STUDYING EFFECTS DUE TO PILE DRIVING ON FREE DOMAIN VIBRATIONAL RESPONSE USING LUMPED MASS MODEL

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(Received: September 09, 2016; Revised: October 19, 2016; Accepted: December 06, 2016)

ABSTRACT

In this paper, lumped mass model is used to study the effect due to pile driving on ground response in the vicinity. This is a popular problem in structural dynamics, however, one issue is how to reduce time elapsed for soil behavior computation with a good enough accuracy of prediction. The major objective of this study is to find out the peak particle displacement, velocity and acceleration in the far field ground during pile driving, using lumped mass method and linear elastic soil model. The numerical results including displacement, velocity and acceleration showed a good match as compared with that from finite element method by Plaxis.

Keywords: pile driving; ground vibration; lumped mass model; governing equations.

1. Introduction

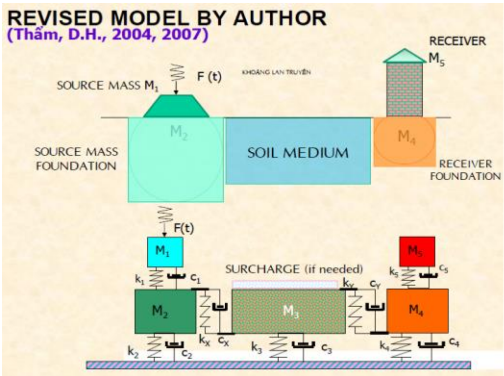
In construction field, pile driving is considered an activity that causes vibration and noise to surrounding environment. Complexity of process includes various parameters. Firstly, vibration due to pile driving happens within the pile shaft, then experienced the pile-soil interaction with surround soil environment, and finally propagated vibration to stir the existing buildings. Tham D.H (2007, 2013) performed a lumped mass model including springs and dashpots, formulated a system of gorverning differential equations to study the effects of a receiver foundation subjected to vibration propagation from a source through soil medium; the system of governing differential equations showed relsults of response in time domain. In addition, analytical models using springs and dashpots are conducted by Deeks, A. J. and Randolph, M. F. (1993), Gazetas, G. et al. (1996), Massarsch, K.R. (1992, 2008), Deckner, F. et al. (2012). Analysis propagation vibration due to pile driving using system's springs – dashpots combined with finite element method was also studied by Ramshaw, C. L. et al. (2000, 2001). And prediction of free field vibrations using with assumptions of linear elastic behaviour soil, and small strain in far-field was postulated by Masoumi, H.R. et al. (2007).

The purpose of the paper is to use lumped mass method for studying vibration effects of pile driving on free domain response. The model includes masses linked by springs and dashpots, then solution of motion differential equations is solved by Matlab Simulink. The results are compared with finite element method by Plaxis software to determine whether lumped mass model can be used as an alternative predictive method.

2. Basic theory

2.1. Reviews on Lumped mass method

Tham D.H (2007, 2013) introduced propagating vibration model in soil environment using lumped mass, springs and dashpots studying the effects of a receiver foundation subjected to vibration propagation from a source (figure 1a), the masses linked by springs and dashpots, stand for elastic and damping properties of soil, respectively. Soil-Structure interaction is considered by shear springs. Vibration time-dependent force F(t) applied on pile (block M_1), propagation of vibration to a receiver (block M_5) through springs and dashpot, and M_2, M_3, M_4 is propagating blocks. Then, separated motion equations for masses were set up. The system of differential equations were solved by Matlab Simulink and response of vibration such as acceleration, velocity and displacement in time domain were shown as in figure 1.



a)

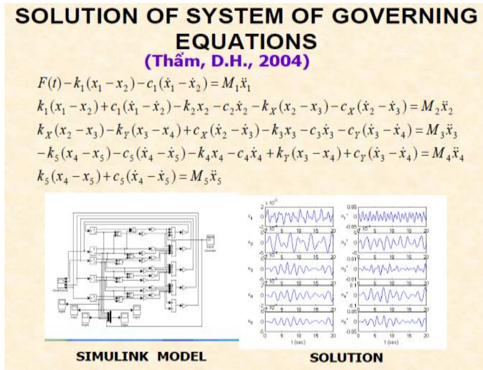


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Figure 1. Lumped mass model in propagation of vibration [1,2]
a) the modeling. b) Motion differential equations and results.

2.2. The parameters of lumped mass model

Parameters of model were used to be in Nguyen Truong Tien's thesis (1987), assumed two blocks

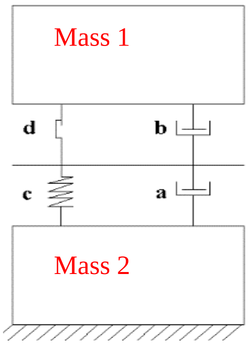


Figure 2. Two blocks linked by two dashpots a and b, spring c, and slide bar d

Linked by two dashpots *a* and *b*, a spring *c*, and slide *d* (figure 2).

- Dashpot *a* representing the effects of radiation damping, C_R, or the energy loss in the surrounding soil of the system. This dashpot disjoints the system when the shear stress is equal to or larger then τ_{max}, where τ_{max} is the ultimate soil resistance, or when plastic flow is produced.

At the shaft of mass:

$$C_R = 2\pi r_0 (G\rho)^{0.5} \Delta L \qquad (1)$$

where, G = shear module (kN/m^2)

ρ = density of soil (kg/m^3)

r_0 = radius of mass (m)

ΔL = length of mass (m)

At the base of mass

$$C_{Rp} = \frac{3.4r_0^2}{1-\upsilon}(\rho G)^{0.5} \qquad (2)$$

ν = Poisson's ratio

- Dashpot *b* representing the effects of material damping, both viscous damping, C_V, and hysteretic damping, C_H. In this paper, viscous damping is neglected.

At the shaft of mass

$$C_H = 2\pi r_0 \Delta L D_r (G\rho_F)^{0.5} \qquad (3)$$

ρ_F = density of pile material (kN/m^3)

D_r = damping ratio

The damping ratio, D_r, can be calculated according to Hardin & Drnevich's method:

$$\frac{D_r}{D_{\max}} = \frac{\gamma_h}{1+\gamma_h} \tag{4}$$

γ_h = hyperbolic shear strain, can be evaluated:

$$\gamma_h = \frac{\gamma}{\gamma_r}[1 + a e^{-b(\frac{\gamma}{\gamma_r})}] \tag{5}$$

a,b = constants, depend on soil types and frequency, determined by Table 1

γ = strain amplitude, determined $\gamma = \frac{V}{(G/\rho)^{0.5}}$

V = particle velocity (m/s)

γ_r = reference strain, $\gamma_r = \frac{\tau_{\max}}{G_i}$

τ_{max} = failure shear stress, depends on the initial state of stress in the soil under geostatic conditions,

$$\tau_{\max} = \left[\left(\frac{1+K_0}{2}\sigma_v^{'}\sin\phi^{'} + c^{'}\cos\phi^{'}\right)^2 - \left(\frac{1+K_0}{2}\sigma_v^{'}\right)^2\right]^{0.5}$$

K_0 = the coefficient of stress (coefficient of at-rest lateral pressure), $K_0 = 1-\sin\phi^{'}$

$\sigma_v^{'}$ = the vertical effective stress

$c^{'}$ and $\varphi^{'}$ = the static strength parameters in terms of effective stress.

Table 1

Values of soil constants *a* and *b* (Tiên N.T, 1987)

Soil type	Value of *a*	Value of *b*
Clean dry sand	-0.5	0.16
Saturated sand	$-0.2\log N_1$	0.16
Saturated cohesive soils	$1+0.25\log N_1$	1.3
where as N_1 = frequency		

At the base of mass:

$$C_{HP} = 4r_0 D_{rP}(\frac{\pi \mathrm{G} r_0 \rho_F}{1-\nu})^{0.5} \tag{6}$$

- Spring k_s, representing the soil stiffness, At the shaft of mass (so called k_x in model):

$$k_s = \pi G \Delta L \tag{7}$$

At the base of mass:

$$k_P = \frac{4Gr_0}{1-\nu} \tag{8}$$

- Plastic slide *d*, limiting the static soil resistance to the ultimate soil resistance. In this paper, slide *d* will not be considered.

Table 2

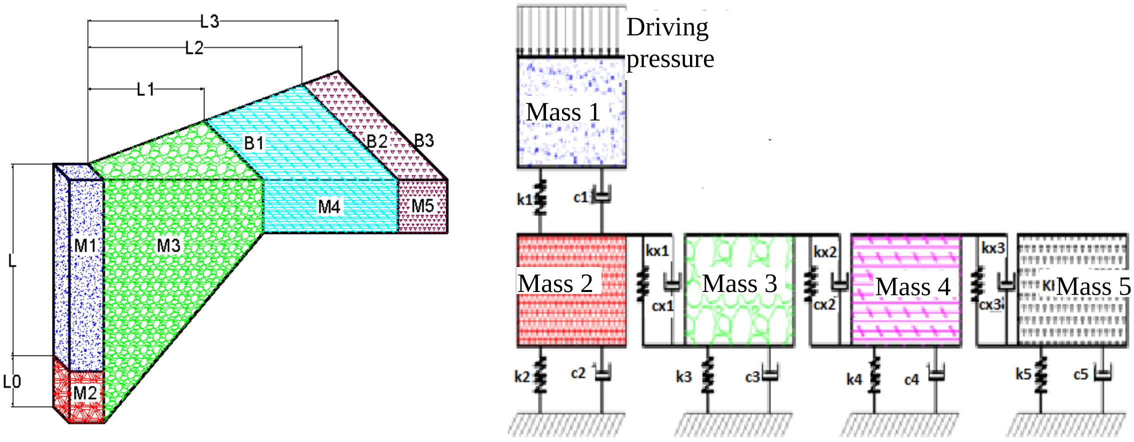
Parameters of spring stiffness and damping ratio

Parameters	At the shaft of mass	At the base of mass
Spring stiffness *k*	$k_s = \pi G \Delta L$	$k_P = \frac{4Gr_0}{1-\nu}$
Hysteretic Damping C_H	$C_H = 2\pi r_0 \Delta L D_r (\mathrm{G}\,\rho_F)^{0.5}$	$C_{HP} = 4r_0 D_{rF}(\frac{\pi \mathrm{G} r_0 \rho_F}{1-\nu})^{0.5}$
Radiation damping C_R	$C_R = 2\pi r_0 (\mathrm{G}\,\rho)^{0.5}\Delta L$	$C_{Rp} = \frac{3.4r_0^2}{1-\upsilon}(\rho \mathrm{G})^{0.5}$

3. Numercial modeling

Modeling using lumped mass method

An example of pile driving subjected to a harmonic load, penetrating to a depth of 10m is studied. Properties of soil and pile materials are given in Table 3 and Table 4. Model in Plaxis 3D axisymmetry and lumped mass modeling are described in Figure 3.



a) b)

Figure 3. Pile driving modeling, a) Axisymmetry model 3D, b) Lumped mass modeling

System of governing differential equations (Tham D.H, 2013) was established as follows:

$$\begin{cases} m_1\ddot{u}_1 = P(t) - k_1(u_1 - u_2) - c_1(\dot{u}_1 - \dot{u}_2) \\ m_2\ddot{u}_2 = k_1(u_1 - u_2) + c_1(\dot{u}_1 - \dot{u}_2) - k_2u_2 - c_2\dot{u}_2 - k_{x1}(u_2 - u_3) - c_{x1}(\dot{u}_2 - \dot{u}_3) \\ m_3\ddot{u}_3 = k_{x1}(u_2 - u_3) + c_{x1}(\dot{u}_2 - \dot{u}_3) - k_3u_3 - c_3\dot{u}_3 - k_{x2}(u_3 - u_4) - c_{x2}(\dot{u}_2 - \dot{u}_3) \\ m_4\ddot{u}_4 = k_{x2}(u_3 - u_4) + c_{x2}(\dot{u}_3 - \dot{u}_4) - k_4u_4 - c_4\dot{u}_4 - k_{x3}(u_4 - u_5) - c_{x3}(\dot{u}_4 - \dot{u}_5) \\ m_5\ddot{u}_5 = k_{x3}(u_4 - u_5) + c_{x3}(\dot{u}_4 - \dot{u}_5) - k_5u_5 - c_5\dot{u}_5 \end{cases} \quad (9)$$

The equations of motion (9) can be solved by Matlab Silmulink as in scheme of Figure 4.

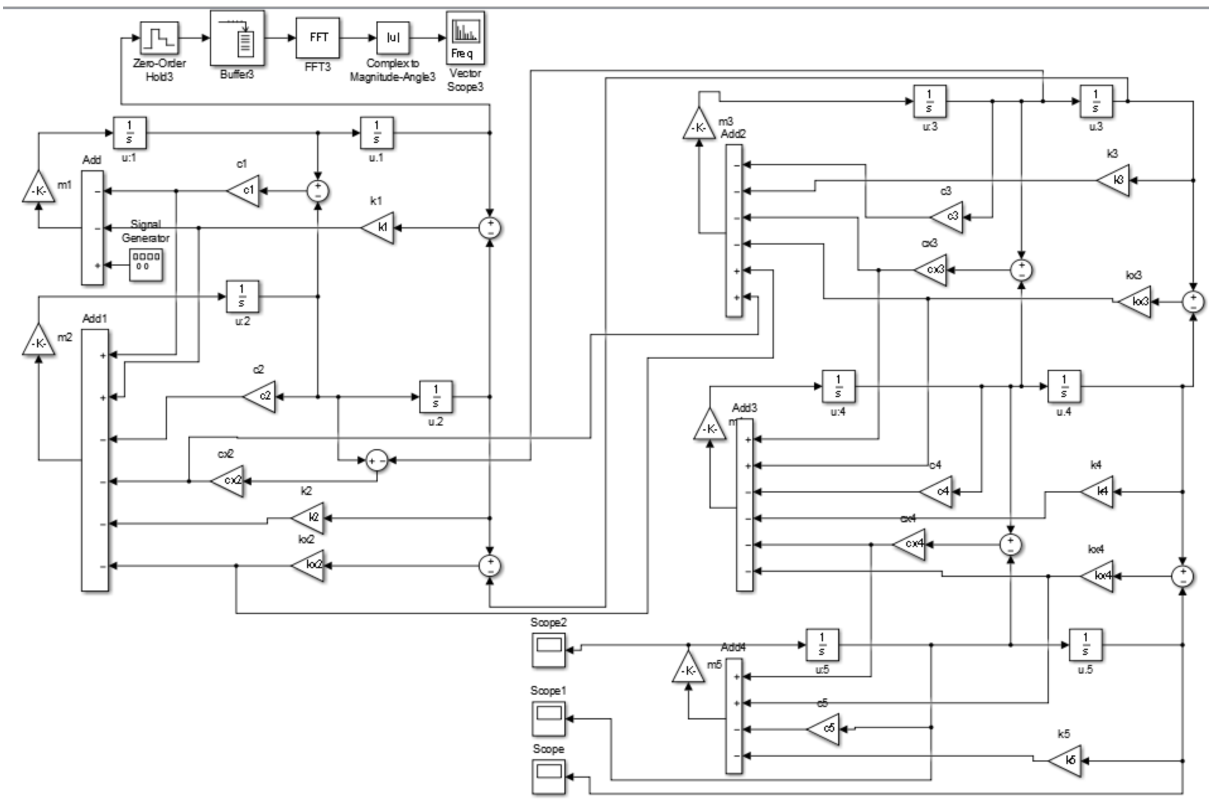


Figure 4. Simulink diagram for the system pile as source – soil medium – target as receiver

Propagating vibration using finite element method, i.e Plaxis software, is plotted as in figure 5a; axisymmetric model is considered, depth of soil is chosen to 40m, harmonic load with amplitude 50 kN meaned 312,5 kN/m^2 and frequency of pile driving is 2 Hz (Figure 5b)

Table 3

Soil Properties

Properties	Symbol	Value
Material model	Model	Linear Elastic
Behaviour type	Type	Undrained
Depth of soil	L	40 m
Density	Γ	17 kN/m^3
Elastic modulus	E	15000 kN/m^2
Poisson ratio	υ	0.3
Shear modulus	G	5769 kN/m^2
Velocity of S_Wave	Vs	57.67 m/s
Velocity of P_Wave	Vp	107.9 m/s

Table 4

Pile Properties

Properties	Symbol	Value
Material model	Model	Linear Elastic
Behaviour type	Type	Non-porous
Length of pile	L_p	10 m
Density of pile	γ_p	24 kN/m^3
Elastic modulus	E_p	3e7 kN/m^2
Poisson's ratio	υ_p	0.1
Shear modulus	G_p	1.36e7 kN/m^2
Amplitude	P	312.5 kN/m^2
Frequency	F	2 Hz

Calculation process includes 2 phases, soil behaviour is linear elastic model.

- Phase 1: Plastic analysis
- Phase 2: Dynamic analysis

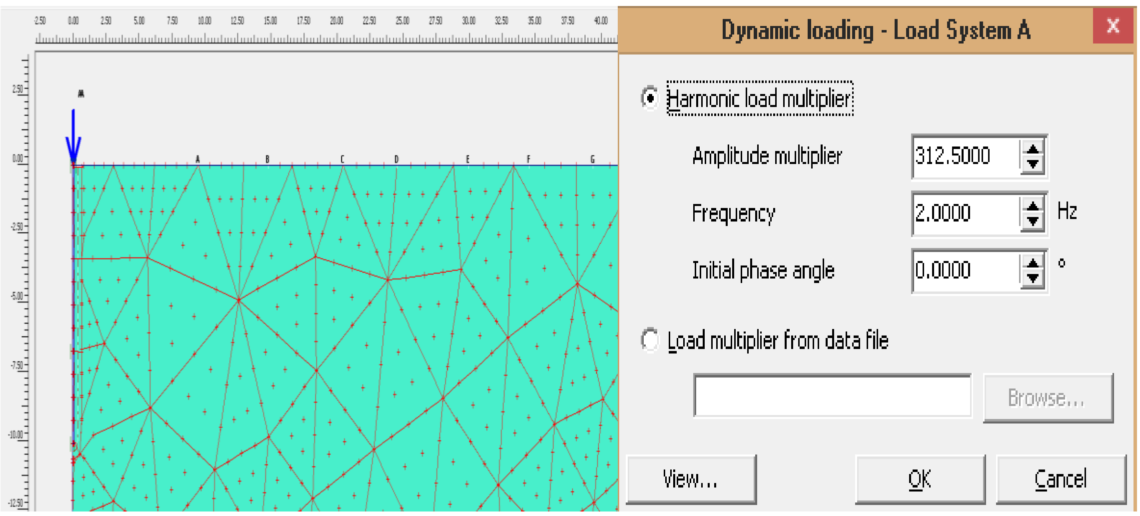
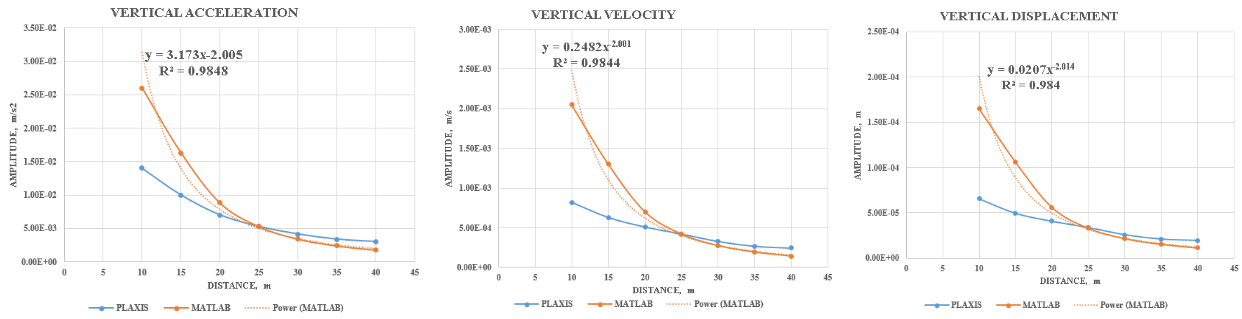


Figure 5. An example of propagation vibration in far-field by Plaxis modeling

a) Modeling and survey points.   b) Dynamic intensity of pile driving load

4. Results

Figure 6 below shows the values of vertical acceleration, vertical velocity and vertical displacement with distances apart from center of pile and response of ground particles in far field (Fig. 7). There is a good match between the two methods.



a) b) c)

Figure 6. Comparison between results of lumped mass method and that of finite element method, a) vertical acceleration, b) vertical velocity, c) vertical displacement

Comparison between response of masses

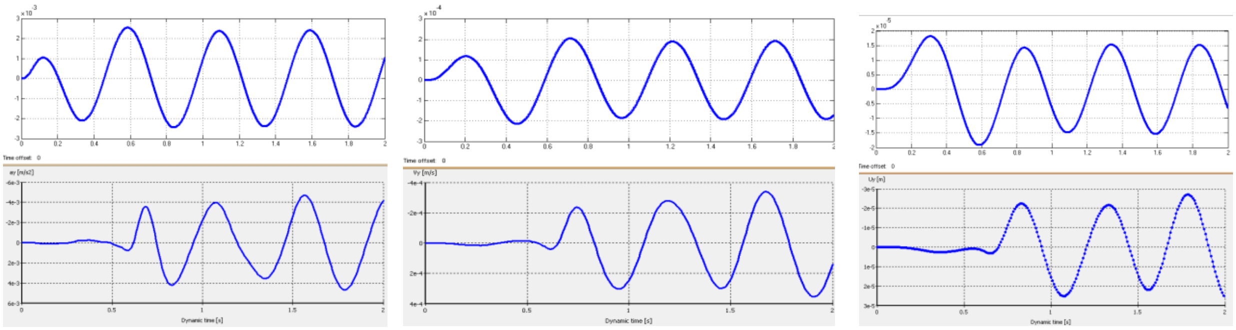


Figure 7. Comparison dynamic response between lumped mass method (above) and FEM (below) at a distance 35m from source; a) vertical acceleration, b) vertical velocity, c) vertical displacement

5. Conclusion

In both models, soil behaviour is linear elastic. Plotted values of lumped mass method are slightly greater than those of finite element method. The reason is the difference in mass of soil. Results of far field response computed from lumped mass model showed a predictable agreement with that of finite element method Plaxis. This implies that lumped mass method can be used to predict the ground vibration in far-field, i.e more 20m from source of vibration; within first 10 meters from the source, it might be a combination of P & S body waves and R surface wave, therefore it is not well-predicted.

In FEM, there is a small delay of phase, meanwhile, the lumped mass method is more sensitive and immediately responsive, and this might be a point to study about this method.

Results from this method can provide parameters such as spring stiffness and damping ratios to some other problem of dynamic effects, for instance, prediction the effects of tunneling using TBM on response of existing buildings in the vicinity… with an acceptable reliability. This is also the selected trend of studying in near future■

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