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Analysis for forced vibration test on a proto-type pile foundation in TSIP

Analyse pour test de vibration forcée sur un prototype de fondations a pieux a TSIP

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ABSTRACT
In order to investigate the ground vibrations probably induced by the high speed rail when will pass through the Tainan Science Industrial Park, a proto-type bridge foundation supported on four large-diametered piles was built in the TSIP for the purpose of in-situ tests. A series of forced vibration tests on the pile foundation had been conducted. The test method, analysis procedure and results of test are briefly introduced in this paper. Besides, a numerical simulation by using the finite element program ABAQUS is conducted. Results obtained are in good agreement with the results of in-situ tests.

RÉSUMÉ
Afin d'étudier les vibrations du sol vraisemblablement provoquées par le passage du train à grande vitesse sur la Base Scientifique du Parc Industriel de Tainan, un prototype des fondations d'un pont comprenant quatre pieux de fondation de large diamètre a été construit à TSIP même dans le but de faire des tests in situ. Une série d'essais de vibrations forcées sur les pieux de fondation a été effectuée pour toute une série d'études. La méthode d'essai, la procédure d'analyse et les résultats de l'essai sont brièvement introduits dans cet article. Par ailleurs, une série de simulations a été menée en utilisant le programme ABAQUS. Les résultats obtenus sont en bonne adéquation avec les résultats des essais in situ.

1 INTRODUCTION

The under-constructing Taiwan High Speed Rail (THSR) will pass through the Tainan Science-based Industry Park (TSIP) which is a newly developed area for the promotion of high-tech technology in Taiwan. Since the high-tech factories and equipments inside the TSIP are very sensitive to the ground vibrations during the process of production, therefore, it is necessary to evaluate the level of ground vibrations that maybe induced by the operation of the planned High Speed Rail. For this purpose, many studies including field tests, analytical predictions and feasible measures for vibration reduction had been conducted. In order to characterize the ground vibrations probably induced by the deep-seated pile foundation of the THSR, a proto-type pile foundation was built in the TSIP for the purpose of testing. In the first stage of testings, a series of in-situ forced vibration test had been conducted on the foundation built. In this paper, the results of forced vibration tests and associated numerical simulations are presented.

2 TEST PLAN

2.1 *Layout of pile foundation*

The proto-type pile foundation is located on a site near the route of THSR in the TSIP. The profile and plan view is shown in Fig. 1. It contains four cast-in-place piles, each has a diameter of 2m and a length of 57m. On top of the piles, a massive pile cap of dimension 10.5m×10.5m×2.7m was constructed to support a pier with a cross section of 3.0m×3.4m. The pier was constructed to a height of only 3m, just above the ground surface, for the convenience of test set-up. A large number of strain gauges were installed in the steel-bars of the pier and piles as shown in the Fig.1, to measure the variations of stresses during the tests.

2.2 *Geological conditions*

The site of TSIP is located on the well-known Chianan Plain where is a major agricultural area in Taiwan. The alluvial deposits in this region are very deep, probably with a depth larger than hundred of meters. The deposits in the upper 70m can generally be characterized as inter-bedded layers of silty clays and clayey sands with various thicknesses. Based on the geological and geotechnical investigations available, a representative soil profile and averaged soil parameters had been summarized as shown in Table 1 (CTCI, 1999). The soil properties shown are small-strain properties and can only be used for micro-vibration studies. Besides, the ground water table at the TSIP site is usually very high, locates at the depth of 2.85m below the ground level.

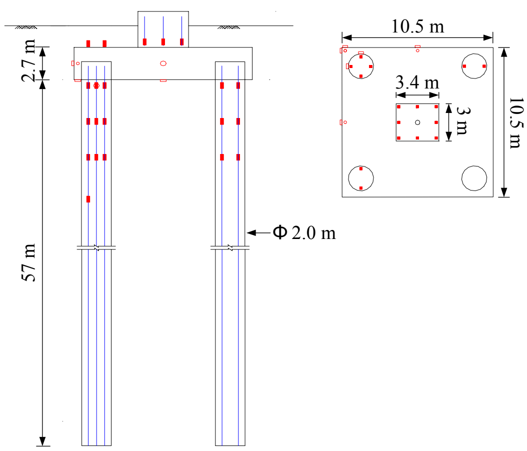

Figure 1. The profile (left) and plan view (right) of the pile foundation(CECI, 2001).

Table 1:The Soil Properties Used in the Analysis (CTCI, 1999)

Layer No.	Thickness m	Density t/m^3	V_S m/s	V_P m/s	E kN/m^2	G kN/m^2	ξ	ν
1	4.5	2.0	122	725	89680	30190	0.015	0.485
2	6.5	2.0	172	1310	178700	59930	0.015	0.491
3	10	2.0	231	1590	321000	107800	0.015	0.489
4	15	2.0	279	1679	459500	154600	0.015	0.486
5	9	2.0	331	1679	645200	218000	0.015	0.48
6	6	2.0	376	1679	827600	280700	0.015	0.474
7	∞	2.0	405	1679	965400	328600	0.01	0.469

2.3 *Test equipments*

For the forced-vibration tests, exciters which can generate harmonic force were mounted on the surface of the pier top. The vibrators used are the eccentric mass vibrator system, the MK4600 and MK460 vibrators, which are both dual-arm rotating vibrator manufactured by the ANCO Engineers, USA. For the horizontal test, two synchronized MK4600 (for frequencies 1 to 10Hz) and two synchronized MK460 (for frequencies 9 to 19 Hz) were adopted to generate a horizontal harmonic force of 4 to 95 kN on top of the pier. For the vertical test, only one MK460 was adopted to generate a vertical harmonic force of 0.8 to 47 kN on top of the pier in the frequency range of 2 to 15 Hz.

2.4 *Layout of monitoring sensors*

The sensors used to monitor the responses of the foundation and nearby ground surface are of velocity-type, VSE-15A, which can operate at a frequency range from 0.1 to 70 Hz. The recording system used is the μ-Musycs system, with 32 channels. The sampling rate adopted in the test is 1000 Hz.

To monitor the decay of ground vibrations with respect to distance, A total of 18 sensors were deployed along Line A, which has a maximum distance of 150m from the foundation center as shown in Fig. 2. For each frequency of test, steady state responses of foundation and grounds were recorded synchronized.

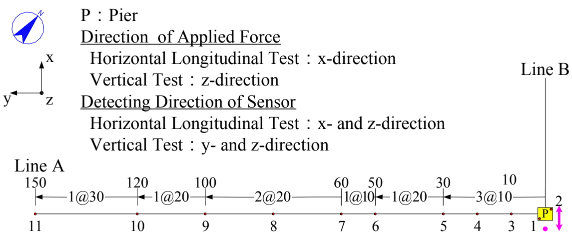

Figure 2. Layout of measuring points during the test.

3 TEST RESULTS

3.1 *Data processing*

To retrieve the vibration amplitude of each frequency obtained from the test, the Root-Mean-Square (RMS) velocity amplitude expressed in terms of decibel (dB) was calculated according to Eqs. (1) and (2),

$$V_{RMS}(f_i) = \sqrt{\frac{1}{T}\int_0^T [\bar{v}(t)]^2 \, dt} \qquad (1)$$

$$L(f_i) = 20 \cdot \log_{10} \frac{V_{RMS}(f_i)}{v_0} \qquad (2)$$

where v_0 is the reference velocity. It is usual to adopt $v_0 = 10^{-6}$ in./sec for semi-conductor industries.

To express the attenuation of ground vibrations with respect to distance, the point-load Rayleigh wave model is adopted as follows:

$$V_2 = V_1 \sqrt{\frac{r_1}{r_2}} e^{-\alpha(r_2 - r_1)} \qquad (3)$$

in which, V_i is the velocity amplitude at point i and r_i is the distance from the foundation center, and α is the coefficient of attenuation. Choosing the point located at the distance of 10m from the foundation as the reference point, the attenuation coefficient α can be retrieved by the method of regressive analysis.

3.2 *Ground vibration response*

In the horizontal longitudinal test, the direction of the applied force is horizontal and parallel to the route of the railway. The horizontal longitudinal (x-direction) vibrations along Line A represent the propagation of SH waves generated by the foundation vibration. Results obtained are shown in Fig. 3. It shows that the vibration levels produced by the shaker are significant for the frequencies larger than 4 Hz, the foundation vibration reaches about 90 dB and the vibrations of the grounds within a distance of 100m from the foundation reache a value of 70~80 dB. Beyond 100m from the foundation, the ground vibrations at higher frequencies are rather scattered because of higher attenuation at these frequencies.

In the vertical test, the direction of the applied force is perpendicular to the ground surface. The sensors on Line A are arranged to monitor the vibrations in the y- and z-directions, respectively. Test results show that the vertical responses are generally larger the horizontal responses. The former are shown in Fig. 4. In general, the responses increase with frequency because the applied force increases with frequency.

3.3 *Ground vibration attenuation coefficient*

Collecting the amplitude responses at all measuring points, a best-fit attenuation curve (Eq. 3) and the corresponding attenuation coefficient α at each test frequency can be deduced. The values of α for the vertical test are deduced as shown in Fig. 5. In general, the attenuation coefficient α increases with respect to frequency, ranged from 0.001 to 0.011 in the frequency range tested.

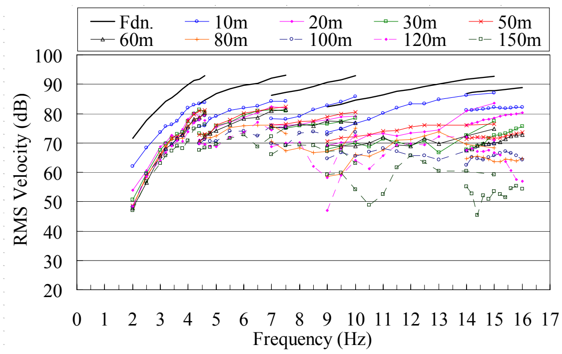

Figure 3. Vibration velocity amplitude in x-dir in the horizontal longitudinal test.

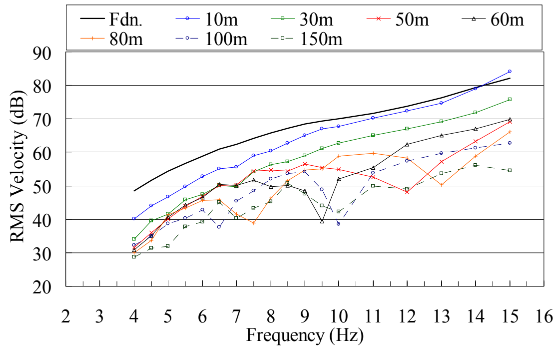

Figure 4. Vibration velocity amplitude in z-dir. in the vertical test.

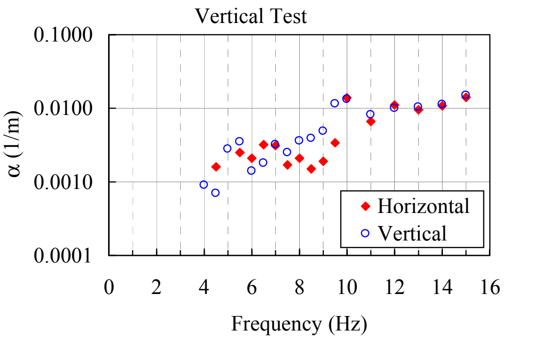

Figure 5. Attenuation coefficient of ground vibration in the vertical test.

4 NUMERICAL SIMULATION

4.1 *Analysis model*

Since the forced vibration test conducted in the field is a small-strain test, a linear elastic analysis by using the computer program ABAQUS is performed in this study. The 3-D FEM mesh adopted is shown in Fig. 6. It is a quarter model by taking the advantage of geometric symmetries with respect to Line A and Line B as shown in Fig. 2.

The entire soil-foundation system is partitioned into a near field, modeled by the 3-D 8-node continuum elements C3D8, and a far field, modeled by the 3-D 8-node infinite elements CIN3D8 to take account the outgoing waves. Due to the limitation of memory capacity of personal computer, the dimension of the near field is chosen at the distance of 33m from the foundation center. For the soils, the material properties chosen are listed as shown in Table 1. In which, the damping of hysteretic type is adopted in the analysis.

4.2 *Dynamic response function of foundation*

Since the forces generated by the shaker during the test are frequency dependent, the normalized response functions are further calculated by dividing the response at each frequency with respect to the force applied at the top of the foundation. The displacement response functions of foundation normalized to an applied force of 10 kN at the pier top is chosen for comparison. Results obtained by numerical simulation for the horizontal longitudinal test and the vertical test are compared with the results of test as shown in Figs. 7 and 8, respectively. From the comparison, it can be seen that the analytical predictions are in good agreements with the test results. For the horizontal longitudinal test, both the prediction and field test show that the peak response is located near the frequency of 3 Hz. As for the vertical test, the first peak response is located near the frequency of 4 Hz, and the second peak response will occur at a frequency larger than 15 Hz, which is beyond the frequency range of field test.

4.3 *Velocity amplitude of ground*

The velocity amplitude of ground at the frequency of 5 and 10 Hz are selected for comparison study. For the horizontal longitudinal test, the comparisons are shown in Fig. 9. At the frequency of 5 Hz, the results of prediction and field test are quite close, both show that the amplitude decays almost monotonically with the distance from the foundation center. As for the frequency of 10 Hz, the predictions show that the amplitudes are much more fluctuated with respect to distance, thus the predictions obtained show larger discrepancies to the results of field test. As for the vertical test, similar results can be obtained, as shown in Fig. 10.

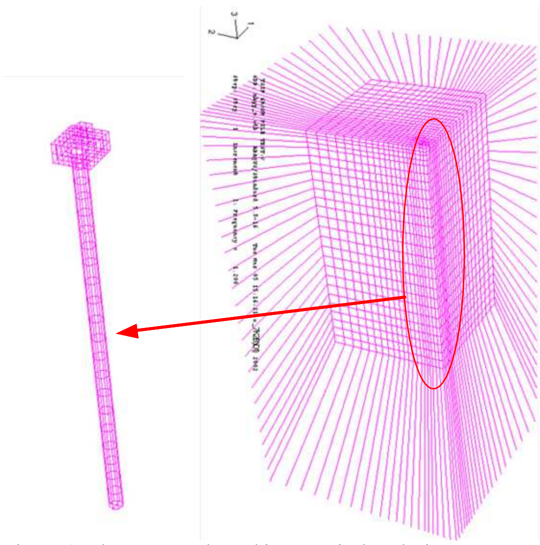

Figure 6. The FEM mesh used in numerical analysis.

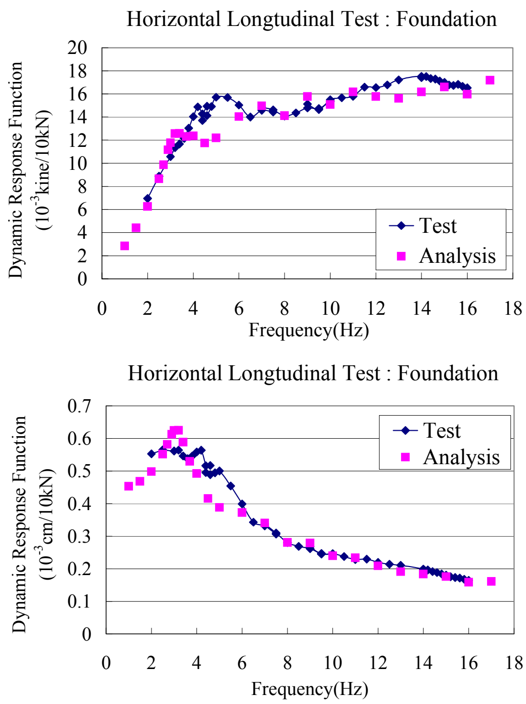

Figure 7. Dynamic response function in x-direction in horizontal longitudinal test (top: velocity; bottom: displacement).

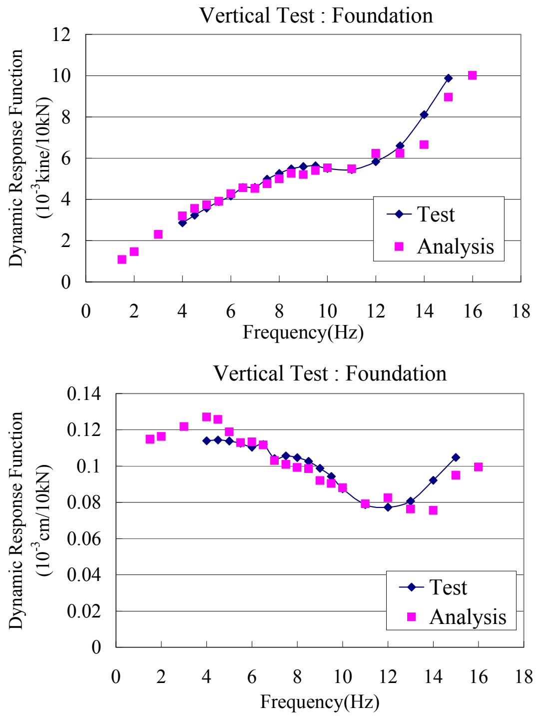

Figure 8. Dynamic response function in z-direction in vertical test (top: velocity; bottom: displacement).

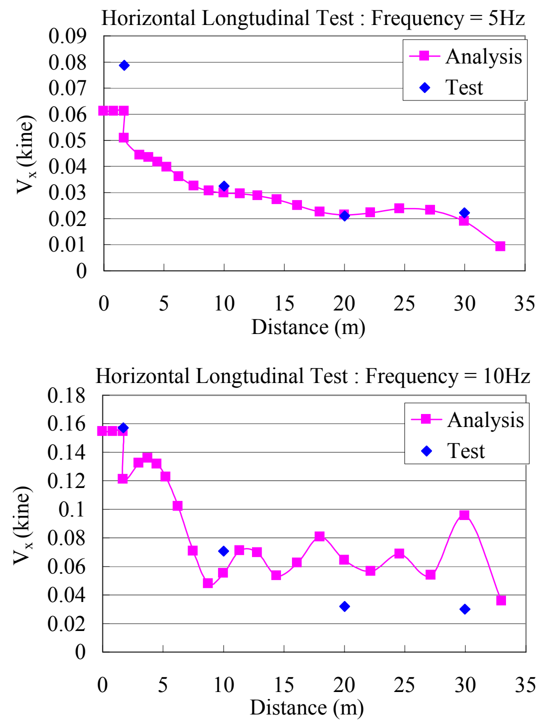

Figure 9. Ground velocity amplitude in x-direction in horizontal longitudinal test (top: 5 Hz; bottom: 10Hz).

5 CONCLUSIONS

Based on the results of field tests and analytical predictions, general conclusions can be deduced as follows:

1. The forced vibration test conducted on the proto-type pile foundation at the TSIP can be used to investigate the characteristics of ground response induced by the vibration of the THSR foundation system.

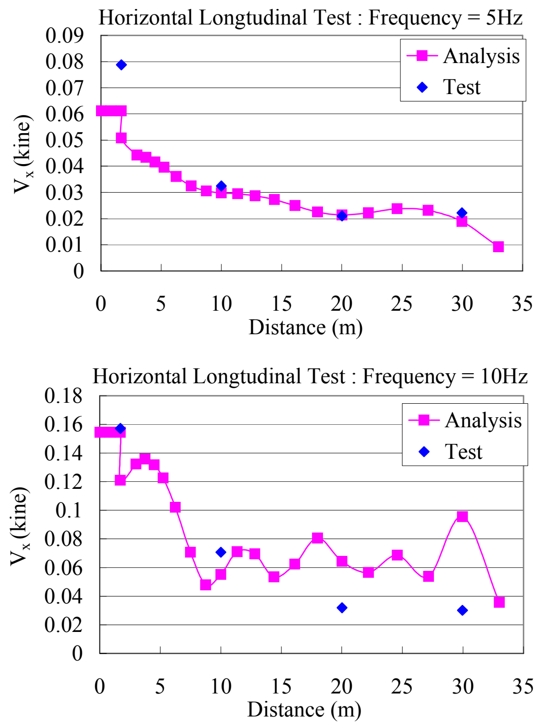

Figure 10. Ground velocity amplitude in z-direction in vertical test (top: 5 Hz; bottom: 10Hz).

2. From the horizontal test, the ground vibration within 100m from the foundation may reach a value of 70~80 dB when the applied horizontal force larger than 10 kN. From the vertical test, the ground vibration within 100m from the foundation may reach a value of 50~60 dB when the applied vertical force larger than 10 kN.
3. The attenuation coefficient of ground vibration deduced from the field test is generally increased with the frequency of vibration. They are ranged from 0.001 to 0.01 at the frequency range of 4 to 15 Hz.
4. The analytical model adopted can effectively simulate the dynamic responses of foundation and surrounding soils. Predicted responses fit quite well with those obtained from the field test.
5. Both the analytical prediction and field test show that the natural frequency of the foundation system is around 3 Hz for the horizontal mode of vibration.

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REFERENCES

CECI 2001. *Design and Construction of Bridge Foundation Model in TSIP for Vibration Test*, China Engineering Consultant Inc.

CTCI 1999. Vibration Impact and Mitigation Measure Development Work for Tainan Science-Based Industrial Park, *CTCI and ICEC Report*.