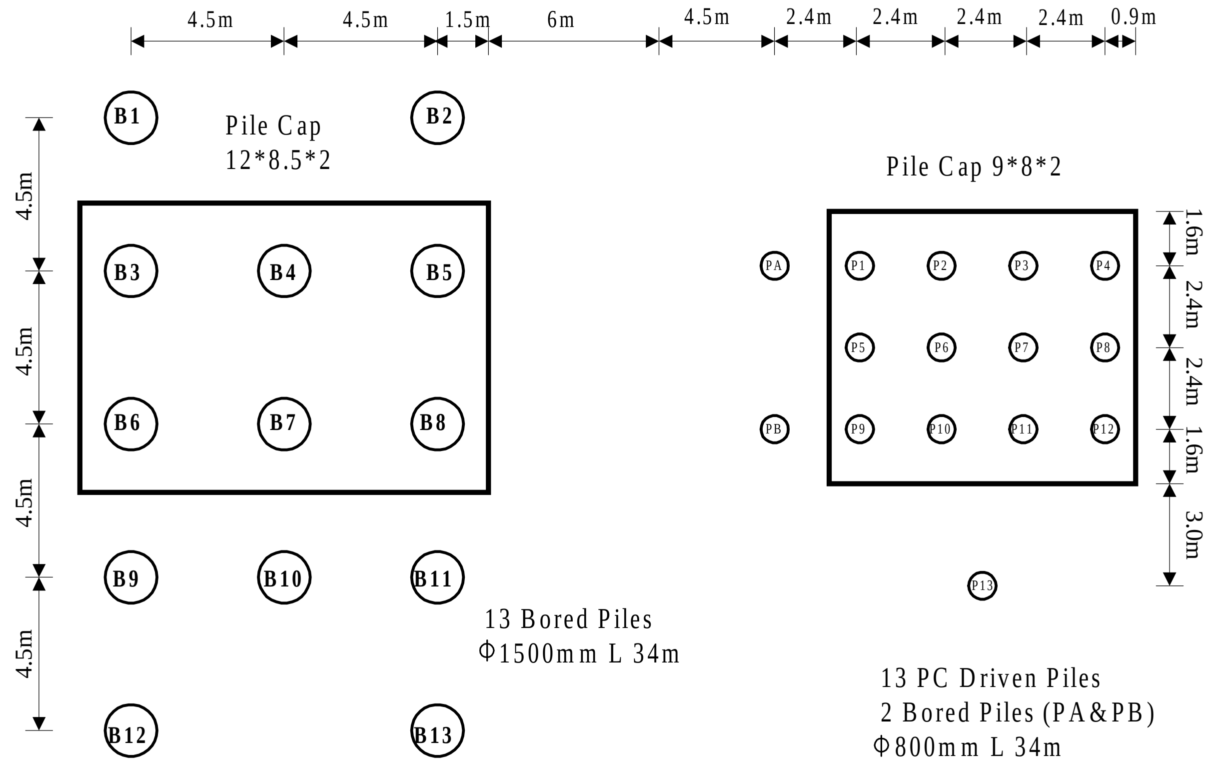


Fig. 1 Layout of pilot pile test

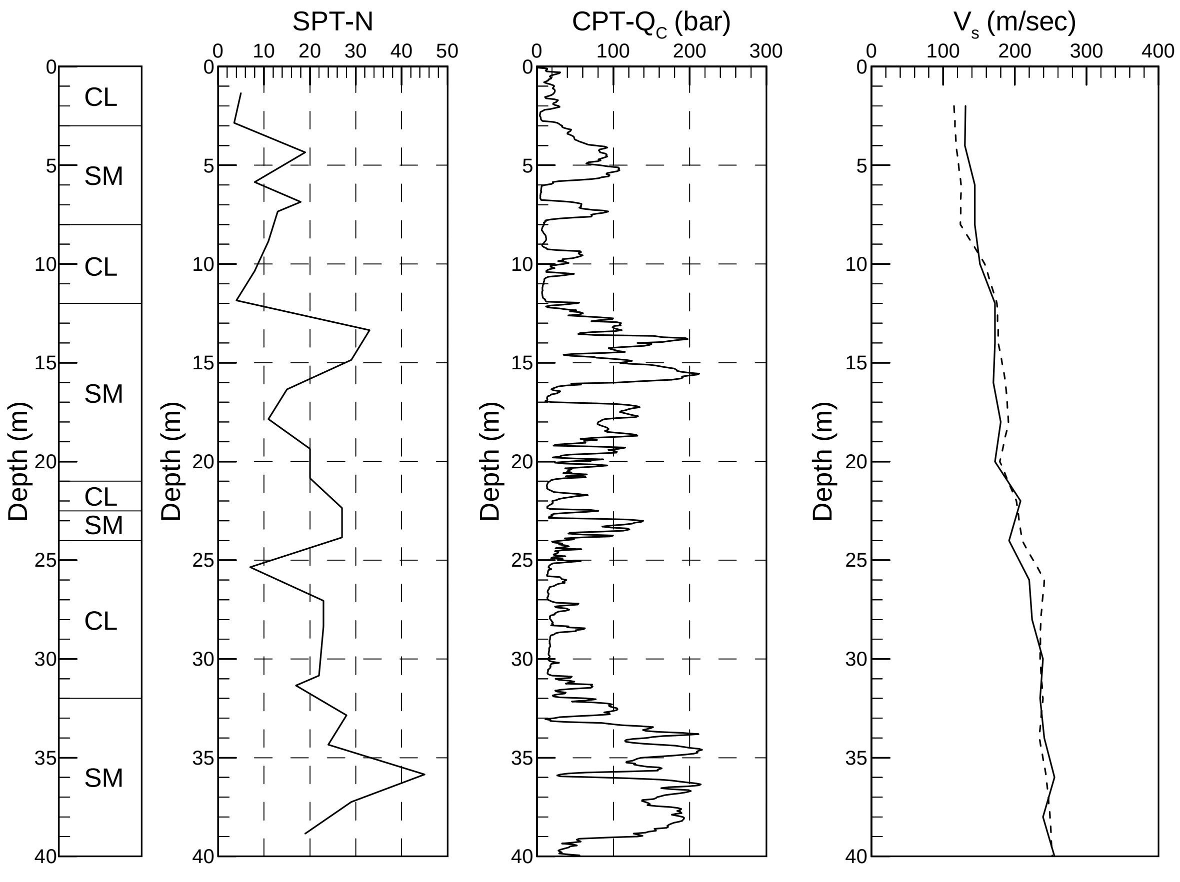


Fig. 2 Geological profile of test site

The smaller one (MK-12-460, ANCO) has a weight 1.67kN and a maximum eccentric moment of 52N-m, which can be run to a maximum frequency of 20 Hz. For both shakers, the maximum force can be generated is 44.5kN.

For single pile tests, the arrangement is shown in Fig. 3. The shaker was mounted on top of a 4cm thick steel plate that was prefixed on top of the pile head. In each test, the shaker was arranged to generate sinusoidal force in the horizontal and vertical directions, respectively. For all frequencies tested, the eccentric mass was adjusted to keep the applied horizontal force below 20kN, to keep the piles vibrate in the linear ranges.

For each set of the group pile tests, a total of six test runs were performed so that the frequency response functions corresponding to all six degrees of freedom of the rigid pile cap can be calculated. The six test runs are denoted as *CX*, *CY*, *CV*, *TX*, *TV*, and *RV*, as shown in Fig. 4. The first letter represents the location of the shaker while the second letter indicates the direction of force generated.

In the tests for group piles, the steady state responses of pile caps were measured by 12 servo-type velocity meters denoted as x_i, y_i, and z_i (i=1,2, 3, and 4), as shown in Fig. 4. For the tests of single piles, the responses were measured in the same way except that the sensors were mounted at four corners of the steel plate. The resolution of the sensors used is 0.001cm/sec. The sampling rate is set to 50 times of the force frequency, and the total number of sampling points per record is 1,000. All tests were conducted with a frequency increment of 0.2 Hz in the frequency range from 1 to 10 Hz and a frequency increment of 0.4 Hz for the force frequencies between 10 Hz and 20 H

TEST RESULTS AND DISCUSSIONS

in the group pile tests, one can compute the responses of interest by manipulating the measured data from all sensors. For example, the horizontal motion of the pile cap in *X*-direction is determined by taking the average of the measured data from sensors x_i (i=1,2, 3, and 4) (see Fig. 4). Then the amplitude is determined by matching a sinusoidal function to the data in the least square sense. For the details of data processing, one should refer to Huang et al.(1997).

Single Pile Test

Figure 5 shows the vertical responses of B10 bored pile subjected to a vertical vibrating force, while Figs. 6 and 7 show the horizontal and rotational pile head responses, respectively, of this pile subjected to a horizontal vibrating force. It should be noted that the top of the pile is about 1m above the ground surface and the head condition is free in rotation during the tests. The measured responses are designated with square symbols in Figs. 5 to 7. Based on the test results obtained, it can be seen that all three components are not significantly changed with the exciting frequencies, especially the phase angles. Neglecting the small variations with respect to the exciting frequency, it is evident that a simplified frequency-independent impedance function can be chosen for engineering applications, which will be more simple and convenient in practice.

Pile Group Test

Figures 8 and 9 show the horizontal responses of both pile caps in the *X* and *Y* directions obtained from the tests *CX* and *CY*, respectively. The response magnitudes in the *X* and *Y* directions are very close. The response of the PC pile group has a clear peak at 5.5 Hz. The vertical responses of both pile caps obtained from the *CV* tests are shown in Fig. 10. In this figure, the responses recorded at smaller frequencies are fluctuated due to the effects of noises, which will affect the responses significantly at very small excitation forces. The responses are quite stable as the frequency of test is increased. Besides, it should be noted that the discontinuities appeared on the response curves obtained are actually resulted from changes of the applied forces, i.e. change of shaker used or change of eccentricity of shaker. Under these circumstances, different magnitudes of input force were applied at different test runs. Small variations of response are unavoidable in a test. Generally speaking, the results obtained are quite consistent in all frequencies interested. From the results shown in Figs. 8 to 10, one can find that the group of 6 bored piles shows much stiffer than the group of 12 PC piles. The horizontal responses have shown peak values at frequency 5.5 Hz, while the vertical responses of both pile groups do not have clear peaks in the frequency range tested.

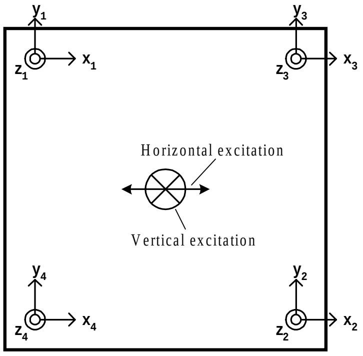


Fig. 3 Layout of single pile test

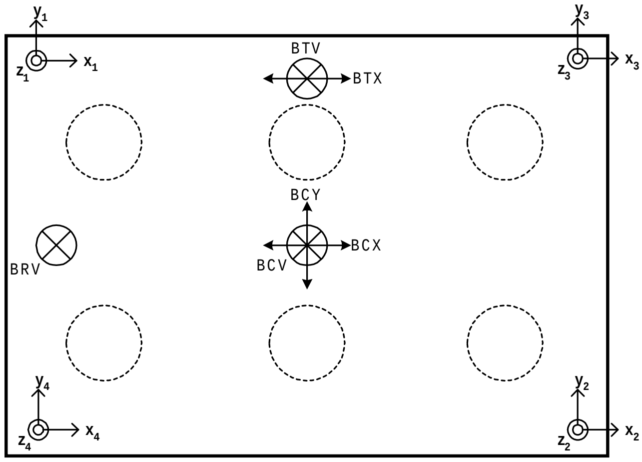


Fig. 4 Layout of group pile test

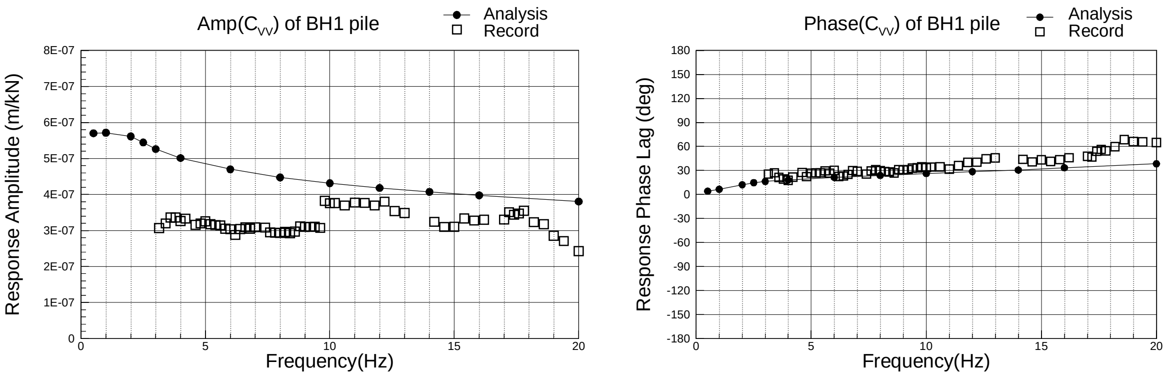


Fig. 5 Vertical response of the bored pile due to vertical excitations

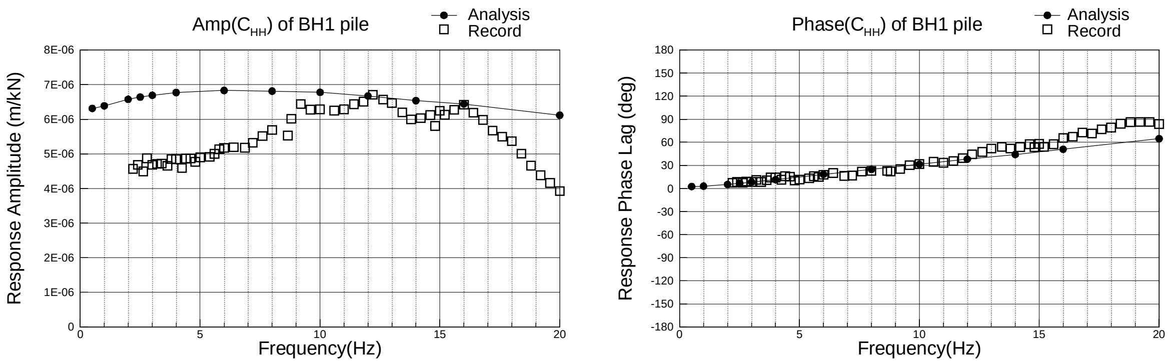


Fig. 6 Horizontal response of the bored pile due to horizontal excitations

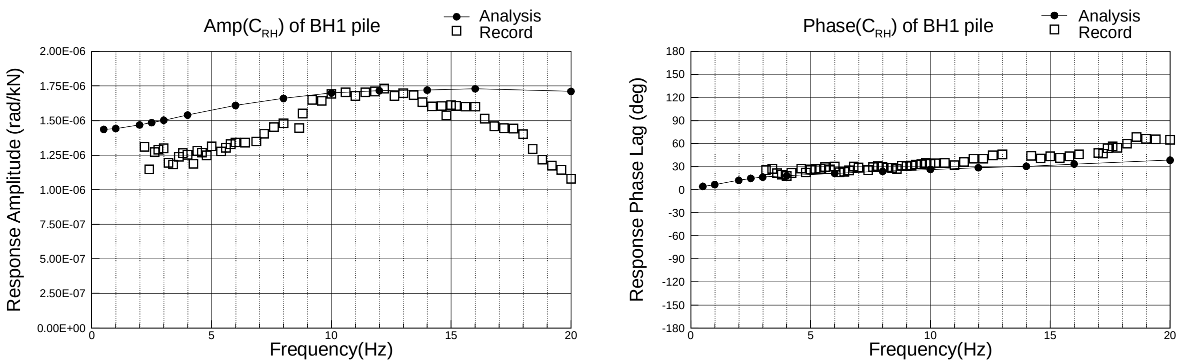


Fig. 7 Rotational response of the bored pile due to horizontal excitations

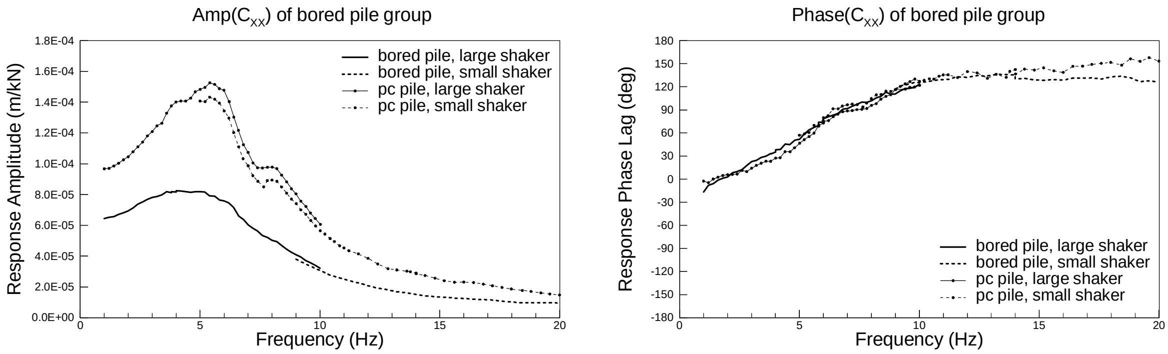


Fig. 8 Translations in X-direction of both pile groups in CX test

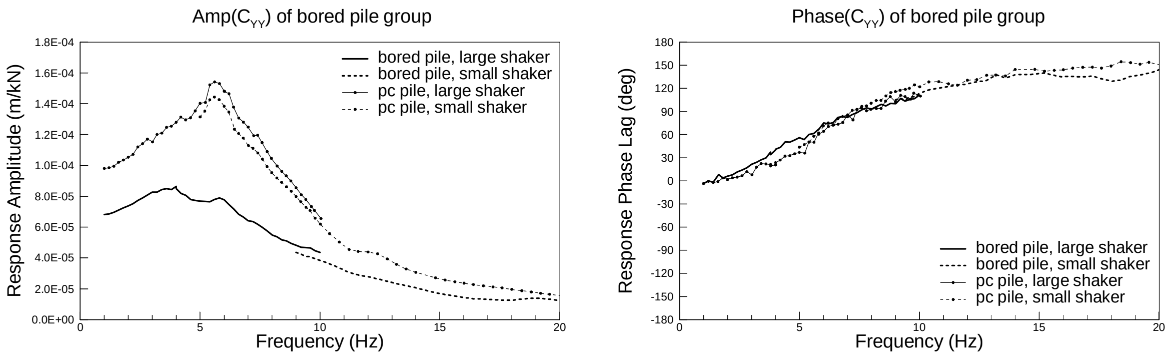


Fig. 9 Translations in Y-direction of both pile groups in CY test

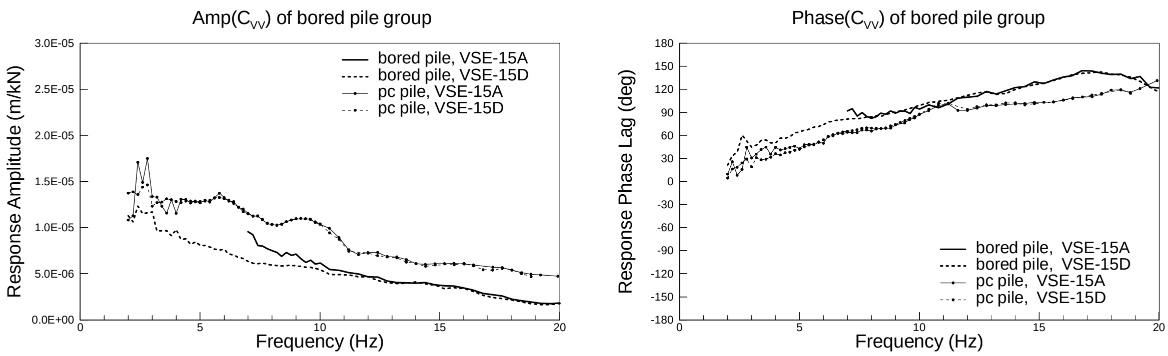


Fig. 10 Vertical responses of both pile groups in CV te

ANALYTICAL MODELING

To model the soil-structure interaction response of single piles, the method of hybrid modeling has been shown to be very effective (Gupta et al., 1982 and Chen, 1988). Basically, the hybrid modelling uses method of substructure by partitioning the entire soil-pile system into a near-field (NF) and a far-field (FF), as shown in Fig. 11. To effectively model the pile, the NF/FF interface can be chosen to be a slender cylinder which cuts through the soil region around the pile. The near-field, consisting of the pile and a finite portion of surrounding soils, can be modelled appropriately using axisymmetrical finite elements. The far-field is a semi-infinite layered half-space with a surface cavity. The dynamic impedance of the far-field can be formulated by using the indirect boundary element method (Lee, 1992), and can thus be represented by a complex-valued boundary impedance matrix. Imposing the conditions of force equilibrium and displacement compatibility along the interface between the near- and far-fields, the impedance of the whole system can then be obtained by assembling the impedance matrices of the near- and far-fields in the frequency domain. By giving the externally applied forcing functions at the pile head, the dynamic responses of the pile can then be solved through a rather small analysis.

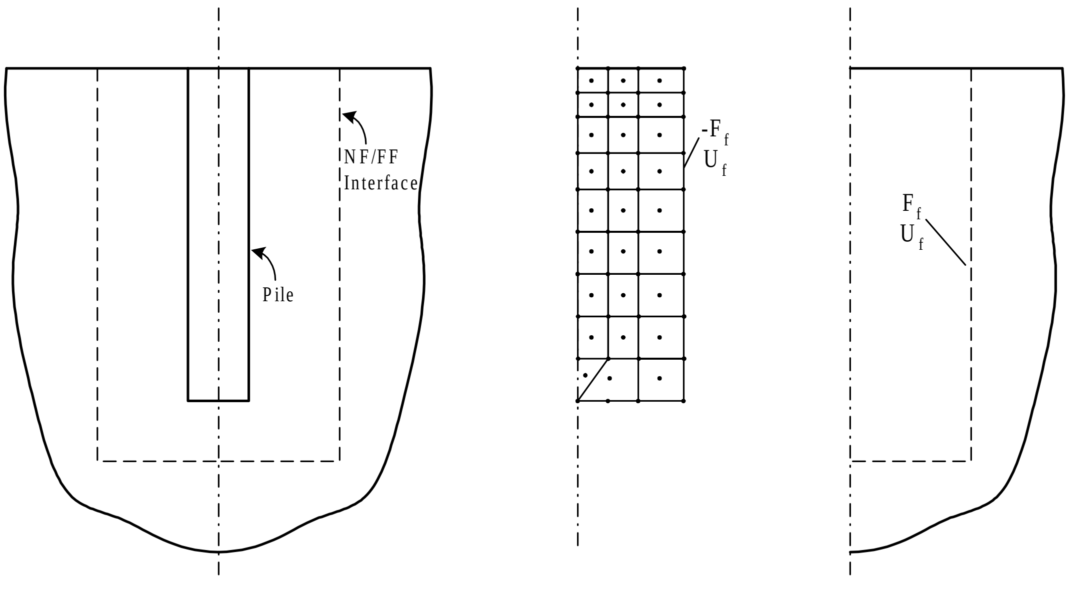
Single Pile Modeling

By using the hybrid modeling to model the above-mentioned B10 bored pile tests at Chaiyi, the near-field is chosen to be a cylinder with a radius of 3m and a height of 40m. The 9-node axisymmetrical solid elements are used to model the pile and the near-field soils located in the near-field region. Element size used ranges from 0.4m near the ground surface to a size of 2m at the deeper soil layers. Properties of soil elements adopted are deduced from the shear wave velocities measured by the cross-hole seismic method as shown in Fig. 2. Damping ratios used for the pile and soil elements are of hysteretic type and set equal to 0.02 and 0.05, respectively. The far-field impedance matrix is formulated based on the same soil properties used in the near-field, by using the indirect boundary element method.

Results of Analysis

Based on the model constructed above, the compliances of the B10 pile due to a unit sinusoidal force applied at the pile head, just as the test conditions, are calculated and compared with the field test results. Solid lines in Figures 5 to 7 are the calculated pile head compliance of the 1.5m-diameter bored pile tested, in which C_{vv} is the vertical compliance due to unit vertical excitations, C_{hh} and C_{hr} are the horizontal compliance and the coupled rotational response, respectively, due to unit horizontal excitations.

From comparisons, it can be seen that the analytical results agree quite well to the field test data in general. The responses of phase angle fit very well at all frequencies. However, the amplitudes calculated from analytical modeling are a little larger than the test results at all frequencies. Regarding the disturbance and uncertainties involved in a pile construction, and the complexity of the soil conditions around the pile, the results obtained from analytical modeling are quite satisfactory from the engineering point of view.



(a) Soil-pile system (b) Near-field (c) Far-field

Fig.11 Hybrid modeling for the soil-pile syste

CONCLUSIONS

Results obtained are very valuable for both the researchers and engineers working on pile engineering. By using the hybrid modeling, results of analytical prediction for single pile are satisfactory in general; however, more studied including the constructional factors and the modeling for pile groups are indeed necessary for engineering applications.

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