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Soil Damping Effects on Integrity Test of Piles

Ramli Bin Nazir*, Osman El Hussien

Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor Malaysia

*Corresponding author: ramlinazir@utm.my

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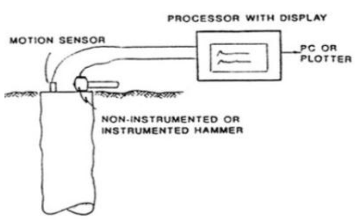
Graphical abstract



Abstract

The effects of surrounding soil on pile integrity test results are still not precisely quantified despite its influence on test output. It is usually difficult to assess the integrity of piles socketed in hard soil strata due to soil damping effects. A method of calculating soil damping effects on stress wave force and velocity values during pile integrity test is presented. Theoretical model based on numerical solution of wave equation was formulated. This model incorporates soil resistance effects on wave propagation in piles. Results generated from the proposed model was compared with PIT-S software, which simulates low strain waves propagation in piles, assuming pile cast in very dense granular soil. The generated Force-Velocity curves were found to be similar comparing both methods; however, some variations were observed at pile toe due to the different procedures used for soil reaction estimation. Furthermore, the model produced results were compared with real in-situ pile integrity test and PIT-S results. The model had showed better prediction of pile toe received signal compared to PIT-S software.

Keywords: Pile, integrity, soil, damping.

1.0 INTRODUCTION

Pile integrity test is commonly carried out using acoustic testing techniques. Acoustic science includes the study of energy generation, transmission and reception in matter in terms of vibrational waves. Sonic sensation is the most common acoustic phenomenon. Low strain integrity test of piles (PIT) involves examining the response of the pile to light impact that creates compressive wave within pile body. The low strain pile integrity test procedure requires measurement and analysis of force and velocity records generated as a result of the excitation at pile top caused by hand held hammer. The PIT equipment should have signal amplification capability to enhance analysis of signals that are reduced by soil and pile material damping. However, it may be difficult in some cases to differentiate between soil and pile responses [1]. Sample of low strain pile integrity test setup is shown in Fig. 1.

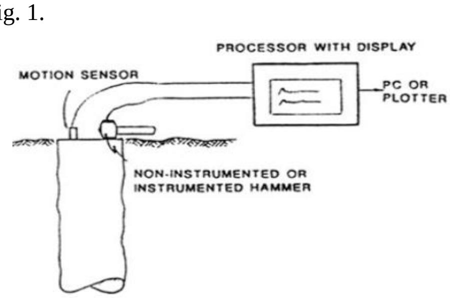


Figure 1 Pile integrity test setup [2]

While signal acquisition technology has improved to the extent that it is now relatively easy to record either echo or mobility signals on piles, the understanding of physical pile/soil interaction has progressed very little since 1970s and quantitative interpretation remains difficult [3]. Soil resistance effects are required to be properly considered for calculation of impedance profile. However, soil effects are never definitely known and for that reason engineering judgment may seriously affect the results [4]. Note that direct measurement of soil resistance or other soil parameters is not the objective of low strain integrity testing. Therefore no attempt has been made to formulate mathematical expressions relating soil resistance as a function of any of the parameters from the mobility spectrum [5].

Nevertheless, one of the disadvantages of the Pulse Echo method is that the records can be analyzed by signal matching to yield an indication of defect size or by the Impedance Log or Pile Profile Method; however, these more advanced analysis methods require assumptions for the effect of soil resistance on the recorded signals [4].

Hence, currently there is no clear idea about the effect of soil resistance on the stress wave propagation into piles as well as the soil impact on the applied analysis methodologies. This fact had caused engineers to go through assumptions in order to compensate for lack of proper identification of pile-soil interaction, which may jeopardize the quality of the test output.

2.0 MATHEMATICAL BACKGROUND

Assuming a bar, as shown in Fig. 2, having density (ρ) is subjected to dynamic force (P) resulted in linear displacement (u) in the (x) direction at time (t). The basic mathematical formulations is:

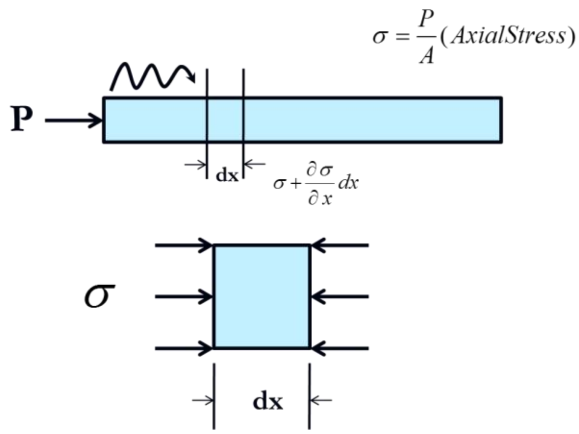


Figure 2 Schematic diagram for a bar subjected to dynamic force

$$-\sigma + \sigma + \frac{\partial \sigma}{\partial x}dx = \rho.dx\frac{\partial^2 u}{\partial t^2} \quad (1)$$

$$\frac{\partial \sigma}{\partial x} = \rho.\frac{\partial^2 u}{\partial t^2} \quad (2)$$

$$E = \frac{\sigma}{\varepsilon} \quad (3)$$

$$\varepsilon = \frac{\partial u}{\partial x} \quad (4)$$

Substituting equation (4) in equation (3),

$$\sigma = \frac{\partial u}{\partial x}E \quad (5)$$

Differentiating of equation 5,

$$\frac{\partial \sigma}{\partial x} = E.\frac{\partial^2 u}{\partial x^2} \quad (6)$$

Substituting in equation 2,

$$\frac{\partial^2 u}{\partial t^2} = \frac{E}{\rho}\frac{\partial^2 u}{\partial x^2} \quad (7)$$

Where,

$$\frac{\partial^2 u}{\partial t^2} = c^2\frac{\partial^2 u}{\partial x^2} \quad (8)$$

Where,

$$c = \sqrt{\frac{E}{\rho}} \quad (9)$$

Note that equation (8) is known as the wave equation.

3.0 MODEL FORMULATION

Equation (8) can be solved numerically considering the pile segment shown in Fig. 3, which shows an axial force acting on top of the segment and frictional forces acting on the circumference.

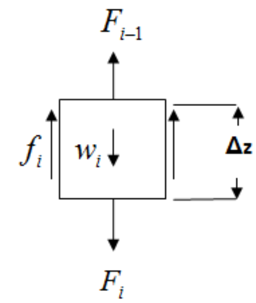


Figure 3 Forces acting on a pile segment subjected to an axial load

The numerical solution for the wave equation after incorporation of soil friction will be as follows:

$$F_i - F_{i-1} - f_i A_{si} = \rho A \Delta z \frac{v_i(t+\Delta t) - v_i(t)}{\Delta t} \quad (10)$$

$$f_i = M u_i \quad (11)$$

$$v_i = .\frac{u_i(t+\Delta t) - u_i(t)}{\Delta t} \quad (12)$$

$$F_i - f_i A_{si} = E_P A \frac{u_{i+1} - u_i}{\Delta x} \quad (13)$$

Where (f_i) is the skin friction generated at pile segment and (A_{si}) is the surface area of that segment. The above equations incorporate the skin friction in wave equation. In addition, (M) is the constant of proportionality between soil frictional stress and pile displacement following Kraft et al. [6] correlation:

$$f_i = \frac{G_s}{r_0.\ln(\frac{r_m}{r_0})} u_i \quad (14)$$

Where (r_0) is pile radius, (G_s) is soil shear modulus and (r_m) is the lateral distance from pile center where soil vibration caused by the dynamic force applied on the pile diminishes. In this model (r_m) value is estimated using ground vibration attenuation equation, Amick and Gendreau [7]:

$$A_1 = A_0 (r_0 / r_1)^{(\gamma)} e^{\alpha(r_0 - r_1)} \quad (15)$$

Where, (A_0), (A_1) are vibration amplitudes at (r_0), (r_1) distances respectively, (γ) is a coefficient depends on wave type and (α) is material damping coefficient.

Furthermore, soil effect at pile toe was introduced in the model through incorporating change of impedance at pile-soil interface and incorporating toe reaction. The incident, transmitted and reflected forces at pile-soil interface are shown in Fig. 4.

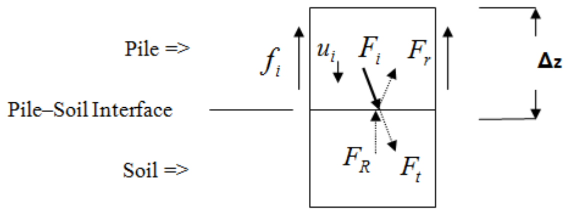


Figure 4 Forces acting at pile-soil interface

The reflected force (F_r) is correlated to the incident force at pile toe as follows:

$$F_r = [\frac{\frac{\rho_s v_s}{\rho_p v_p} - 1}{\frac{\rho_s v_s}{\rho_p v_p} + 1}] \quad F_i \tag{16}$$

Where (ρ_s) is soil density and (v_s) is wave velocity in soil.

The soil reaction (F_R) at pile toe is calculated as per the following correlation of Kagawa [8],

$$F_R = E_{sb} r_{0b} \delta_{0b} z + 2(1+\nu_{sb})\sqrt{\rho_{sb} G_{sb}}\, r_{0b}^2 \delta_{0b} T_3\, v_p \tag{17}$$

Where (F_R) is soil reaction at pile tip, (E_{sb}) is Young's modulus of soil, (r_{0b}) is radius of pile tip, (δ_{0b}) is soil reaction coefficient, (z) is pile tip displacement, (ν_{sb}) is Poisson's ratio of soil at pile tip, (ρ_{sb}) is soil density at pile tip, (G_{sb}) is shear modulus of soil at pile tip, (T_3) is polynomial function coefficient and (v_p) is pile tip velocity.

The model was assembled using the abovementioned correlations and then executed using computer programmed spreadsheets. The pile is discretized into small segments as shown in Fig. 3. Force and velocity values are calculated for each pile segment utilizing the numerical solution of wave equation after incorporation of soil friction provided in equations 10, 12 and 13. Soil friction was calculated using the friction-displacement and attenuation correlations provided in equations 14 and 15, respectively. Force distribution at pile toe is analyzed based on impedance change as well as dynamic soil reaction calculation following the correlations provided in equations 16 and 17, respectively.

Based on the above methodology, the force and velocity values were obtained for both downward and upward movement of stress wave in order to identify stress wave characteristics at different pile depths.

4.0 RESULTS AND DISCUSSION

4.1 Model and PIT-S Software Comparison

The output of the abovementioned analysis procedure is compared with PIT-S software output. PIT-S is simulation software, which takes user input data such as soil properties; pile information and impact load characteristics, and then execute the analysis and displays force and velocity curves. The following soil, pile and dynamic load data was used in the analysis for methods assuming concrete pile cast in very dense granular soil

Table 1 Soil, pile and impact load data used in the analysis

Item	Value
Pile Length, L (m)	10.0
Concrete Density, ρ_c (t/m^3)	2.5
Pile elastic modulus, E (kN/m^2)	4x10^7
Pile Radius, r_0 (m)	0.18
Soil Density, ρ_s (t/m^3)	2.0
Poisson's Ratio, ν	0.4
Soil Shear Modulus, G (kN/m^2)	50,000
Force Amplitude, F (kN)	5.0
Pulse duration, (sec)	0.00025
Attenuation coefficient(γ)	1.0
Attenuation coefficient(α)	0.13

Pile influence radial distance (r_m) is calculated using equation 15 after substitution of the abovementioned pile-soil data. Wave amplitude attenuation with radial distance is shown in Fig. 5. As shown in the figure, the attenuation reaches 95% at 2.6m radial distance. Hence, (r_m) is considered as 2.6m.

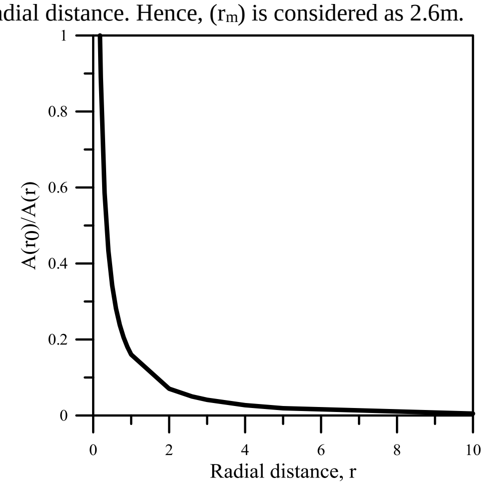


Figure 5 Wave attenuation at different radial distances from pile center

The velocity curves in time domain based on PIT-S and numerical analysis are provided in Fig. 6 and Fig. 7, respectively. Furthermore, the generated force and velocity amplitudes are provided in Table 2.

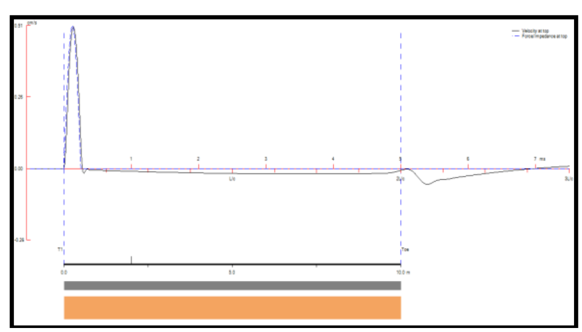


Figure 6 PIT-S software velocity versus time at 0.0m depth

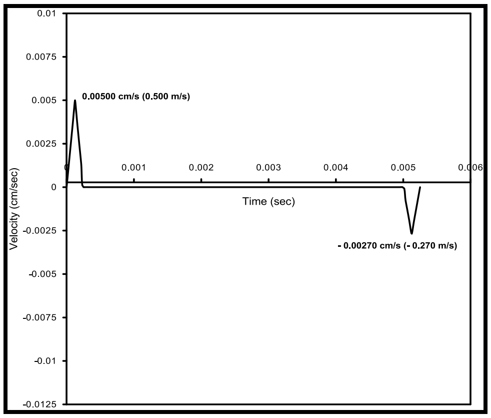


Figure 7 Numerical analysis velocity versus time at pile top

Table 2 Produced velocity amplitudes at different depth using numerical analysis and PIT-S software

Depth (m)	v (m/s) (Model)	v (m/s) (PIT-S Software)
0.000	0.500	0.507
5.000	0.385	0.392
9.875	0.392	0.321

At 0.0m depth the wave has its initial amplitude, while at 5.0m and 9.875m depths the wave will be received after travelling down to pile toe and then partially reflected to the target depths. It has been noticed that the force and velocity amplitudes received at pile top and mid of pile are more close for the two different methods compared to the velocity amplitude value produced at 9.875m depth near pile toe as shown in Fig. 8 and Fig. 9. This is attributed to the differences between both methods in terms of tackling pile-soil interaction at pile toe.

The introduced method of analysis assumes that soil effect takes place at pile toe due to the change in impedance between pile and soil materials at pile-soil interface as well as the effect of soil reaction to the dynamic load. The change in impedance at pile-soil interface results in partial transmission of the incident wave and reflection of the un-transmitted part. However, PIT-S software considers soil effect at pile toe in terms of soil reaction as well as soil quake.

In addition, as per the analysis the stress wave with initial velocity amplitude of 0.50 m/s was subjected to attenuation as a result of soil effects of 0.115m/s at 5.0m depth and of 0.108m/s at 9.875m depth of pile. Hence, the wave had lost 23.0% and 21.6% of its amplitude at 5.0m and 9.875m depths, respectively.

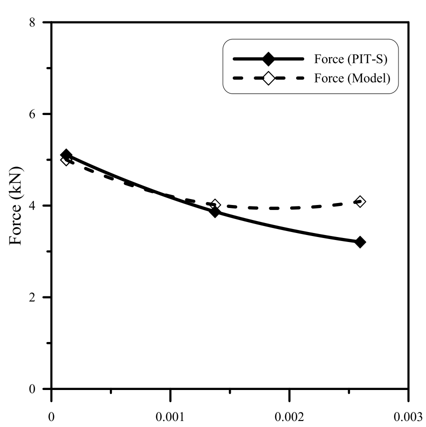


Figure 8 Model and PIT-S software produced force amplitudes

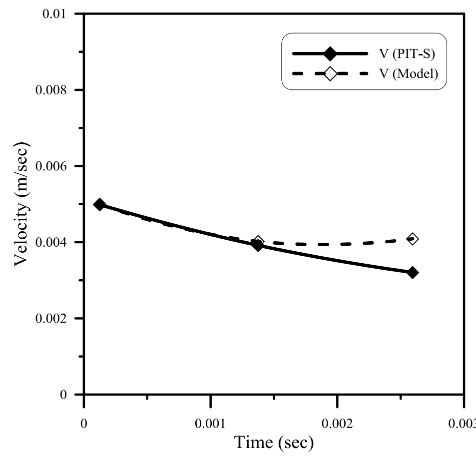


Figure 9 Model and PIT-S software produced velocity amplitudes

4.2 Comparison between In-situ, Model and PIT-S results

A comparison between the model, in situ pile integrity test and PIT-S software was carried. Pile No. 109, in Ammonia Storage Tanks project in Mesaied Industrial City in Qatar, was selected for this comparison while it was casted exactly in a location, where a borehole was drilled during the geotechnical investigation carried out for the site, which assure accuracy of subsurface soil data. Subsurface condition at pile location consists of soft to medium dense silty sand down to 17.7m depth and slightly to moderately weathered limestone from 17.7m to 30.0m depth, which was the final investigated depth. The in situ integrity test result of pile No. 109 had classified the tested pile in Category "A1", which is "Indication of Sound Shaft above a Rock Socket". This category includes shafts in which the velocity records do not show a major impedance reduction but due to the deep socket, a clear toe reflection is not observed [9].

The applied dynamic load and pulse duration used in the analysis are similar to the values calculated from the real PIT test. Load, pile and soil input data used in the comparison are shown in Table 3.

Table 3 Soil, pile and impact load data based on the actual testing conditions

Item	**Value**
Pile Length, L (m)	25.82
Concrete Density, ρ_c (t/m^3)	2.5
Pile elastic modulus, E (kN/m^2)	4x10^7
Pile Radius, r_0 (m)	0.45
Soil Density, ρ_s (t/m^3)	2.00
Rock Density, ρ_s (t/m^3)	2.25
Soil Poisson's Ratio, ν_s	0.40
Rock Poisson's Ratio, ν_r	0.25
Soil Shear Modulus, G_s (kN/m^2)*	100,000
Rock Shear Modulus, G_r (GPa)*	1.55
Force Amplitude, F (kN)	12.535
Pulse duration, (ms)	0.84375
Attenuation coefficient(γ) for soil	1.0
Attenuation coefficient(α) for soil	0.13
Attenuation coefficient(γ) for rock	1.7
Attenuation coefficient(α) for rock	0.1

The generated velocity curves for the real PIT test, PIT-S software and Model are shown in Fig. 10, Fig. 11 and Fig. 12, respectively. After "2L/c" period, which is calculated by dividing the traveled distance by wave speed, the model had identified a velocity of -0.0186cm/s to be received at pile top, while the PIT-S software had showed -0.120cm/s velocity. Note that the real PIT test did not show toe reflection as a result of hard rock damping effect.

It should be noted that PIT-S models rock strata irrespective of weathering condition, which explains the stronger negative reflection compared to model produced signal. For the real test, it can be argued that a small negative reflection was received, while toe reflection was not identified. In addition, the tested pile had showed bulges as shown in the situ PIT results. These bulges are attributed to the absence of permanent casing and the presence of soft subsurface soil layers. These increases in pile cross section are not considered for both Model and PIT-S.

The proposed model for low strain integrity test can accommodate more detailed soil characteristics compared to the PIT-S software. This allows better analysis for multi layering in subsurface and when variations in soil strength or density are encountered. This is achieved in the model through pile discretization, which facilitates macro analysis of each pile segment under its localized loading and surrounding soil condition.

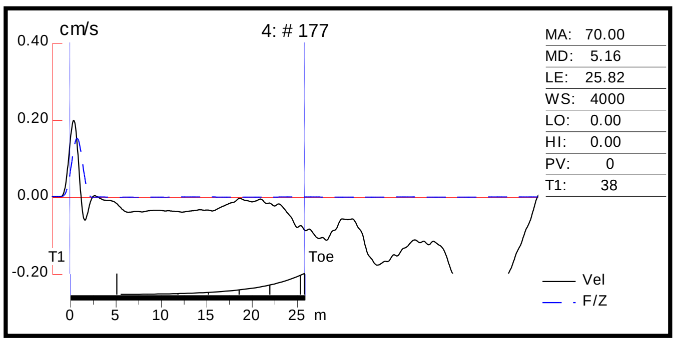


Figure 10 In situ Pile Integrity Test of Pile No. 109

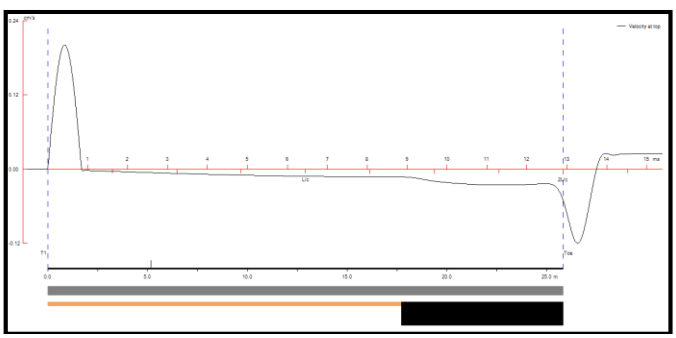


Figure 11 PIT-S simulation for the Pile Integrity Test of Pile No. 109

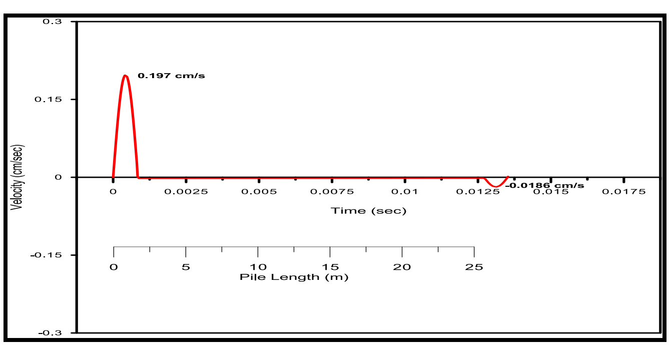


Figure 12 Model simulation for the Pile Integrity Test of Pile No. 109

5.0 CONCLUSIONS

Numerical solution of wave equation after incorporation of soil effect had been utilized in order to evaluate soil damping effects in a concrete pile subjected to light impact during low strain pile integrity test.

The proposed model is based on introducing soil resistance at pile surface and pile toe in the basic wave equation. The skin friction is assumed to be mobilized proportionally to pile displacement, while soil resistance at pile toe is assumed to be caused by the change of impedance as well as the dynamic reaction at pile tip.

Shear stress is considered to be negligible beyond a redial distance. This radial distance was estimated assuming that soil does not deform beyond the distance where vibration amplitude will be reduced by 95%.

The introduced method of analysis had showed comparable results with PIT-S simulation software output at pile top and mid of the pile. However, the generated results relatively diverged near pile toe. This can be attributed to the differences in the procedures adopted by the two methods for calculation of soil effects at pile toe.

The stress wave was found to be subjected to 23.0% and 24.4% reductions in amplitudes at 5.0m and 9.875m depths, respectively. Hence, the proposed analysis procedure may help in the quantification of soil resistance effects on stress wave strength.

About 91% loss on wave strength was obtained by the Model after 2L/c period as a result of soil effects when pile is socketed in hard rock stratum.

The Model has shown a lower value of pile top velocity after 2L/c period than PIT-S when compared with real PIT results. This makes the Model closer to the in situ PIT test in which the toe reflection was not clear.

It is required to identify the sensitivity of the PIT equipment in order to assess whether Model calculated values after 2L/c can be recognized by the equipment or no; and this can help in identifying the PIT limitation for a specific pile and soil condition.

The presented method of analysis can identify the low strain integrity test limitations based on pile, soil conditions and hardware sensitivity.

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