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Research Paper

STRUCTURAL INTEGRITY EVALUATION OF PILE FOUNDATIONS BY PILE INTEGRITY TESTING

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Many civil structures, such as buildings, bridges, towers, dams and other massive structures sometimes need special foundation in the form of piles, built using precast and cast in situ techniques. Sometimes, precast piles may get damaged under the pile driving impact process, due to which long and deep cracks may appear. On the other hand, "necks" or "bulbs" may be created in the process of drilling. In both cases, these defects may affect considerably the bearing capacity of the piles. So the structural evaluation and monitoring of new and existing piles are becoming increasingly important. This is normally carried out by using pile integrity tester (PIT), which is a non-destructive integrity testing instrument for assessing the integrity of pile foundations. The instrument consists of a small accelerometer, a hand held hammer and a data acquisition unit. The length and defects in pile foundations are evaluated by identifying and analyzing the travelling time, phase, direction, and the amplitude of the reflections captured by the accelerometer. This paper presents a study on the damage mechanics of typical cast in situ pile foundations through PIT.

Keywords: Transient dynamic analysis, resolution, mobility.

INTRODUCTION

Pile foundations have been widely used to support heavy superstructures on soft soil. A pile foundation may be either prefabricated and driven into soil or constructed in situ. During or after the construction, a pile is often inspected for possible defects and flaws. The importance of assessing the actual quality of a pile foundation has long been recognized. To achieve this goal, various kinds of destructive and nondestructive tests were developed. (Nasser Massoudi and Wondem Teffera, 2004, Daniel Ambrosini and Javier Ezeberry, 2005, Kuo-Feng Lo, Sheng-Huoo Ni and Yan-Hong Huang, 2010). In this aspect, Nondestructive Testing (NDT) was considered

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to possess high potential for application because it is featured as cost-effective, damage-free, and time saving. The impact-echo technique, based on the use of transient elastic waves, was developed many years ago for non-destructive detection of defects in pile foundation structures. However, with the development of hardware in computers and new sensors and dynamic response measuring equipment, it is possible now to use this method for long piles.

THEORETICAL BASIS

Pile Integrity Test (PIT) is based on one dimensional stress wave theory. Wave propagation through a prismatic rod can be easily derived and the second order partial differential equation that governs the process can be written as:

$$V_P^2 \frac{\partial^2 u}{\partial x^2} - \frac{\partial^2 u}{\partial t^2} = 0; \; V_p = \sqrt{\frac{EA}{\rho A}} = \sqrt{\frac{E}{\rho}} \qquad ...(1)$$

where *u, x* = Displacement/Co-ordinate in the axial (longitudinal) direction; V_p is the wave propagation velocity in axial direction; E, ρ, A are respectively modulus, mass density and area of cross section of the pile foundation (Yan-Hong Huang *et al.,* 2010, Schellingerhout and Van Rietschoten-Rietveld, 2011). For a linear elastic pile having a length an order of magnitude greater than its width, stress waves travel in the pile at a wave speed, V_p, such that $V_p = \sqrt{\frac{E}{\rho}}$ where *E* is the pile material elastic modulus and ρ is its mass density. The applied force, F, imparted by hammer impact and the particle velocity, v, at any point are related such that F = Z v.

where Z is proportionality constant, also known as impedance. (Liang and Beim, 2008). Pile impedance for various size piles can be defined as Z = E A / c .The inverse of pile impedance is defined as mobility (N).

Change in impedance is related to change in pile cross-sectional area A, as well as pile material quality. Increase in pile impedance or soil resistance forces results in a decrease in measured pile top velocity. Conversely, decrease in pile impedance, results in increased velocity. By observing changes in impedance, pile quality can be assessed and dimensions estimated.

EXPERIMENTAL INVESTIGATIONS

Stress wave propagation tests using PIT were performed on nine selected piles of a bridge site. These piles were meant to support the piers and abutments of the bridge girder. These piles are of 1.0 m diameter and the depth varies from 20 m to 30 m. One pile out of four piles below each pier (there are seven piers) and one pile out of eight piles below each abutment (two abutments) were tested for structural integrity. Description of the piles selected for PIT are given in Table 1.

Instrumentation Used

Instrumentation involved a Pile Integrity Tester manufactured by M/s Pile Dynamics Inc consisting of an accelerometer and an instrumented impact hammer fitted with force transducer (Gassman and Finno, 1999). A fast Fourier transform is performed on both the force and the velocity signals. The resulting velocity spectrum is divided by the force spectrum to give the mobility as a function of frequency. The response signals from the accelerometer and the force transducers are conditioned by respective conditioning amplifiers in the PIT instrument and displayed. The data analysis is done in two methods.

Pulse Echo Method

Pulse echo method requires the measurement of only velocity record. Powerful record enhancement techniques are available and presents resulting curves as function of time.

Transient Response Method

Transient response method requires both pile top motion and impact force record. Results are displayed in frequency domain. For each pile six impacts were used and the averaged time response data is taken for further analysis. PIT allows the user to obtain PIT data from a PIT Collector, analyze records in the time or frequency domain.

Properties and Parameters Description

LO Low pass filter number in length unit (m or ft).

HI High pass filter number in length unit (m or ft).

Fds Frequency value at which dynamic stiffness is calculated.

Z The impedance calculated from wave speed, area, and specific weight (Z=SW*WS*AR/g, where g is the acceleration due to gravity)

Stiffn The dynamic stiffness corresponding to the Fds value mentioned above in MN/m (1000 kips/ft or 1000 tons/m).

Sqrt(PQ) A characteristic or average non-dimensional mobility value in terms of 1/Z.

VMX The maximum velocity in cm/s.

FMX The maximum force in kN

METHODOLOGY

The methodology adopted is termed as stress wave propagation based non-destructive pile integrity testing. (Frank Rausche *et al.,* 1991, Ernst Niederleithinger and Alexander Taffe, 2006). Methodology of stress wave propagation involves giving a small force impulse using a hammer strike at the top of an existing pile and capturing the dynamic response in terms of velocity. The stress wave travels through the length of the pile and gets reflected from the toe and returns back. The time elapsed between the wave start captured through a trigger and the return wave indicate twice the length of the pile. The compression wave velocity is taken as 4000 m/s. Figures 1 and 2 show typical instrumentation setup in PIT and view of a typical pile selected for investigation.

Figure 1: Experimental Setup

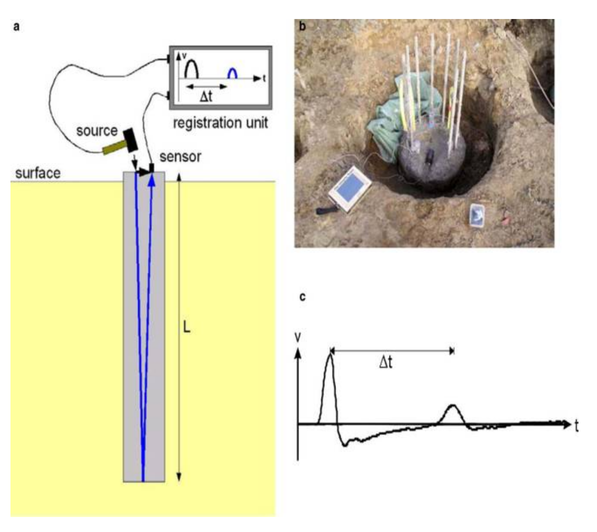


Figure 2: Pier7-P1

Resolution of Impulse Response Signals

[2] Resolution of impulse response signals can be defined in terms of the ratio of *P/Q,* the maximum and minimum mobilities. If the *P/Q* ratio for a given resonance approaches 1, then it cannot be identified as such, and thus the resolution is an important indicator of the applicability of the test to a given set of conditions.

For a cylindrical rod embedded in a uniform elastic material, the resolution is primarily a function of the *l/D* ratio, the ratio of the shear-wave velocity of the soil to that of concrete, and the ratio of soil density to concrete density.

The shaft mobility N is given by

$$N = \sqrt{PQ}$$

RESULTS

Figure 3 represents ideal mobility plot. Δf is the difference in frequencies corresponding to consecutive peak mobility value(V/F).The length of pile can be determined using Δf.

Table 1 summarizes the length of pile with varying cutoff levels. Figure 4 represents the

Figure 3: Ideal Mobility Plot

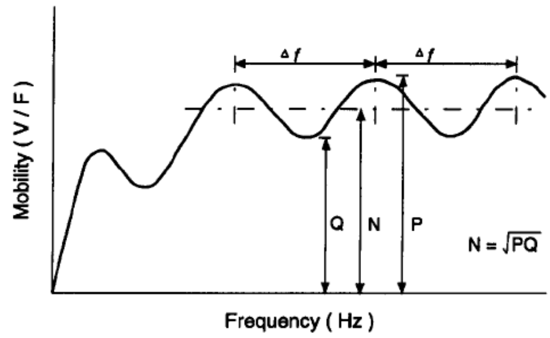
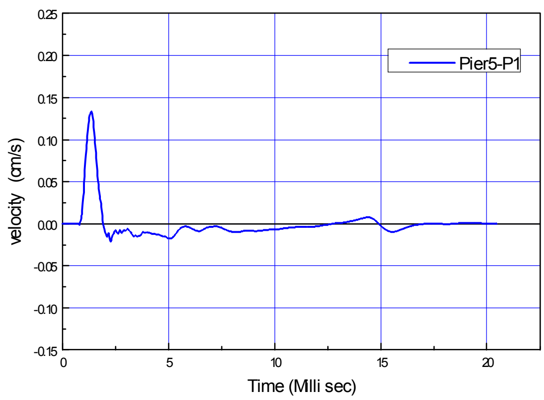


Table 1: Determination of Pile Length Using Pile Integrity Tester

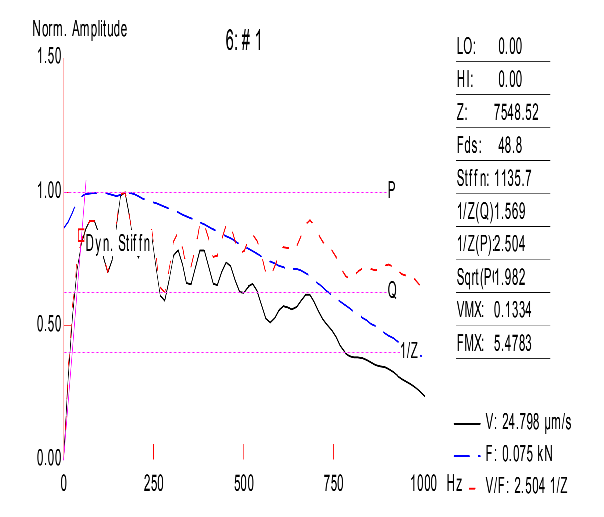
S. No.	Description of the Pile	Inferred Pile Length (m)
1.	Pier-1-Pile-1 (P11)	26.40
2.	Pier-2-pile-1 (P21)	26.56
3.	Pier-2-pile-4 (P24)	25.80
4.	Pier-3-pile-1 (P31)	26.60
5.	Pier-4-pile-1 (P41)	28.68
6.	Pier-5-pile-1 (P51)	24.68
7.	Pier-6-pile-3 (P63)	25.24
8.	Pier-7-pile-1 (P71)	20.96
9.	Abutment –A1, pile-7	25 to 26 m

Figure 4: Velocity Response of Pier5-P1



velocity response of a particular pile(P-51). Figure 5 represents the velocity, force, mobility spectra of record of pile designated as Pier-5-pile-1 (P51).

Figure 5: Velocity, Force and Mobility Spectra of Record for Pier5-P1



SUMMARY AND OBSERVATIONS

Experimental investigations were conducted on 9 piles using pile integrity tester and length of pile foundations were determined by axial wave propagation analysis.

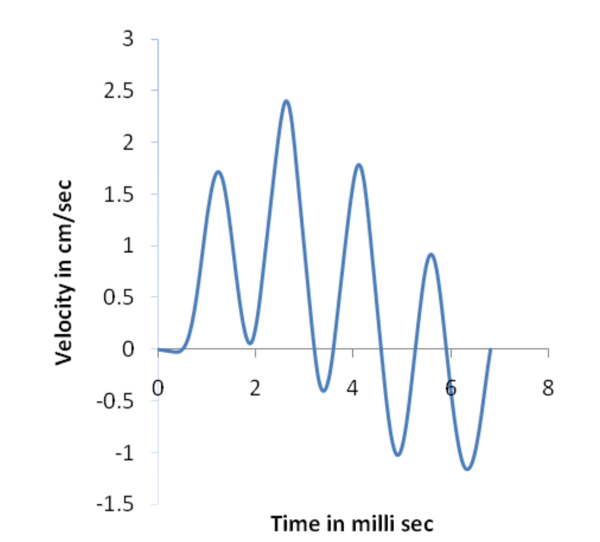
1. Vibration signatures collected from piles on pier-2, pier-4 and abutment-1 has not clearly indicated a reflection wave pattern from the toe.
2. The pile below abutment-1 (A1-P7) has shown that the finished mortar surface has been highly interfering with the regular vibration data.
3. For Pier-4, pile-1, a reflected wave from 7.0 m of level from the top is seen, which indicates a potential non-homogeneous concrete at that level.
4. For Pier-2, pile- 4 and pile-1 reflected waves from 6.8 m and 7.2 m of level from the top is seen, which indicates a potential non-homogeneous concrete at that level.

GEOMETRICAL AND MATERIAL PROPERTIES OF MEMBER

Description of Axial Member

The beams were of 150 mm x 150 mm cross-section and overall length of 2.5 m. For introducing the damage, the width of member was reduced from 150 mm to 100 mm for the central section for a length of 250 mm. The members were designed based on limit state theory. In the undamaged beam, four 12 mm diameter bars at top and bottom were provided throughout the length whereas in damaged member, two 12 mm diameter bars at top and bottom were curtailed for the damaged portion. Two legged vertical stirrups of 6 mm diameter at 100 mm c/c were used as shear reinforcement.

Figure 6: Velocityof Axial Member

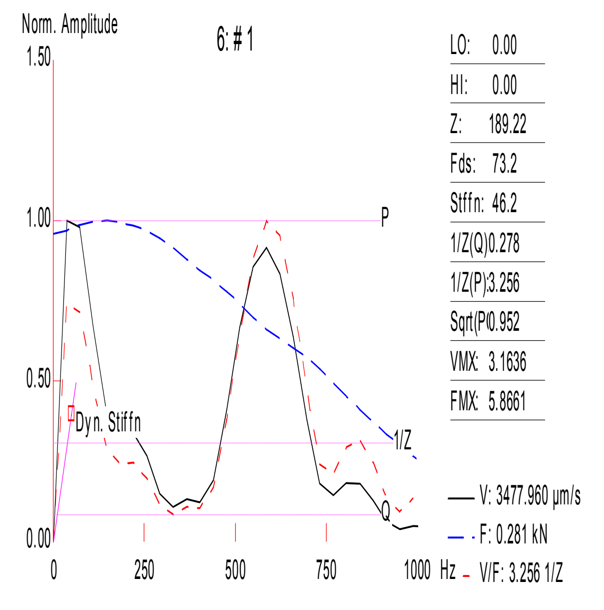


RESULTS AND DISCUSSION

$$N_{min,max} = \sqrt{P}.Q_{min,max}$$

$$C_p = 2149 \text{ m/s}$$

Figure 7: Velocity, Force and Mobility Spectra of Beam



$$N_{min} = \sqrt{(3.256 \times 0.278)} = 0.951$$

$$N_{max} = \sqrt{(3.256 \times 0.21)} = 0.827$$

$$A_{min} = \frac{1}{0.951 \times 2500 \times 2149 \times 0.00001}$$

$= 0.0196\text{m}^2$

$$A_{max} = \frac{1}{0.827 \times 2500 \times 2149 \times 0.00001}$$

$= 0.0225\text{m}^2$

Percentage reduction in area

$$= \frac{0.0225 - 0.0196}{0.0225} \times 100$$

$= 12.89\%$

Table 2: Results of Frequency Domain Analysis

Freq in Hz	V: 3477.960 µm/s	F: 0.281 kN	V/F: 3.256(1/Z)
0	0.00001	0.95772	0.00001
36.62109	1	0.9695	0.74295
73.24219	0.97819	0.98581	0.71472
109.8633	0.66833	0.99774	0.48248
146.4844	0.40274	1	0.29009
183.1055	0.33555	0.9943	0.24308
219.7266	0.33762	0.984	0.24714
256.3477	0.26733	0.96864	0.19879
292.9688	0.15121	0.94528	0.11522
329.5898	0.10852	0.91388	0.08553
366.2109	0.13332	0.8792	0.10922
402.832	0.12434	0.84626	0.10583
439.4531	0.19157	0.81485	0.16934

Table 2 (Cont.)			
Freq in Hz	**V: 3477.960 μm/s**	**F: 0.281 kN**	**V/F: 3.256(1/Z)**
476.0742	0.41332	0.78034	0.38151
512.6953	0.6672	0.7401	0.64934
549.3164	0.85534	0.69779	0.88293
585.9375	0.9168	0.66036	1
622.5586	0.83502	0.63084	0.95342
659.1797	0.63709	0.60499	0.7585
695.8008	0.38181	0.57561	0.47778
732.4219	0.18126	0.5389	0.24228
769.043	0.14563	0.49658	0.21123
805.6641	0.18477	0.45306	0.29375
842.2852	0.18083	0.41161	0.31644
878.9063	0.12799	0.37284	0.24726
915.5273	0.06398	0.33603	0.13714
952.1484	0.0395	0.30076	0.0946
988.7695	0.0506	0.26722	0.1364

Length of the member = $\frac{C_p}{2\Delta f}$

$$= \frac{2149}{2 \times 476} = 2.26\,m$$

The difference in frequencies corresponding to consecutive peak mobility values is obtained from table 2.The frequency value obtained from table 2 is 476Hz.This ?f value is used to determine the length of member.

SUMMARY AND CONCLUSION

Experiment was conducted on axial wave propagation to find out velocities, length of pile and damage. The plots are shown and analysis results are tabulated in Table 2.

1. The duration of initial reflection is greater than the time taken for the wave to reflect back from toe and reach the top.
2. The duration of impact force should be less than time required for wave to reflect and return to the top for determination of length of pile from velocity response plot.

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