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A simple approach for quality evaluation of non-slender, cast-in-place piles

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Abstract. This study proposes a conceptual framework of in-situ vibration tests and analyses for quality appraisal of non-slender, cast-in-place piles with irregular cross-section configuration. It evaluates a frequency index from vibration recordings to a series of impulse loadings that is related to total soil-resistance forces around a pile, so as to assess if the pile achieves the design requirement in terms of bearing capacity. In particular, in-situ pile-vibration tests in sequential are carried out, in which dropping a weight from different heights generates series impulse loadings with low-to-high amplitudes. The high-amplitude impulse is designed in way that the load will generate equivalent static load that is equal to or larger than the designed bearing capacity of the pile. This study then uses empirical mode decomposition and Hilbert spectral analysis for processing the nonstationary, short-period recordings, so as to single out with accuracy the frequency index. Comparison of the frequency indices identified from the recordings to the series loadings with the design-based one would tell if the total soil resistance force remains linear or nonlinear and subsequently for the quality appraisal of the pile. As an example, this study investigates six data sets collected from the in-situ tests of two piles in Taipu water pump project, Jiangshu Province of China. It concludes that the two piles have the actual axial load capacity higher than the designed bearing capacity. The true bearing capacity of the piles under investigation can be estimated with accuracy if the amplitude of impact loadings is further increased and the analyses are calibrated with the static testing results.

Keywords: cast-in-place pile; in-situ vibration test; bearing capacity; soil-resistant force; nonstationary data process and analysis.

1. Introduction

Assessment of bearing capacity of a pile plays a key role in securing the reliability and functionality of the pile. It also aids in integrity check and damage diagnosis of the pile if significant loss of the capacity is found. While evaluating the true bearing capacity of a pile is of paramount importance, verifying the pile to achieve the designed capacity is typically the primary purpose of quality appraisal in practice. Such a capacity-related quality evaluation is required for almost all large, important projects of pile foundation (e.g. ASTM D4945-89 1989, JGJ 94-94 1994, and JGJ 106-97 1997).

Traditionally, the capacity-related quality evaluation of a pile is carried out with static load tests, i.e., measuring the settlement while gradually adding dead loads over the top of the pile. Analysis of the load-settlement curves can show if the pile achieves the designed capacity or not. While this static approach is most reliable among the existing techniques for the quality evaluation, the requirement of enormous

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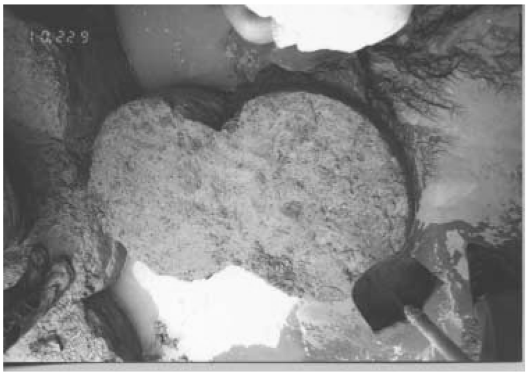


Fig. 1 The cross section of double-head pile for quality evaluation (the diameter of each circular head is 0.7 m and the center-to-center distance of two heads is 0.5 m)

human and financial resources, in addition to the time consumption for setting up and performing the tests in sequential, makes it neither cost-effective nor affordable (e.g. Abu-Hejleh, *et al*. 2003). This is particularly true for a large number of piles under test, exemplified as the 1-5% (the typical ratio required in JGJ 94- 94, 1994 and JGJ 106-97, 1997) of about 2,000 cast-in-place piles or 20-100 piles required for quality evaluation in the Taipu water pump project in China, the largest project of its kind in Asia.

The evaluation can also be performed with high-strain dynamic tests, in which use is made of such approaches as pile-driving formulas and Case Pile Wave Analysis Program or CAPWAP (e.g. Rausehe, *et al*. 1985, Goble Rausehe Likins and Associates, Inc. 1995, Coduto 2001). While these dynamic approaches are widely used in practice and indeed efficient in comparison with static load tests, they are inadequate for non-slender, cast-in-place piles with irregular cross-section configuration. For example, the pile with double heads shown in Fig. 1 used in the Taipu water pump project in China cannot be tested for capacity-related evaluation with the above approaches. First, the pile-driving formulas are not applicable to cast-in-place piles. Second, since the cross section of the pile is so irregular and so large in comparison with its length (ratio of the largest cross-section size and the length = 1.2/6.15 = 0.195), the recordings collected at the side of and near the top of the pile will contain signals not only primarily from P-waves reflected at the two tips (i.e. top and bottom) of as well as along the pile, but also significantly from multiple P and S-wave reflections and scattering at the side of the pile, as well as other type waves such as surface waves. Consequently, the traditional high-strain dynamic approaches that rely on one-dimensional wave theory such as CAPWAP are not valid for the problem at hand.

This study examines an alternative, in-situ vibration test for evaluation of actual soil resistance forces of non-slender, cast-in-place piles with irregular cross-section configuration, such as those used in the Taipu water pump project in China. It aims to explore time-dependent frequency signatures from vibration recordings to an impacting load, with the aid of a method for nonstationary data process and analysis (Huang, *et al*. 1998). It then quantifies the signatures that are used as an index to relate to the soil resistance force, bearing capacity, damage, and integrity of the pile.

2. Frequency signature in pile-soil dynamic responses

When a cast-in-place pile is subject to a large-amplitude impulse load at its top, the vibration responses recorded at near the top of the pile should contain signals with broad frequency band that are closely

Table 1 Strengths of pile and soil

Surrounded soil	Pile with concrete	Soil below the pile
105 kPa	1420 kPa	300 kPa

related to the dynamic characteristics of the pile and surrounded soil in addition to the noise. Data processing and analysis of the recordings can theoretically provide an estimation of soil resistance forces and/or bearing capacity of the pile, among others. Below is the qualitative analysis of frequency signature in the recordings.

The soil resistance to bear the axial load exerted on the top of a pile comes from the pile-soil contact boundaries along and at the bottom of the pile. The soil resistant force along the pile is heavily dependent upon the surrounded soil behavior, which varies from one depth to the other. Due to the stochastic nature of soil heterogeneity and pile-soil contact condition in construction, a large variance of the soil resistant forces and capacities is expected even if the soil profile and strength at site is provided. This suggests that modeling and evaluating soil resistance along the pile (i.e. distribution of the resistance at discretized locations along the pile) is neither cost-effective nor necessary if the capacity-related, total soil resistance is of sole interest for quality appraisal. In fact, one of the most important missions in quality evaluation of piles is to validate if the piles achieve the designed bearing capacity, in spite of true bearing capacity.

Table 1 shows the strengths of pile material and surrounded soil in Taipu water pump project, indicating that the pile is much stiffer (3.73 times stronger) than the soil. Accordingly, the pile vibration can be regarded as a mass-spring system with pile as the mass and soil resistance from the skin along and at the bottom of the pile as the spring. The designed load capacity can then be related to the spring coefficient with a given, elastic deformation limit and subsequently to the fundamental natural frequency of the pile vibration. In other words, the fundamental natural frequency is an indicative to the load capacity.

The fundamental natural frequency of the above mass-spring system is typically lower than that of multiple-degree-of-freedom (MDOF) system with the continuous pile-soil vibration system as a reference. This can be seen from an example in Rei (2001) that the fundamental natural frequencies of Single-DOF and 2-DOF systems are respectively 64% and 90% of the fundamental natural frequency of a continuous system with the same soil resistance along and at the bottom of a pile. In addition, damped natural frequencies are also smaller than the undamped frequencies. Therefore, the product of squared damped fundamental natural frequency estimated from the recordings and the pile mass provides a conservative estimation of the soil resistance force of the pile.

The above mass-spring system for pile vibration can be theoretically improved with MDOF system with damping under consideration. While doing this increases the accuracy of modeling and thus is particularly useful in design stage, it typically requires more recordings to solve for the inverse problem in estimating system parameters such as spring coefficients at different depths of the pile. This is very difficult, if not completely impossible, to achieve for the quality evaluation of cast-in-place piles, for only a portion of the piles is reachable.

Moreover, the above approach also increases the estimation uncertainty of such system parameters as total soil resistance force of the pile through modeling, and likely assuming partially, the soil resistant behavior and damping mechanism at each and every discretized location along the pile. As a result, the increased level of the sophisticated MDOF models does not help improve the accurate evaluation of load capacity of the piles. To this end, the approach with MDOF system is not considered further in quality appraisal of piles.

It should be noted that the recordings also contain signals from waves propagating and scattering in the

Table 2 Cross-sectional area and material properties of cast-in-place piles

Cross-sectional area of the pile	Young's Modulus for mediate-strength concrete	Young's Modulus for high-strength concrete	Density
0.6427 m^2	$21(10^9)$ N/m^2(Pa)	$31(10^9)$ N/m^2(Pa)	$2.41(10^3)$ kg/m^3

Table 3 Fundamental frequencies of 6.15 m-long pile

	Waves in piles with fixed bottom		Vibration of pile-soil system
Concrete strength	Mediate-level	High-level	Mediate- or high-level
Fundamental frequency	120 Hz	146 Hz	26 Hz

piles, the frequencies of which are however quite higher than the fundamental natural frequency of pile vibration, which is illustrated below.

The wave signals with lowest frequency are associated with the waves in the pile that travel axially along the pile and reflect at the two tips. Note that the wave reflection between the top of the pile and somewhere along the pile with such defects as crack/void or soil resistance will generate signals with frequencies higher than the aforementioned lowest frequency, which is due to the fact that the former has shorter traveling distance than the latter. Based on the one-dimensional wave theory which can be found in standard textbooks and codes (e.g. Rei 2001), the lowest frequency of the wave signals in the pile with fixed bottom end and uniform distributed friction force along the pile can be calculated, as shown in Table 3 in which use has been made of Table 2 that is based on the information provided by engineers and designers for the Taipu water pump project and on subsequent straightforward calculation. While approximate due to the assumed boundary conditions, the frequencies of waves in the pile are significantly larger than the fundamental natural frequency of a mass-spring system for the pile-soil vibration of 26 Hz in Table 3, which is calculated based on the design capacity (329 kN) of the pile, the linearly elastic deformation limit (2 mm), and pertinent information. This suggests that the lowest frequencies of wave signals in recordings can be well distinguished from the capacity-related, fundamental natural frequency of the vibration.

In summary, the above analysis suggests that the lowest dominant frequency extracted from the recording is the fundamental natural frequency of the pile-soil vibration system, an index related to total soil resistant force that may be linear or nonlinear.

3. Time-frequency data analysis

Vibration recording at the side of and near the top of a pile to an impulse load is not only inherently nonstationary, but also the result of nonlinear dynamic process. Therefore, the effectiveness of recording-based approach for singling out the capacity-related frequency index relies on the appropriateness and accuracy of nonlinearity characterization from the data analysis of the nonstationary recordings.

In practice, Fourier spectral analysis (FSA) of recordings is widely used for the aforementioned nonlinearity characterization. Fourier amplitude spectrum defines harmonic components globally and thus yields average characteristics over the entire duration of the data. While the use of short-time or windowed Fourier transform in FSA may possibly minimize the nonstationarity in the data, it reduces frequency resolution as the length of the data window shortens. Thus, one is faced with a trade-off. The shorter the

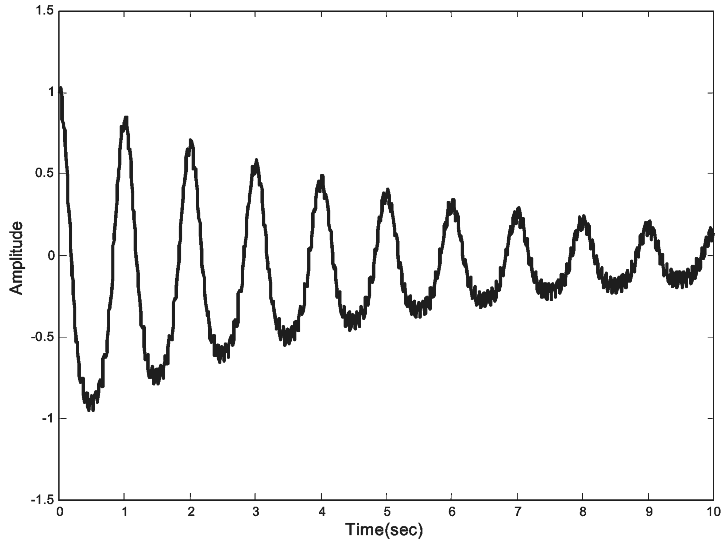


Fig. 2 A hypothetical recording, consisting of nonlinear and linear responses with frequencies being $1+0.5\cos(2\pi t)$ and 15 in Hz, respectively.

window, the better the temporal localization of the Fourier amplitude spectrum, but the poorer the frequency resolution, which directly influences the measurement of downshift of temporal dominant frequency in the recordings at a low-to-intermediate frequency band.

More important, FSA cannot resolve the issues of nonstationarity rooted in the system nonlinearity or nonlinear responses. This can be seen from a hypothetical record $y(t) = y_1(t) + y_2(t)$ in Fig. 2, where the nonlinear response with damping $y_1(t) = \cos[2\pi t + \varepsilon\sin(2\pi t)]e^{-0.2t}$ has time-dependent frequency of $1 + \varepsilon\cos(2\pi t)$ Hz that is bounded by $1-\varepsilon$ and $1+\varepsilon$ with ε denoting a small factor, and the linear response without damping $y_2(t) = 0.05\sin(30\pi t)$ has constant or time-independent frequency of 15 Hz. Note that the waves $y_1(t)$ have a non-sinusoidal waveform with sharp crests and rounded-off troughs, which is physically related to nonlinear responses.

The nonlinear response can be expanded into and thus interpreted by a series of linear responses, as done with FSA. For example, $y(t)$ can be interpreted as to contain Fourier components at all frequencies, as shown in Fig. 3.

Alternatively, Taylor expansion of $y_1(t) \approx [-0.5\varepsilon + \cos(2\pi t) + 0.5\varepsilon\cos(4\pi t)]e^{-0.2t}$ for $\varepsilon << 1$ suggests that Fourier transform of $y_1(t)$ consists primarily of two harmonic functions respectively at 1 and 2 Hz, and the width of these two harmonic functions in Fourier amplitude spectrum in Fig. 3 is proportional to the exponential parameter 0.2 that is related to damping factor. Note that Figs. 2 and 3 use $\varepsilon = 0.5$ that is not a small number in comparison with unit. Therefore, the Fourier amplitude spectrum in Fig. 3 shows the third observable peak at 3 Hz. To this end, one can equally well describe $y_1(t)$ by saying that it consists of just two frequency components for $\varepsilon << 1$, each component having a time varying amplitude that is proportional to $e^{-0.2t}$. The above Fourier-based analysis or interpretation can also be seen in Priestley (1981), among others.

Because the true frequency content of the nonlinear response $y_1(t)$ is bounded between $1-\varepsilon$ and $1+\varepsilon$, much less than 2 Hz, analysis of the record suggests that FSA typically needs higher-frequency harmonic functions (those at 2 and 3 Hz for the record) to simulate nonlinearity-related nonstationary data. Stated differently, FSA distorts the nonlinearity-induced non-stationary data. Similar assertions are concluded in

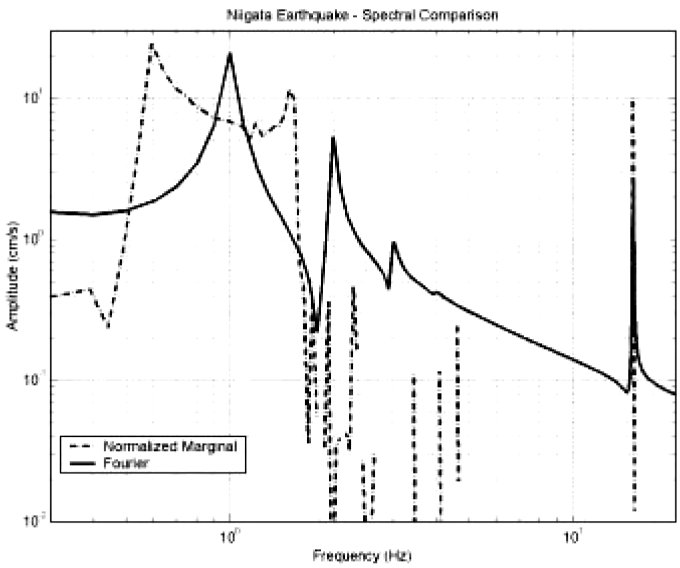


Fig. 3 Fourier and marginal amplitude spectra of the recording in Fig. 2

Huang, *et al*. (1998), Worden and Tomlinson (2001), among others, with the aid of solutions to classic nonlinear systems.

Alternative to the Fourier-based approach, this study proposes the use of a method for nonlinear, nonstationary data processing (Huang, *et al*. 1998), referred to as Hilbert-Huang transform (HHT), to depict nonlinear features from nonstationary vibration recordings.

The HHT method consists of Empirical Mode Decomposition (EMD) and Hilbert Spectral Analysis (HSA). Any complicated time domain record can be decomposed via EMD into a finite, often small, number of intrinsic mode functions (IMF) that admit a well-behaved Hilbert transform. The IMF is defined by the following conditions: (1) over the entire time series, the number of extrema and the number of zero-crossings must be equal or differ at most by one, and (2) the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero at any point. An IMF represents a simple oscillatory mode similar to a sinusoidal component in FSA, but more general.

The EMD explores temporal variation in the characteristic time scale of the data and thus is adaptive to nonstationary data processes. The HSA defines an instantaneous or time-dependent frequency of the data via Hilbert transformation of each IMF component. The confidence limits of these two unique features are further examined by Huang, *et al*. (2003), making the HHT method more robust and reliable in analysis of nonlinearity-related, nonstationary data and revealing a possible enhanced interpretive value, alternative to Fourier components and amplitude spectrum.

The HHT representation of vibration recording $X(t)$ is

$$X(t) = \Re \sum_{j=1}^{n} a_j(t) e^{i\theta_j(t)} = \Re \sum_{j=1}^{n} [C_j(t) + iY_j(t)] \tag{1}$$

where $C_j(t)$ and $Y_j(t)$ are respectively the j-th IMF component of $X(t)$ and its Hilbert transform $Y_j(t) = 1/\pi P \int (C_j(t'))/(t-t')dt'$ with P denoting the Cauchy principal value, and the time-dependent amplitudes $a_j(t)$ and phases $\theta_j(t)$ are the polar-coordinate expression of Cartesian-coordinate expression of $C_j(t)$ and $Y_j(t)$, from which the instantaneous frequency is defined as $\omega_j(t) = d\theta_j(t) / dt$. The Hilbert amplitude spectrum $H(\omega, t)$ and marginal Hilbert amplitude spectrum $h(\omega)$ over time duration T of the data are defined as

$$H(\omega, t) = \sum_{j=1}^{n} a_j(t) \tag{2}$$

$$h(\omega) = \int_0^T H(\omega, t)dt \tag{3}$$

While the marginal Hilbert amplitude spectrum $h(\omega)$ provides information similar to the Fourier amplitude spectrum obtained from short-time Fourier transform, its frequency term is different. Fourier-based frequency is constant over the harmonic function persisting through the data window, while HHT-based frequency varies with time. As the Fourier transformation window length reduces to zero, the Fourier-based frequency approaches the HHT-based frequency. Fourier-based frequency is, however, locally averaged and not truly instantaneous for it depends on the window length.

To illustrate the HHT-based characterization of system nonlinearity, the record in Fig. 2 is considered again. The Hilbert amplitude spectrum in Fig. 4 shows a clear picture of temporal-frequency energy distribution of the data, i.e., the nonlinear response with frequency dependence modulated around 1 Hz and bounded by 0.5 and 1.5 Hz, linear response at 15 Hz, and the decaying amplitude of the nonlinear response with the color changing from the beginning to the end of the record. In contrast, the Fourier amplitude spectrum in Fig. 3 distorts the nonlinearity information of the record by introducing higher-order harmonics, notably at 2 and 3 Hz. Note again that the Fourier amplitude spectrum obtained from short time Fourier transform can provide the information on temporal characteristics of the motion frequency, but cannot essentially solve for the aforementioned nonlinearity distortion. This point has been presented by the aforementioned analysis with Taylor expansion of the record, where data window is out

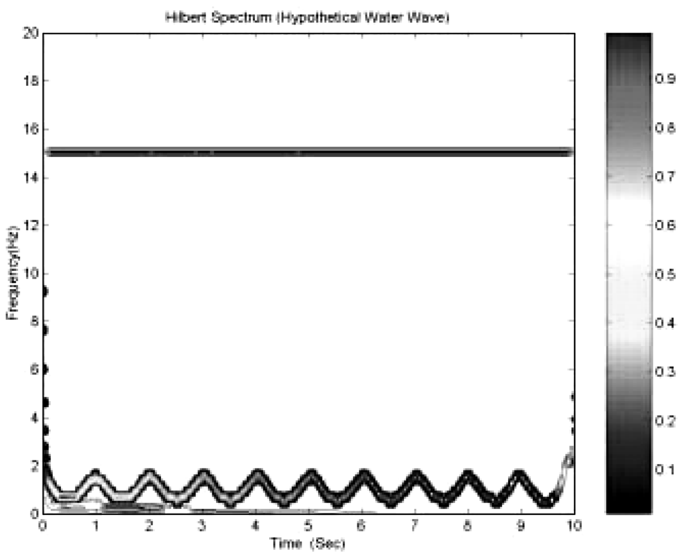


Fig. 4 Hilbert amplitude spectrum of the recording in Fig. 2

of the question. For comparison, the marginal Hilbert amplitude spectrum is also plotted in Fig. 3, showing truthfully the amplitude distribution of the motion in frequency.

Because of the above unique features in singling out the temporal change of the dominant frequencies from nonstationary recordings that are closely related to system nonlinearity, the HHT method finds broad applications, ranging from structural damage detection to nonlinear soil site identification (e.g. Zhang, *et al*. 2005a,b and 2006), among others. With the use of seismic recordings, Zhang (2006) shows that both Fourier- and HHT-based approaches are essentially equivalent in quantifying linear or weakly nonlinear soil with seismic wave motion. The HHT-based approach is however more effective in quantifying strong soil nonlinearity in terms of frequency downshift in the low-frequency range and amplitude-reduction factor in intermediate-frequency range than Fourier-based one.

For the capacity-related quality appraisal at hand, the HHT technique can also be applied to isolate the temporal change of fundamental natural frequencies from short-period, nonstationary recordings that are related to soil resistance and thus bearing capacity for large-amplitude loading, even if the change shown in the recordings is small in amplitude and short in time duration, or equivalently if the soil experiences a weak, short-period nonlinearity.

4. Conceptual framework of in-situ testing and analysis

Building on the previous analysis, a conceptual framework of in-situ vibrations and analyses is proposed for quality appraisal of non-slender, cast-in-place piles with irregular cross-section configuration, for which traditional approaches cannot be adequately used.

(1) In-situ pile-vibration tests in sequential are carried out, in which dropping a weight at different heights and/or dropping different weights at certain height generates series impulse loadings with low-to-high amplitudes. The high-amplitude impulse is designed in way that the load will generate equivalent static load that is equal to or larger than the designed bearing capacity of the pile. A seismometer mounted at the side of and near the top of the pile will record acceleration time history of the pile vibration to the impulse loading.

(2) With the use of HHT method for nonstationary data process and analysis, the fundamental natural frequency can be identified from the Hilbert amplitude spectrum of each recording. In addition, the design-based fundamental natural frequency of the pile can be conservatively estimated with the use of the designed bearing capacity and pile materials and configuration.

(3) Comparison of the fundamental natural frequencies identified from the recordings to a series of low-to-high impact loadings with the design-based frequency would tell if the total soil resistance force remains linear or nonlinear, for the total force is closely related to the frequency with confidence as discussed in section 2. In particular, if two sets of fundamental natural frequencies, identified respectively from the corresponding recordings to one low-amplitude and one high-amplitude impulse loadings, are the same as or larger than the design-based frequency, the pile is regarded as having achieved design quality. Otherwise, the pile is regarded as capacity deficiency, which can be quantified with the reduction of fundamental natural frequency identified in the recording to the high-amplitude impulse loading from that to the low-amplitude impulse loading and/or from the designed-based one.

(4) The true bearing capacity of the pile under test can be estimated with accuracy if the amplitude of impact loadings is further increased and analysis of the recordings is calibrated with static testing results. While evaluating true bearing capacity of piles is important, verification of piles with

designed capacity is typically the primary purpose of quality appraisal in practice. Such a quality evaluation will make the soil surrounding the pile remaining primarily linear and thus non-destructive if the designed quality is achieved.

5. applications to taipu water pump project

On June 22, 2001, three sets of in-situ vibration tests were performed in Taipu, Jiangshu Province of China for quality appraisal of three selected piles out of about 2,000 piles. The cross section of the piles is shown in Fig. 1. One sensor was installed in the side of and near the top of the pile, which can record the vertical vibration velocity of the pile subject to an impulse load that is generated by dropping a weight from a certain height. Fig. 5 shows the lifted weight hovering over the top of the pile which was covered by some materials to avoid bouncing back of the dropped weight on the pile.

For each pile under test, two lifted weights of 2.26 and 7.85 kN were used. The lifted heights are respectively 0.5 and 1 meter. The selected weights and heights are based on calculation, rules in codes, and engineers' experience (e.g. JGJ 94-94, 1994, JGJ 94-97, 1997, Rei 2001, Tang and Yei 1999). All the data sets were collected and then converted to acceleration time histories by Mr. Gang Chen from Shanghai Investigation, Design, and Research Institute, Minister of Water Resources in China. Due to inappropriate data acquisition and spoiled data sets (e.g. some peaks are cutoff in the recordings) primarily in testing pile one, only six quality data sets collected from the tests of piles two and three were analyzed below, which are shown in Figs. 6(a)-1l(a).

Figs. 6(a)-9(a) show the acceleration time histories of pile three induced by the series of low- to-high impulse loadings. While the amplitudes of responses proportionally increase with the amplitude of impulse loadings, the lowest dominant frequencies remain almost the same at 50 Hz, which is identified from Hilbert amplitude spectra in Figs. 6(b)-9(b). Note that the aforementioned dominant frequencies correspond to the local, high amplitude in the Hilbert amplitude spectra, exemplified as 50 Hz corresponding to the contour amplitude 75 at time period 0.012-0.014 s in Fig. 6(b).

The identified lowest dominant frequency 50 Hz is much larger than the design-based natural frequency of pile-soil system at 26 Hz in Table 3, implying that the pile has larger capacity than the designed one.

Fig. 5 A lifted weight to be dropped on the pile covered over its head with protection materials

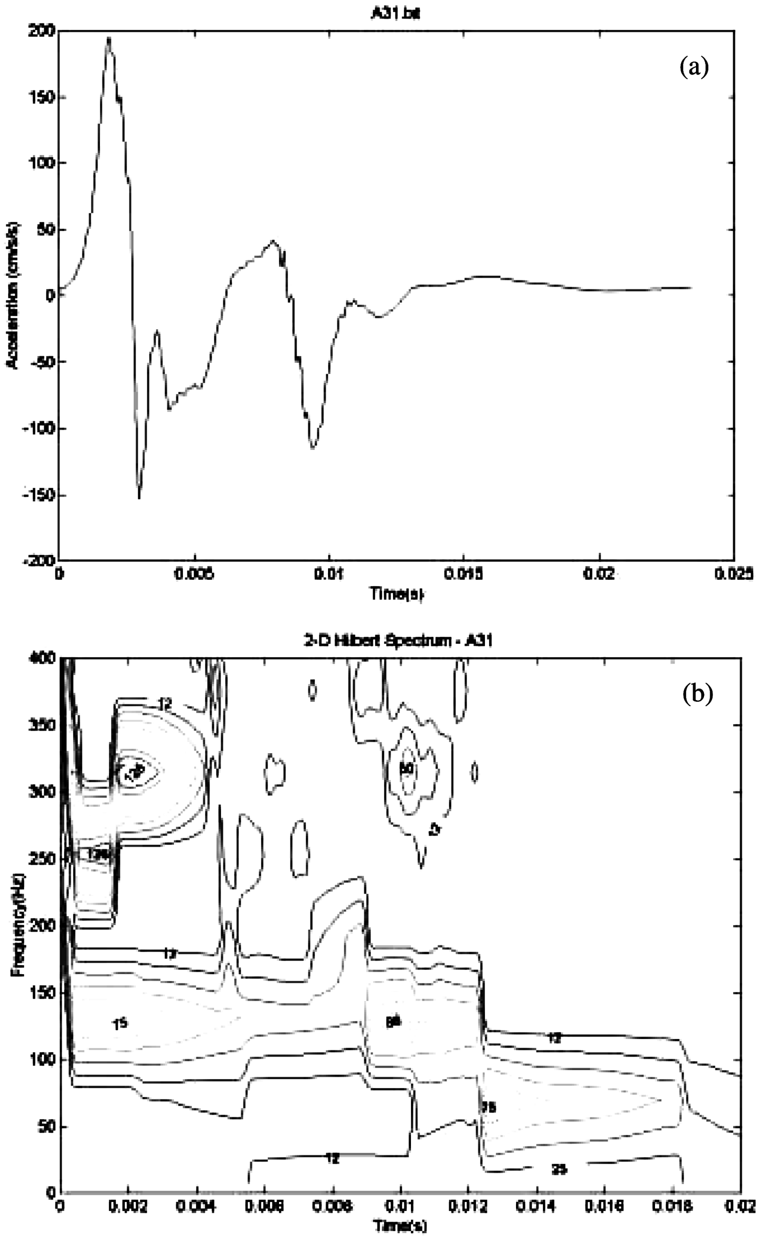
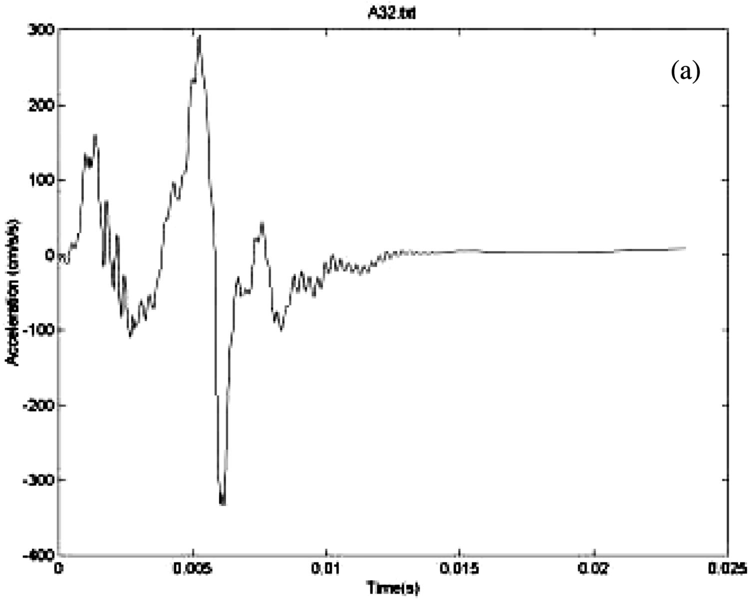


Fig. 6 (a) Acceleration time history of pile three under an impulse load 2.26 kN dropped from the height of 0.5 meter, (b) Hilbert amplitude spectrum of acceleration time history of pile three in Fig. 6(a) under an impulse load 2.26 kN dropped from the height of 0.5 meter

This does not, however, mean that the true capacity of the pile under investigation is proportionally higher than the design-based one, for the condition of the pile under test is quite different from that for the design-based calculation. In particular, the soil is fully saturated in the test, while underground water table is not considered in the design-based calculation. Nevertheless, this does not greatly influence the study that focuses on the relative change of the proposed frequency index.



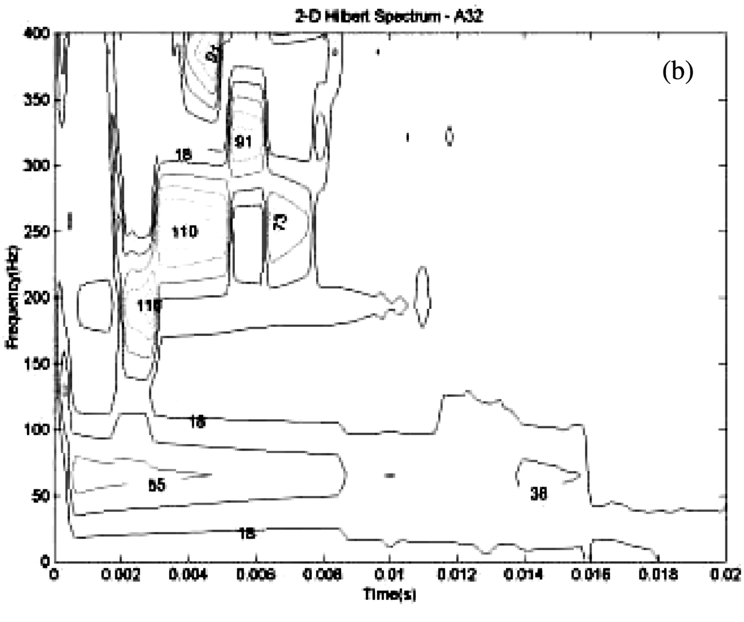


Fig. 7 (a) Acceleration time history of pile three under an impulse load 2.26 kN dropped from the height of 1.0 meter, (b) Hilbert amplitude spectrum of acceleration time history of pile three in Fig. 7(a) under an impulse load 2.26 kN dropped from the height of 1.0 meter

If the capacity of the pile was not as large as designed one, the soil resistant force of the pile-soil system might become nonlinear and thus reduced in amplitude under a large-amplitude impulse loading like the one by dropping the weight of 7.85 kN. One should therefore observe the downshift of the lowest dominant frequency. However, the corresponding Hilbert amplitude spectra in Figs. 8(b) and 9(b) do not

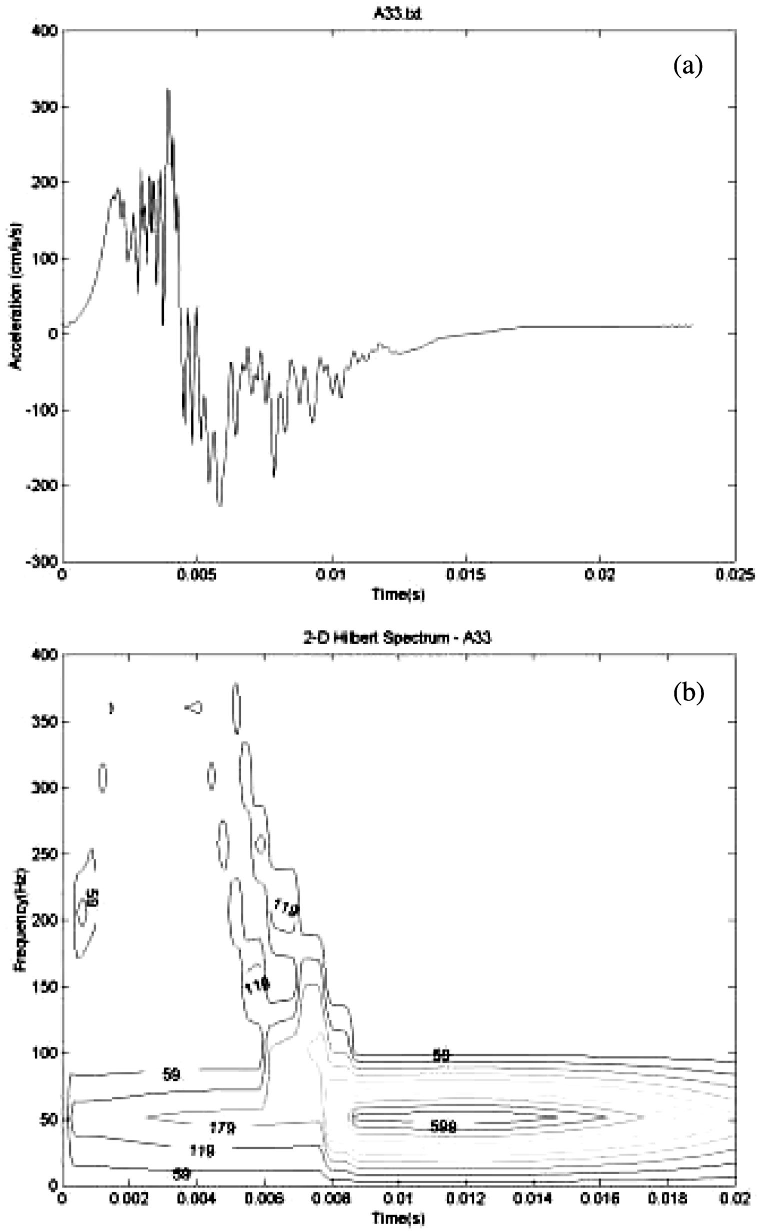


Fig. 8 (a) Acceleration time history of pile three under an impulse load 7.85 kN dropped from the height of 0.5 meter, (b) Hilbert amplitude spectrum of acceleration time history of pile three in Fig. 8(a) under an impulse load 7.85 kN dropped from the height of 0.5 meter

show such phenomena. This suggests that the pile under test achieves the designed quality in terms of bearing capacity.

The above conclusion from pile three can be further supported from Figs. 10(a,b) and 11(a,b) for the pile two, in which the dominant low frequency is reduced from 50 Hz with low-amplitude

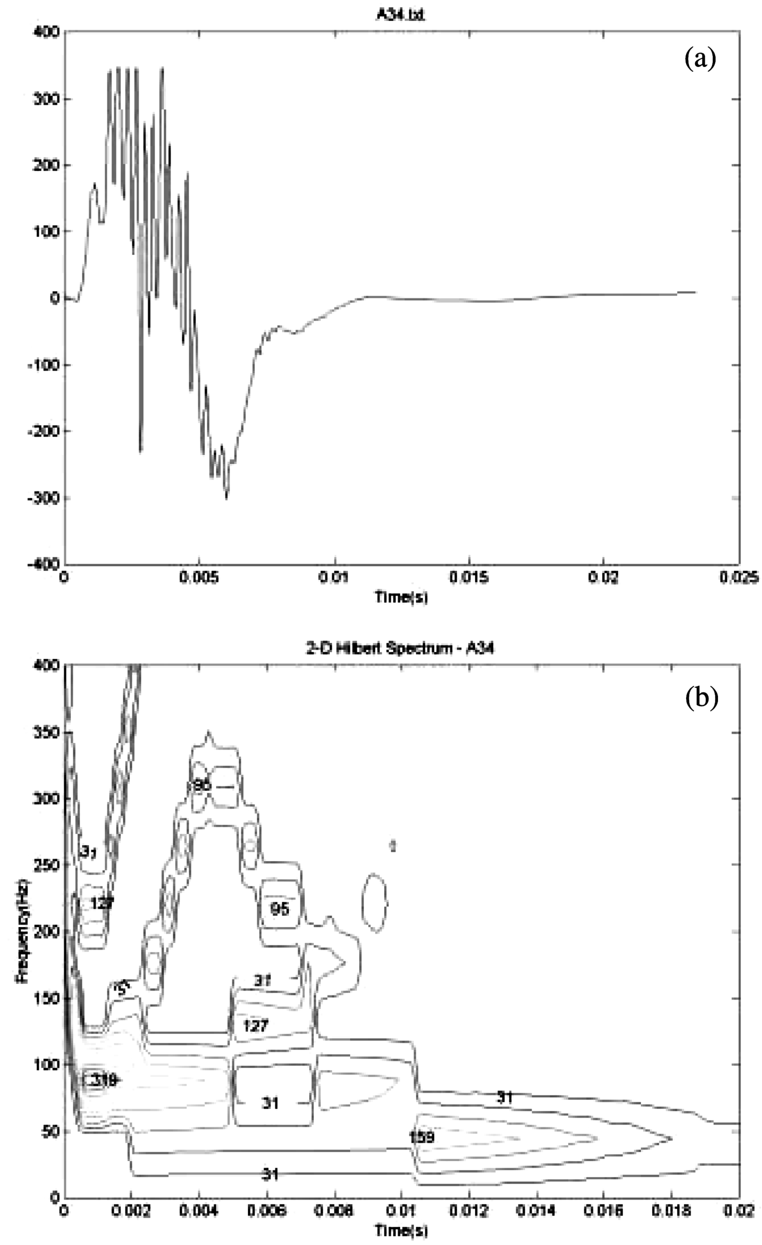


Fig. 9 (a) Acceleration time history of pile three under an impulse load 7.85 kN dropped from the height of 1.0 meter, (b) Hilbert amplitude spectrum of acceleration time history of pile three in Fig. 9(a) under an impulse load 7.85 kN dropped from the height of 1.0 meter.

loading to about 30 Hz with high-amplitude loading, which is still larger than the design- based one.

The above case study suggests that the proposed approach is trustworthy in quality appraisal of cast-in-place piles based on limited number of testing.

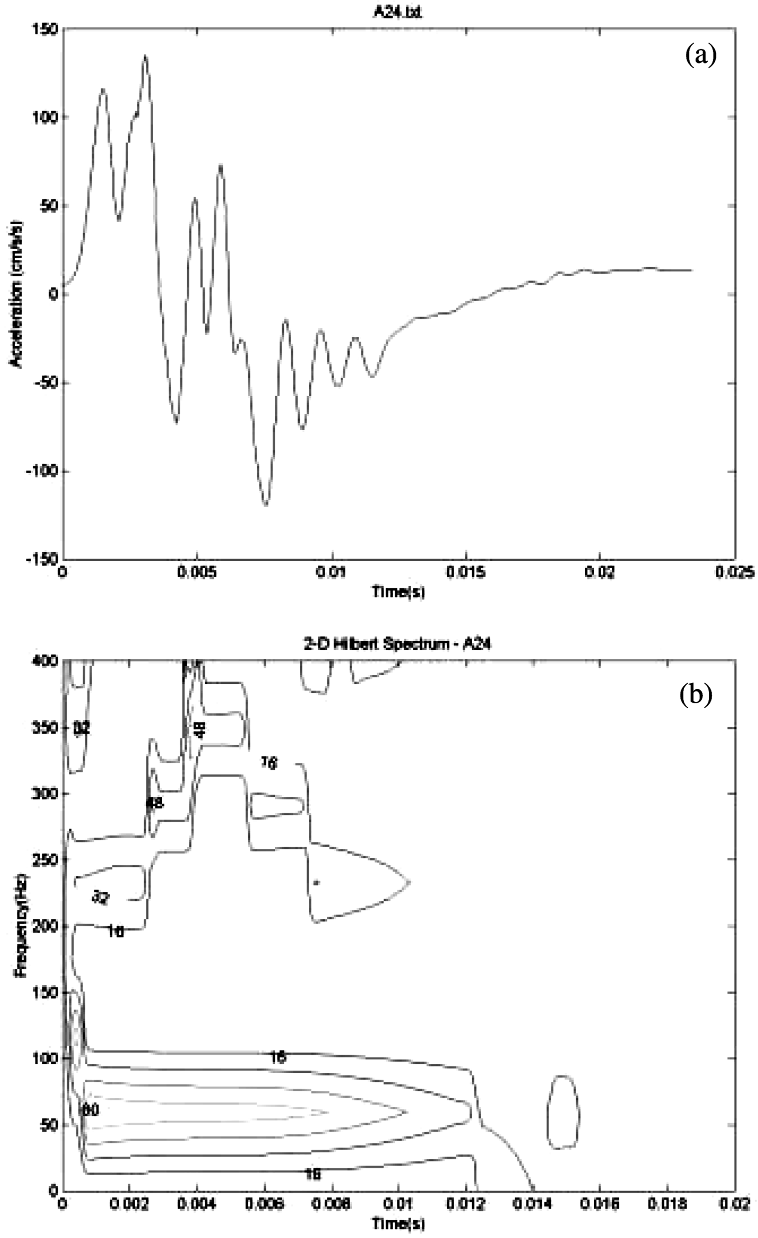


Fig. 10 (a) Acceleration time history of pile two under an impulse load 7.85 kN dropped from the height of 0.5 meter, (b) Hilbert amplitude spectrum of acceleration time history of pile two in Fig. 10(a) under an impulse load 7.85 kN dropped from the height of 0.5 meter

6. Conclusions and discussions

Following the review of existing approaches for capacity evaluation of piles and qualitative analysis of response recordings in piles, a framework of in-situ vibration testing and analysis is proposed for capacity-related quality evaluation of the non-slender, cast-in-place piles with irregular cross-section configuration.

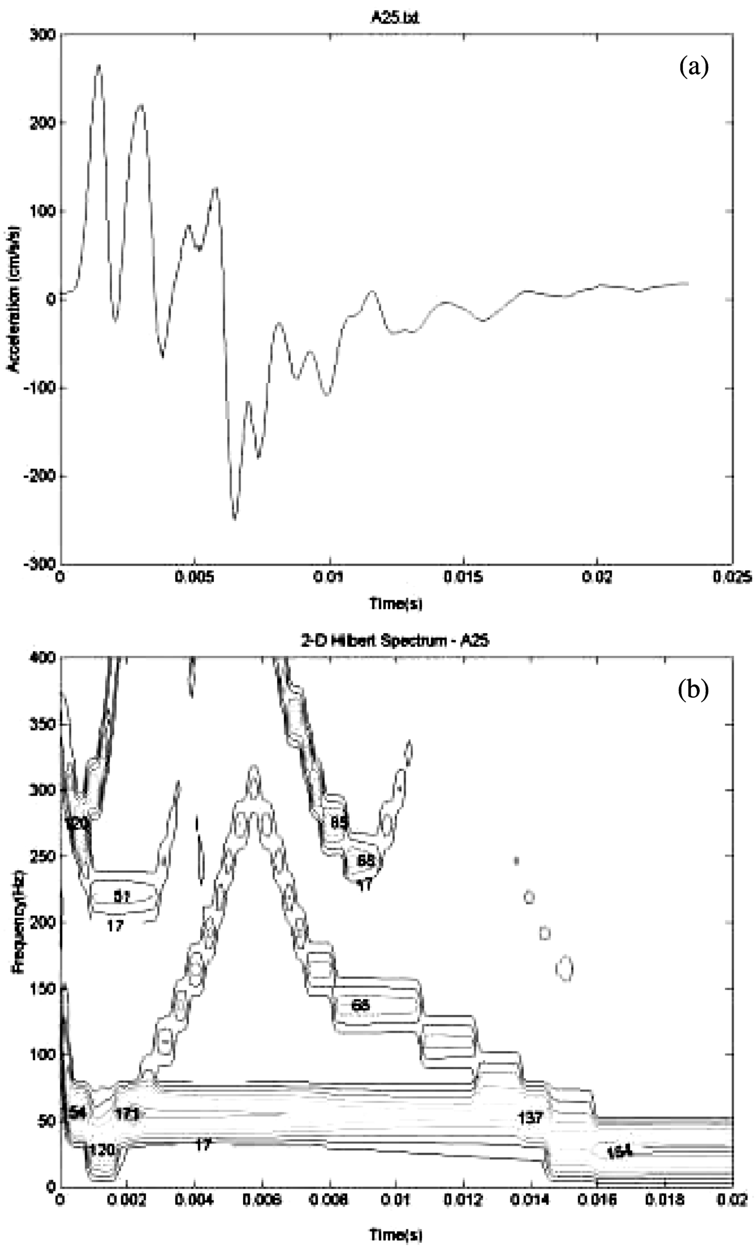


Fig. 11 (a) Acceleration time history of pile two under an impulse load 7.85 kN dropped from the height of 1.0 meter, (b) Hilbert amplitude spectrum of acceleration time history of pile two in Fig. 11(a) under an impulse load 7.85 kN dropped from the height of 1.0 meter

The proposed approach is also applied to evaluate the quality of selected piles in Taipu water pump project, showing promising and viable.

It should be pointed out that the proposed framework and in-situ testing results from this study rely on the vibration- and wave-based qualitative analysis of frequency signature in response recordings of pile-soil system. They must, therefore, be validated by model-based simulation, which is the subject of future research. In addition, the problem under investigation is strongly stochastic. Therefore, establishment of statistical bounds for the identified or to-be-identified physical quantities (e.g. frequency or capacity) would improve the reliability of the quality appraisal of piles. However, the limited number of available in-situ vibration tests provided insufficient data sets for a statistical approach. Consequently, the results and conclusions drawn from the study could be improved with other in-situ vibration data sets.

This study also suggests the use of HHT method for singling out the capacity-related fundamental natural frequency from short-period, nonstationary recordings, alternative to Fourier spectral analysis. While this study does not provide the comparison study of the two data-analysis approaches in solving the problem at hand, interested readers can see the like in detail in Zhang, *et al*. (2005a,b) and Zhang (2006), in which the unique feature of the alternative HHT method is thoroughly investigated with Fourier spectral analysis as a reference tool in accurately exploring time-dependent fundamental natural frequency from short-period, nonstationary recordings.

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References

Abu-Hejleh, N, O'Neill, M. W., Hannerman, D. and Atwooll, W. J. (2003), "Improvement of the geotechnical axial design methodology for Colorado's drilled shafts socketed in weak rocks", *Colorado Department of Transportation*; Report No, CDOT-DTD-R-2003-6.

ASTM D4945-89 (1989), *Standard Test Method for High Strain Dynamic Testing of Piles*. American Society for Testing and Materials.

Coduto, D.P. (2001) *Foundation Design, Principles and Practices*, Prentice Hall, Upper.

Saddle River, New Jersey. Goble Rausche Likins and Associates, Inc. (1995), *CAPWAP Manual*, Ohio, USA. JGJ 94-94 (1994). *Technical Code for Building Pile Foundation*, The Ministry of Building and Construction of the People's Republic of China.

JGJ 106-97 (1997), *Specification for High Strain Dynamic Testing of Piles*, The Ministry of Building and Construction of the People's Republic of China.

Rausche, F., Goble, G. G. and Likins, G. E. (1985), "Dynamic determination of pile capacity", *J. Geotech. Eng.*, **111**, 367-383.

Huang, N. E., Zheng, S., Long, S. R., Wu, M. C., Shih, H. H., Zheng, Q., Yen, N-C., Tung, C. C. and Liu, M. H. (1998). "The empirical mode decomposition and Hilbert spectrum for nonlinear and nonstationary time series analysis", *Proc. Roy. Soc. Lond.*, A**454**, 903-995.

Huang, N. E., Wu, M. L., Long, S. R., Shen, S. P., Wu, W., Gloersen, P. and Fan, K. L. (2003), "A confidence limit for the empirical mode decomposition and Hilbert spectral analysis", *Proc. Roy. Soc. London.*, A**459**, 2317-2345.

Priestley, M. B. (1981), *Spectral Analysis and Time Series, Vol. 2., Multivariate Series, Prediction and Control*, Academic Press, London.

Rei, L. Y. (2001), *Dynamics of Pile Foundation*, Yan-jin Industrial Publisher, Beijing.

Tang, Y. Q. and Yei, W. M. (1999), *Handbook of Testing Techniques in Civil Engineering*, Tongji university Publisher, Shanghai.

Worden, K. and Tomlinson, G. R. (2001), *Nonlinearity in Structural Dynamics - Detection, Identification and Modeling*, Institute of Physics Publishing, Bristol and Philadelphia.

Zhang, R., King, R., Olson, L. and Xu, Y. L. (2005a), "Dynamic response of the Trinity River Relief bridge to controlled pile damage: modeling and experimental data analysis comparing Fourier and Hilbert-Huang techniques", *J. Sound Vib.*, **285**, 1049-1070.

Zhang, R., Hartzell, S., Liang, J. and Hu, Y. X. (2005b), "An alternative approach to characterize nonlinear site effects", *Earthq. Spectra*, **21**(1), 243-274.

Zhang, R. (2006), "Characterizing and quantifying earthquake-induced site nonlinearity", *Soil Dyn. Earthq. Eng.*, **26**(8), 799-812.

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