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NUMERICAL ANALYSIS OF DRIVABILITY OF NON-UNIFORM PILES

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ABSTRACT

This paper presents a numerical analysis of pile driving for tapered piles using FLAC software. The approach involves idealization of pile-soil system in pile drivability. The pile is assumed to be vertical and have elastic and linear behaviour. The soil is assumed to be elasto-plastic material which obeys the Mohr-Coulomb failure criterion. To allow slip between the pile and the soil in pile driving, interface elements are used at the pile-soil borders along the shaft and the toe. Quiet boundaries are considered in the lateral and vertical directions for the soil to absorb traveling waves. The obtained numerical results are compared with experimental results, leading to a satisfactory agreement. It will be shown that with increasing the angle of taper, the driving stresses decrease and the permanent pile toe settlement increases. These are interesting phenomena in pile driving and are on the safe side for driven piles.

INTRODUCTION

The first application of piles is attributed to an African tribe, who lived in dwellings erected on lofty piles driven into a lake bed, according to the father of history, Herodotus. More recently, piled foundations have been used extensively to support structures in a variety of situation involving both static and dynamic loads.

The intensive pile use may occur in traditional areas such as buildings and machine foundation as well in large scale applications in new areas of civil engineering, particularly where thick layers of alluvial and unconsolidated soil are present. Nowadays, piles are used extensively in various engineering applications including machine foundations, high rise buildings, platforms and so on, where the loading may be due to dead and live loads, wind, earthquakes, nuclear power plants, airplane impact, moving traffic, gas explosion and so on.

One of considerable aspects of piles is their drivability. It is a good idea to find a quick method to analyze the pile drivability and use it to optimize the process of pile driving. The important parameters affecting pile drivability are the stresses developed in the pile during pile driving process and the amount of penetration of pile into the soil caused by blows of hammer. The latter can be useful in estimation of the pile capacity.

Due to the importance of pile installation, pile driving analysis has been a significant task to geotechnical engineers. A one-dimensional wave equation analysis as applied to the pile driving problems was first put to practical use by smith (1960). This method takes into account the time-dependent events occurring as a result of a hammer blow. A series of mass-spring elements are used to discretize the hammer-cushion-cap-pile system, while the soil around the pile below,
It is represented by discrete non-linear spring and dashpots. While the wave equation method has been widely used for the solution of the driving problem, the accuracy of the results has not always been satisfactory. This is mainly due to the simplicity of one-dimensional models. It is therefore necessary to model a full-scale three-dimensional pile driving problem to achieve more accurate results.

With advance in computing techniques, three-dimensional analyses have been developed to investigate the complexity of pile driving phenomenon. Chow and Smith (1984) performed axisymmetric finite elements analysis for solid and pipe piles driven in undrained clays. In this analysis, an elastic-perfectly plastic soil model with a Von Mises yield function, dependent on its undrained shear strength was used. These studies have shown significant differences in the pile behaviour in comparison with one-dimensional analysis, especially for piles driven in stiff clays.

Coutinho et al. (1988) carried out research work on the drivability of piles and in, co-ordination with petrobras, applied the results to actual cases of piles driven in the Brazilian coast. In this research, a parametric study of several factors affecting driving like pile-soil interface, damping, etc. have been incorporated. Uzag (1988) examined the problem of open-ended steel pipe pile driven in saturated dense sand by performing a finite element study on a model pile. He verified the results with available experimental data. The soil was modeled using the Von Mises criterion with isotropic hardening to study of the soil plug behaviour for several pile-soil interface friction angle. Mabsout et al. (1994) examined the feasibility of conducting a detailed analysis of pile driving into account the non-linear behaviour of the soil and tracing the penetration of the pile into the soil. They studied the behaviour of closed-end round concrete piles with a conical tip driven into the soil in undrained clayey soils in three-dimensional model.

All the approached considered cylindrical or uniform piles. While the use of uniform piles are still widespread in routine practice, a reasonable attempt may be to distribute the pile mass along the shaft economically. The advantages of tapered piles compared to cylindrical pile have been investigated in recent years and such idea has been taken into account. For example, axial response of such piles under static loading has been investigated using 1-D finite element method (Ghazavi et al., 1997) and laboratory tests using model piles and pressure chamber (Wei and El Naggar, 1998). The cinematic response of such piles under earthquake loading was also investigated (Ghazavi, 2000). Field load tests were also conducted on tapered piles to investigate their load-carrying capacity (Rybnikov 1990). More recently, full-scale tests were performed on both cylindrical and tapered piles driven into a cohesive soil profile in the field. These tests showed that, in long term, the tapered pile had 80% more capacity than a uniform pile of the same volume and length (Ahmadi, 2004).

This paper focuses on three-dimensional modeling of piles driven into the ground using FLAC software (2002). A cylindrical driven pile is modeled and its response in pile driving is simulated. The numerical results in this study are compared with those obtained from a finite element analysis performed by Mabsout et al. (1994). This comparison has shown a satisfactory agreement. Then the driving of a non-uniform concrete pile is simulated and the results will be obtained and discussed.

ANALYSIS METHOD

FLAC is a three-dimensional explicit finite-difference program for engineering mechanics computation simulating the behaviour of three-dimensional soil structures constructed on rock or other materials undergoing plastic flow when their yield limits are reached. Materials are represented by polyhedral elements within a three-dimensional grid that is adjusted by the user to fit the shape of the object to be modeled. Each element behaves according to a prescribed linear or nonlinear stress/strain law in response to applied forces or boundary restraints. The material may yield and flow and thus the grid can deform at large strain. The explicit, Lagrangian, calculation scheme and the mixed-discretization zoning technique used in *FLAC* ensure that plastic collapse and flow are modeled very accurately. Because no matrices are formed, large three-dimensional calculations can be made without excessive memory requirements. It offers an ideal analysis tool for solution of three-dimensional problems in geotechnical engineering. The purpose of the grid generator is to facilitate the creation of all required physical shapes in the model. At first, grid generator is defined and built with radial cylinder shape to model radially graded mesh around cylindrical-shaped tunnel and cylindrical mesh to model the pile. One important aspect in grid generation is that all physical boundaries to be represented in the model simulation must be defined before the solution stepping begins.

Following the model generation, the boundary conditions are assigned. The boundary conditions in numerical modeling consist of the values of field variables such as displacements that are prescribed at the boundary of the numerical grid. The initial condition also is set to reproduce the in-situ state of stress in the ground, before any excavation or construction is started. Ideally, information about the initial state comes from field measurements but when these are not available, the model can be run for a range of possible conditions. Although the range is potentially infinite, there are a number of constraining factors.

In the present analysis, the cylinder pile is assumed to be linear and elastic. The Mohr-Coulomb plasticity model is used for materials that yield when subjected to shear loading, but the yield stress depends on the major and minor principal stresses only; the intermediate principal stress has no effect on yield. Also, Mohr-Coulomb parameters for cohesion and friction angle are usually available more often than other properties for geo-engineering materials.

Quiet boundaries are used in the model to absorb energy at the boundaries. Quiet boundaries scheme proposed by Lysmer and Kuhlemeyer (1969) involves dashpots attached independently to the boundary in the normal and shear directions. The dashpots provide viscous normal and shear traction that can be introduced directly into the equation of motion of the grid points lying on the boundary. Quiet boundary conditions can be applied in the global coordinate direction or along inclined boundaries, in the normal and shear directions.

The resistance of the cohesive soil in pile driving appears as the skin friction and end bearing and is related to the soil undraind shear strength. The skin friction, τ_x, distributed along the pile shaft is determined using:

$$\tau_x = \alpha c_u \qquad (1)$$

where c_u is the undrained shear strength and α is adhesion factor.

VERIFICATON

In this section, as an example, a concrete pile is considered as studied by Mabsout et al. (1994). This pile was solid round concrete pile with a diameter of D_p=50 cm and length of 20 m. The pile-soil system used by Mabsout et al. (1994) and modeled in the present study by FLAC is shown in Figure 1.a and 1.b. The pile toe shape was parabolic, therefore the mesh definition under the pile toe and along pile shaft is refined. The pile properties are shown in Table 1.

The soil was assumed to be elasto-plastic material which obeyed the Mohr-Coulomb failure criterion. Mabsout et al. (1994) proposed that soil obeyed the bounding-surface model. The initial void ratio of the soil was 0.63 and its specific gravity was 2.6. The soil cohesion was a function of depth Z. The soil parameters used in the study of Mabsut et al. (1994) and the present study are shown Table 1.

Table 1. Properties of soil and pile parameters used in analysis

Material	ρ (Kg/m^3)	n	c (MPa)	Φ (°)	E (MPa)
Clayey Soil	1600	0.35	2Z	0	1e3
Pile	2400	0.2	-	-	24.8e6

Figure 1 shows the pile discretized by Mabsut et al. (1994) and that modeled in the present study by FLAC. Figure 2 shows the three-dimensional model of the pile-soil system with 517492 grids.

The hammer blow impact used in the top of the pile is simulated by a force function introduced by Goble et al. (1984) and Mabsout et al. (1994). The force function is shown in Figure 3.

Boundary condition is used as a roller to resist grid displacements and allowed to move in vertical direction. Quiet boundary is used in boundary conditions and bottom of the model to absorb transmission wave not to return to model region. In order to modeling the interface between soil-pile system, interface elements are used at pile-soil borders along the shaft and toe to allow slip between the pile and the soil in pile driving.

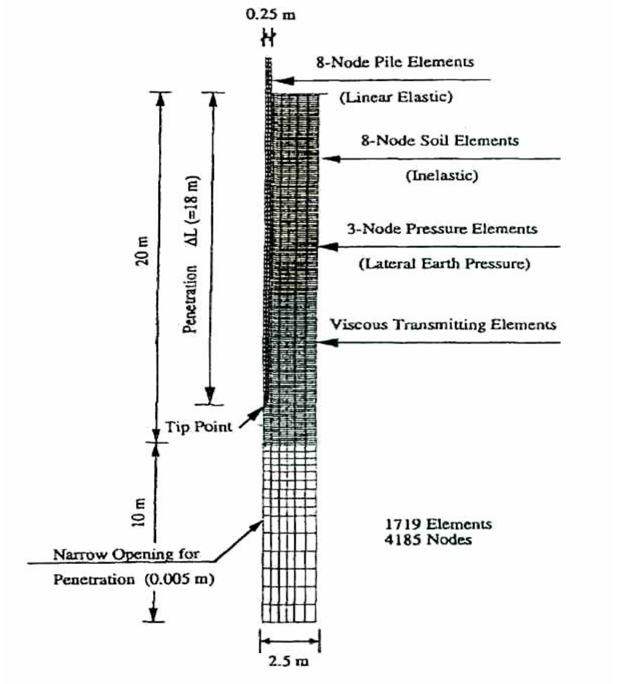

Fig. 1.a. Pile-Soil System ax symmetric model [Mabsout et al. (1994)]

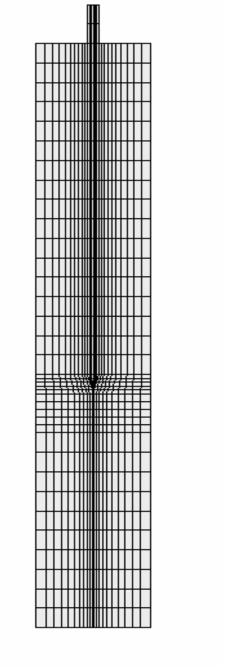

Fig. 1.b. Soil-pile system ax symmetric model in FLAC

As mentioned before, this paper presents numerical analysis of pile driving for tapered piles. For this purpose, the same pile is modeled with FLAC. The internal friction angle of the soil pile interface is assumed to be ϕ = 6°.

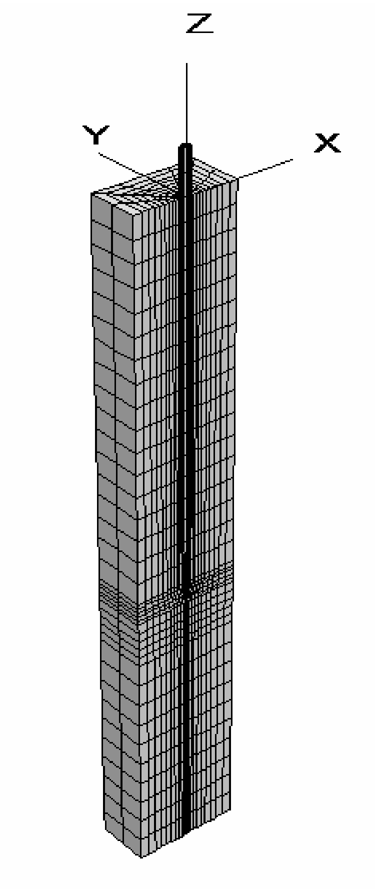

Fig. 2. Three-dimentional soil-pile system in FLAC

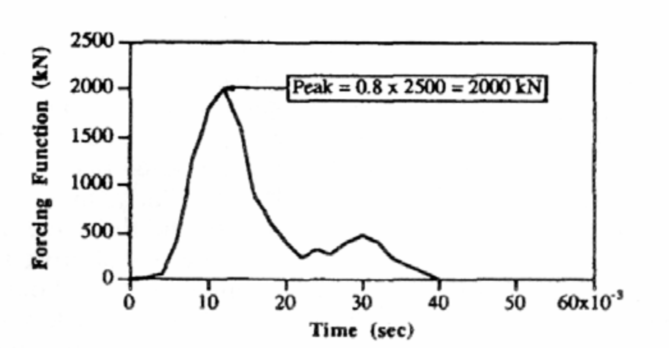

Fig. 3. Force function simulating hammer blow [Goble et al., (1984); Mabsout et al.,(1994))

Figure 4 shows the results for the cylinder driven pile prebored at 18 m in normally consolidated clay. As seen, the pile top and toe displacements are 0.03882 and 0.03878 m, respectively. Also the pile top and toe velocities are 1.545 and 2.604 m/s. In Figure 4, the pile displacement and velocity are illustrated and indicate that the obtained numerical results from FLAC analysis are comparable with those reported by Mabsout et a. (1994).

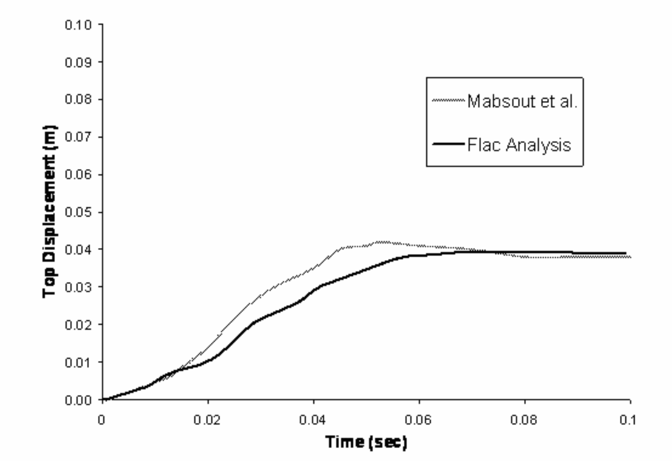

Fig. 4.a. Comparision of top displacement between FLAC and Mabsout et al. (1994)

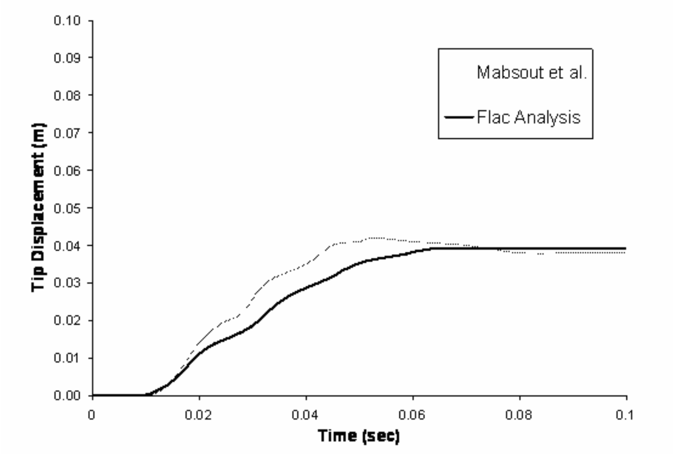

Fig. 4.b. Comparision of tip displacement between FLAC and Mabsout et al. (1994)

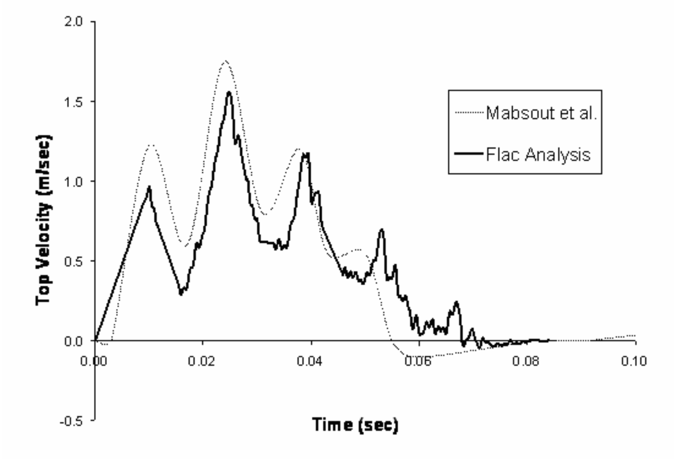

Fig. 4.c. Comparision of top velocity between FLAC and Mabsout et al. (1994)

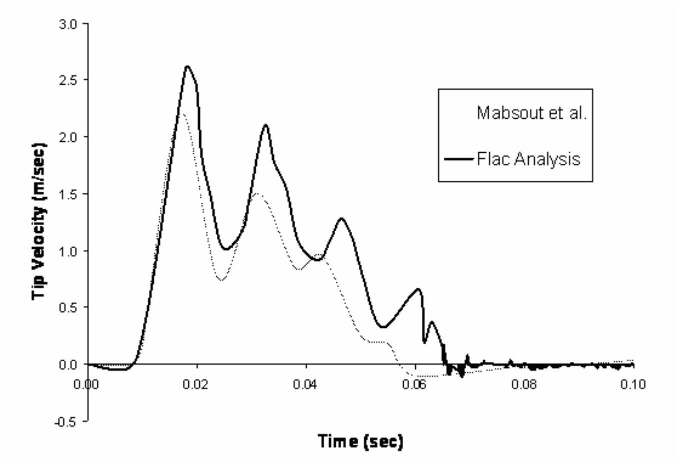

Fig. 4.d. Comparision of tip velocity between FLAC and Mabsout et al. (1994)

PARAMETRIC STDUDY FOR NON-UNIFORM PILES

In this section, the drivability of non-uniform pile is analyzed and compared with cylindrical pile. Figure 5 shows the pile configuration considered in this study.

The pile is 20 m in length with equivalent volume in comparing with cylinder pile that it leads to the different tapered angle. All initial and boundary conditions are as the same as mentioned before. The pile is assessed on a hammer blow with the force function applied on its top shown in Figure 3. In this study, a tapered pile is assumed to be of the same length and volume of the cylindrical pile ($\delta=0^o$) in three different taper angle (δ = 0°, 0.5°, 1°), where δ is the taper angle.

Figure 6 and 7 show pile toe and top displacements for tapered pile with different taper angles. The pile top displacement increases with increasing the taper angle. The same trend is observed for the pile toe displacements. This stems from the fact that more soil volume is present around the pile head and therefore, the rate of the load transferred to the soil grows up.

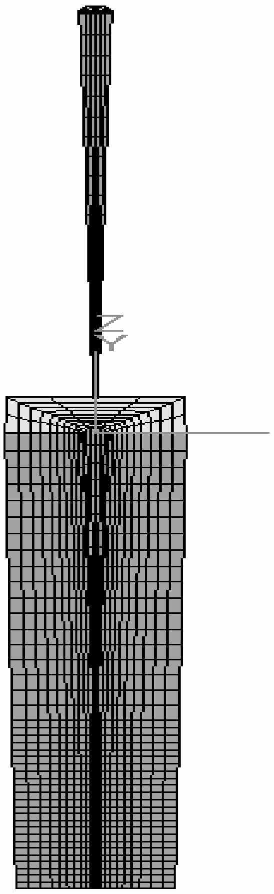

Fig. 5. Three-Dimensional Tapered Pile-Soil system in FLAC

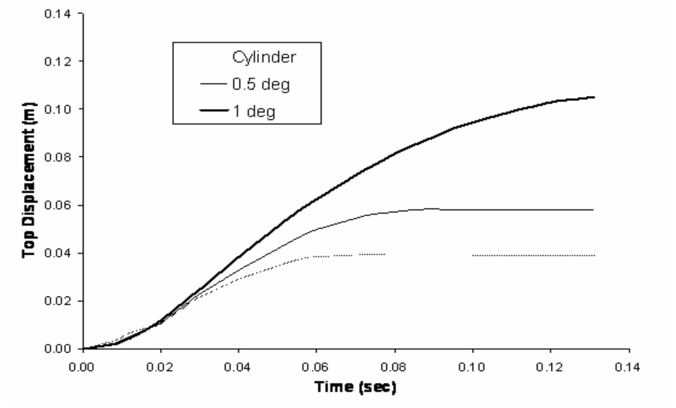

Fig. 6. Comparison of pile top displacement for various taper angle versus time

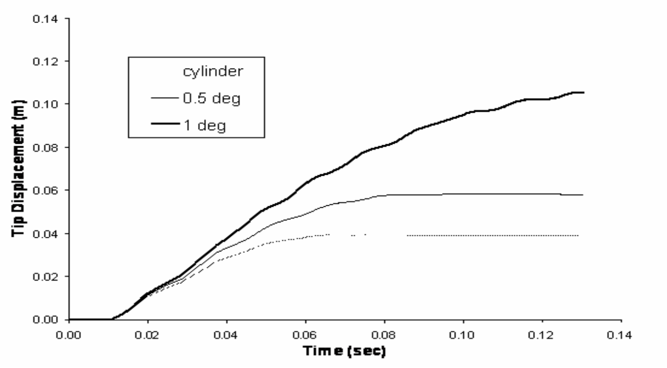

Fig. 7. Comparison of pile tip displacement for various taper angle versus time

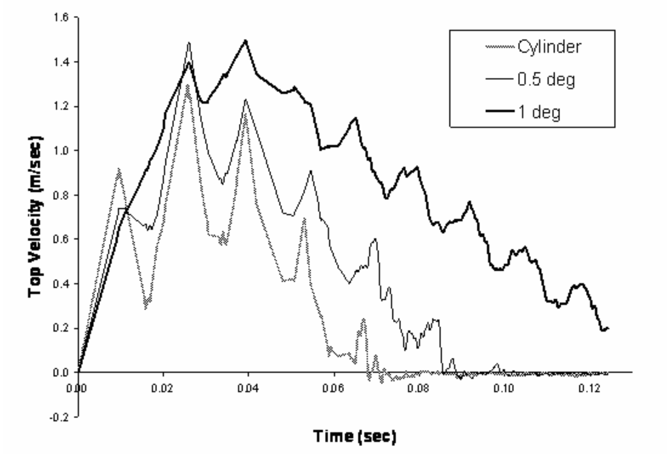

Fig. 8. Comparison of pile top velocity for various taper angle versus time

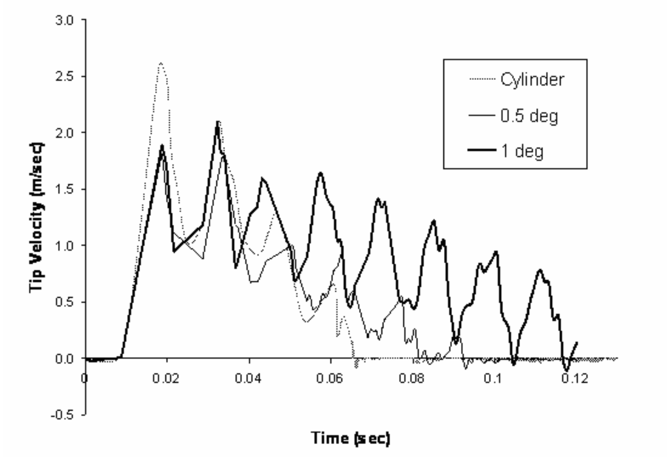

Fig. 9. Comparison of pile top velocity for various taper angle versus time

Figure 8 and 9 illustrate velocities for tapered pile with different taper angles. As seen, when the hammer impacts the pile top, the stress wave are transferred from the top to the toe. Figure 7 indicates that the tip displacement occurs at 0.01 s after the force function acts on the pile top.

Figure 10 shows the stresses of pile toe during driving with time. As shown, with increasing the taper angle, the driving stress decreases. This is on the safe side for pile driving.

Figure 11 shows the driving stress at different points along the pile shaft.

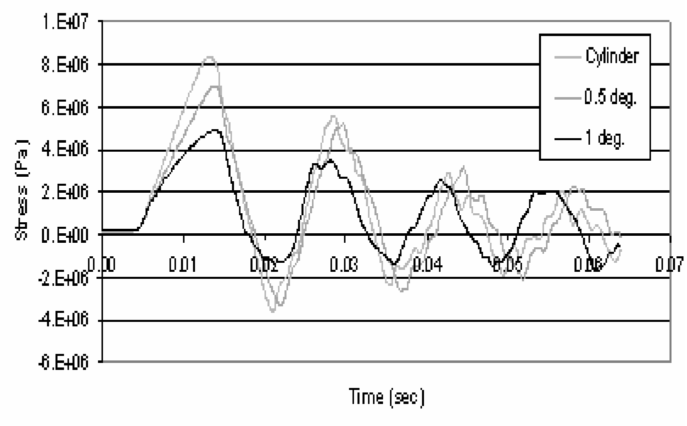

Fig. 10. Distribution of tapered pile tip stress with various taper angle versus time

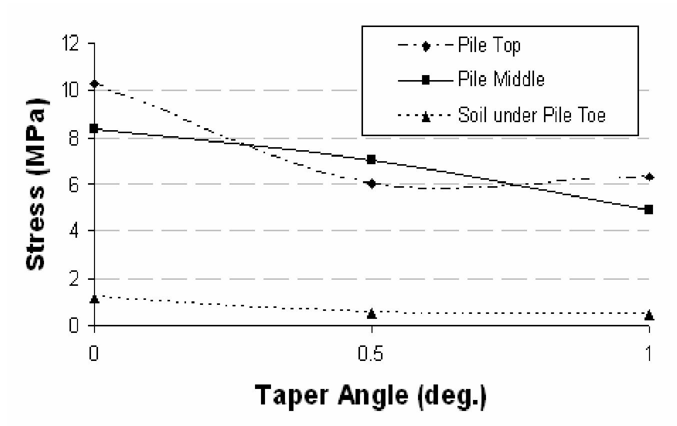

Fig. 11. Stress on top, midelle of pile and soil under pile toe versus taper angle

CONCLUSION

A three-dimensional model for both cylindrical and tapered piles driving into the soil has been developed in this paper using FLAC software. The elastic pile has been assumed to be driven into a Mohr Coulomb material. The pile-soil system in pile driving phenomenon was first simulated and verified with data available from other numerical analyses. Parametric studies were performed on tapered piles with various taper angles. The results showed that:

- With increasing the taper angle, the pile toe and tip displacements increase.
- The driving stresses decrease with increasing the taper angle.
- Generally speaking, if the drivability of piles is critical, tapered piles are advantageous over cylindrical piles of the same volume and length. This leads to an economical design and use of piles.

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