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# Factors Influencing the Vibratory Installation of Non-Displacement Piles

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SYNOPSIS: This study examines the factors influencing the vibratory installation of non-displacement sheet piles in drained granular soils. Several variables were examined to assess their relative importance on vibratory installation. Analyses were performed using two-dimensional numerical modeling with an elasto-plastic hyperbolic stress-strain model and the Mohr-Coulomb model. The variables investigated include: pile-soil interface friction, bias weight, driver operating frequency, driver centrifugal force, lateral earth pressure coefficient, pile embedment, and soil model. The results of the study show that the soil stress-strain response has little influence on the penetration rate for non-displacement piles and that the driver frequency and interface friction angle are of major importance.

## INTRODUCTION

Installation of piles with vibratory drivers has many advantages over impact hammers, namely: less noise generated, little or no pile damage, and reduced driving time in granular soils. However, vibratory pile installation is a very complex process due to the large number of variables associated with the characteristics of the driver, pile and soil. Research into vibratory pile driving began concurrently in Germany and Russia in 1930's. Approaches that have been used include: interpretation of field records, simplified theoretical and numerical models, and laboratory models. The objective of this study is to extend the earlier work by examining the relative importance of various parameters on the installation of non-displacement "sheet" piles using two-dimensional numerical modeling.

Sheet pile penetration was examined by simulating the pile-driver-soil system using the finite difference program, FLAC (1995). The soil was modeled using an elasto-plastic hyperbolic stress-strain model and an elastic perfectly plastic Mohr-Coulomb model.

## BACKGROUND

A vibratory driver transmits a sinusoidal force at controlled frequency to the top of the pile. In general, this centrifugal force must overcome the dynamic resistance along the pile shaft and at the tip to penetrate the pile. The centrifugal driving force, $F_c$, can be calculated as:

$$F_c = me\omega^2 \qquad (1)$$

where m = eccentric mass,
e = distance between center of mass and center of rotation,
ω = operating frequency.

Equation (1) illustrates the important influence of frequency on the driving force as the centrifugal force is proportional to the frequency squared. Vibratory drivers typically include an isolated "bias" weight that ranges between approximately 4 to 40 kN. The bias weight improves penetration by providing a net downward load during driving. The peak-to-peak amplitude of the vibrating driver hanging free in air typically ranges between 6 mm and 38 mm (ICE). During driving the amplitude varies depending on the dynamic driving resistance and pile/soil interaction.

The vibratory driving process is influenced by the characteristics of the pile, driver, and soil. The variables investigated for this study include: pile-soil interface friction, lateral earth pressure, operating frequency, bias weight, centrifugal force, and pile embedment length. The results provide insight into the relative influence of these parameters on vibratory installation of sheet piles.

## NUMERICAL MODEL

The program FLAC (Fast Lagrangian Analysis of Continua) was employed to simulate vibratory installation. FLAC is an explicit time domain finite difference code (Itasca, 1995).

A plane strain configuration is assumed for the sheet piles. A line of symmetry was utilized along the pile axis. A typical mesh used for simulations with the non-displacement pile is shown in Figure 1. The pile was modeled using structural "pile" elements that are available in the FLAC element library. The pile is assumed to have skin friction and no tip resistance, and the response at the pile/soil interface is simulated using an elasto-plastic interface element. The driver was modeled using solid elements at the top of the pile to account for the mass subjected to inertial forces. A constant vertical force was used to simulate bias weight. A sinusoidal forcing function was applied to the driver to induce vibration. Absorbing viscous boundaries were used at the bottom and right boundaries of the mesh. The ground is modeled as a drained granular soil.

A relatively simple plasticity based model was used. It is an isotropic strain hardening model with a Mohr-Coulomb yield surface. A basic assumption of the model is that the friction angle increases hyperbolically with plastic shear strain. The details of the constitutive model used were reported by Feng (1997).

The model assumes elastic response for stress levels inside the yield surface and Rayleigh damping of 5 %. The elastic soil parameters were obtained using the initial shear modulus (Gmax) calculated from Hardin's equation (Hardin, 1978). A nominal value of Poisson's ratio of 0.2 was used. The hyperbolic model was used in all cases except in Case F-1 where the standard elastic-plastic Mohr-Coulomb model was used.

The properties of the driver, pile and soil were varied for the parametric study. Hammer characteristics were set to simulate a specific vibratory driver and vibratory installation was initiated. Pile penetration rate, stresses in the pile, and stresses and strains in the soil were monitored during installation.

## BASELINE CASES

Typical results from a baseline case are presented first to illustrate various features of driving behavior. The baseline case is designated F-Base and the parameters are listed as follows:

Pile: LARSSEN 4B×56 U-pile, 25 meter long
Pile embedment length: 5 meters
Hammer: ICE model 416L, $F_c = 405$ kN, bias wt. = 14.2 kN, operating frequency = 20 Hz
Soil: hyperbolic model, ultimate $\phi'_u = 40^\circ$, 5% damping ratio, initial $K_O = 0.36$
Pile/soil interface friction: $\delta = 30^\circ$

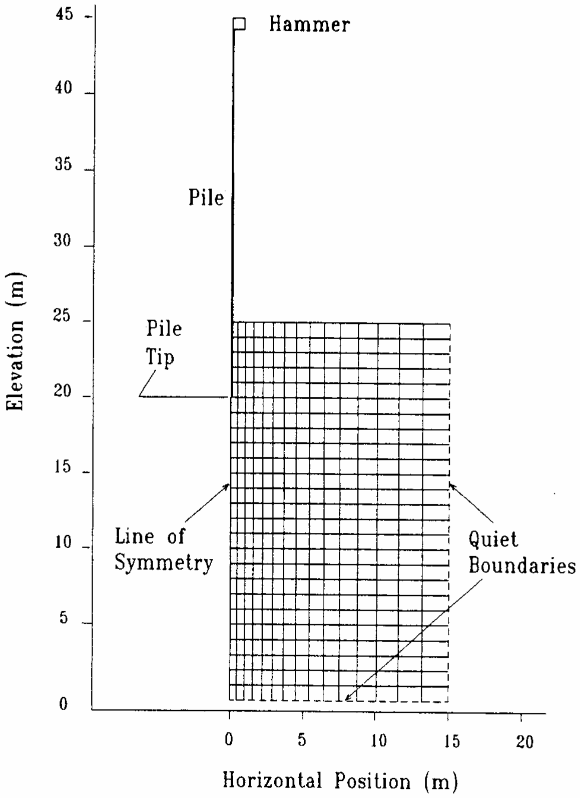

Figure 1 A typical mesh for non-displacement sheet pile

Figure 2 shows the pile penetration versus time during the first 30 seconds of driving. The penetration rate decreases gradually as the shaft resistance increases. The inset in Figure 2 shows the detailed response for a few cycles. The down-stroke amplitude is about 20 mm while the up-stroke is only about 2 mm. At practical refusal the pile continues to vibrate but no additional net penetration takes place.

## PARAMETRIC COMPARISONS

The results of 17 simulations for non-displacement piles were used to assess the influence of the various parameters. These cases are summarized in Table 1 for the variation in parameters discussed previously.

### Interface Friction

The influence in the magnitude of interface friction is shown in Figure 3. Two values of pile/soil interface friction are compared, $\delta = 30^\circ$ and $\delta = 20^\circ$. The average penetration rate after 30 seconds at an interface friction of 30° is about half of that for an interface friction of 20°. The difference is greater than would be expected from static resistance only ($\tan 20^\circ / \tan 30^\circ = 0.63$ when $K_o = 0.5$).

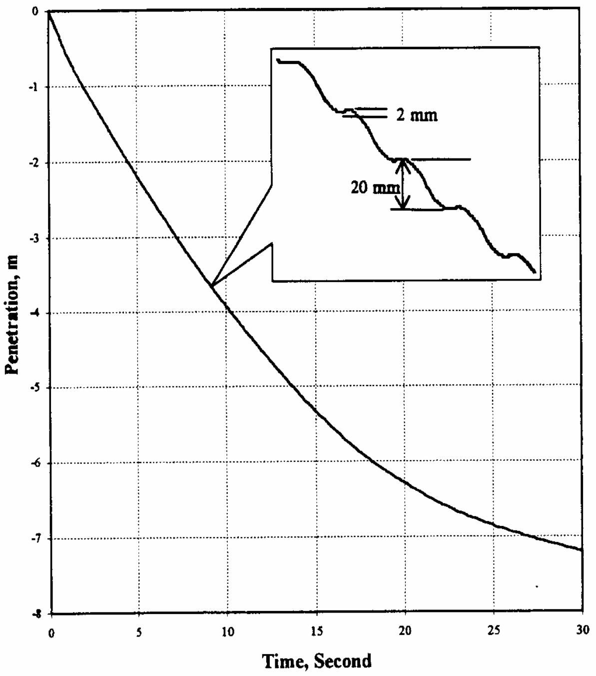

Figure 2 Penetration profile for the baseline case (F-BASE)

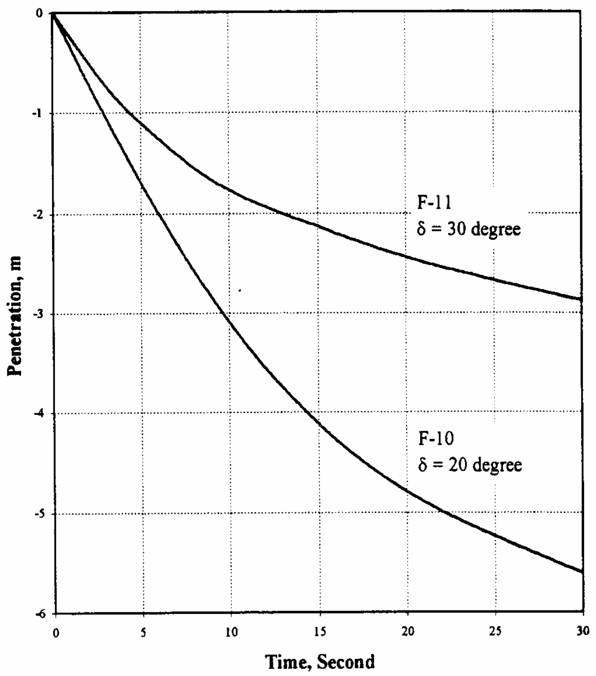

Figure 3 Penetration profiles for sheet piles (10m embedded, 20 Hz)

Table 1 Parameters used for non-displacement sheet piles

| Case | Freq. Hz | Bias Wt. , kN | $F_c$ kN | Shaft Fric. δ | Soil | Soil Model | Embed m | Ko |
|---|---|---|---|---|---|---|---|---|
| F-BASE | 20 | 1 Bias | 405 | 30 | Dense | Hyper. | 5 | 0.36 |
| F-1 | 20 | 1 Bias | 405 | 30 | Dense | Mohr | 5 | 0.36 |
| F-2 | 20 | 1 Bias | 405 | 20 | Loose | Hyper. | 5 | 0.56 |
| F-3 | 20 | 0 Bias | 405 | 30 | Dense | Hyper. | 5 | 0.36 |
| F-4 | 20 | 0.5 Bias | 405 | 30 | Dense | Hyper. | 5 | 0.36 |
| F-5 | 20 | 1.5 Bias | 405 | 30 | Dense | Hyper. | 5 | 0.36 |
| F-6 | 26.6 | 1 Bias | 716 | 30 | Dense | Hyper. | 5 | 0.36 |
| F-7 | 10 | 1 Bias | 101.2 | 30 | Dense | Hyper. | 5 | 0.36 |
| F-8 | 26.6 | 1 Bias | 405 | 30 | Dense | Hyper. | 5 | 0.36 |
| F-9 | 10 | 1 Bias | 405 | 30 | Dense | Hyper. | 5 | 0.36 |
| F-10 | 20 | 1 Bias | 405 | 20 | Dense | Hyper. | 10 | 0.36 |
| F-11 | 20 | 1 Bias | 405 | 30 | Dense | Hyper. | 10 | 0.36 |
| F-12 | 20 | 1 Bias | 405 | 30 | Dense | Hyper. | 15 | 0.36 |
| F-13 | 20 | 1 Bias | 405 | 30 | Dense | Hyper. | 5 | 0.5 |
| F-14 | 20 | 1 Bias | 405 | 30 | Dense | Hyper. | 5 | 0.66 |
| F-15 | 20 | 1 Bias | 405 | 30 | Dense | Hyper. | 10 | 0.5 |
| F-16 | 20 | 1 Bias | 405 | 30 | Dense | Hyper. | 10 | 0.66 |

Note: 1 Bias Weight = 14.2 kN; pile length = 25 m

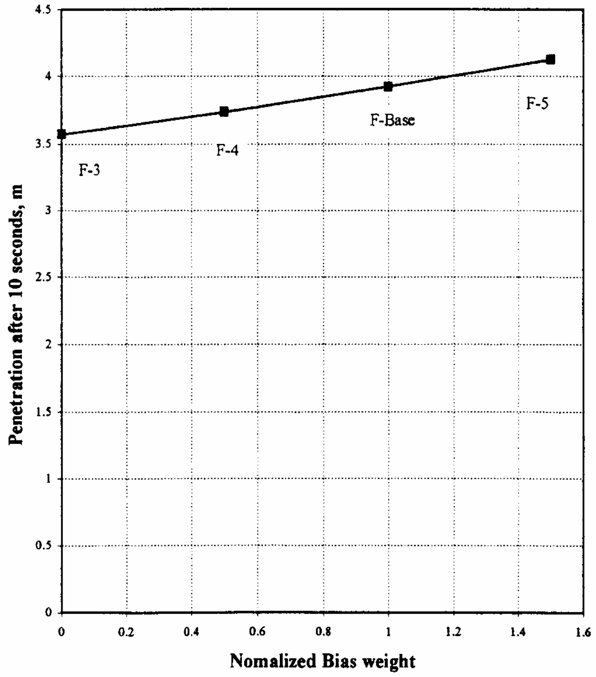

Figure 4 Effect of bias weight on penetration rate (1 bias weight = 14.2 kN)

### Bias Weight

The bias weight is a mass that is isolated from the vibratory system to eliminate inertia forces. Figure 4 shows the pile displacement after 10 seconds of driving with bias weights of 0, 0.5, 1.0 and 1.5 times the baseline case of 14.2 kN. The penetration rate increases linearly with the bias weight; however, the variation is only modest, about 15% for the range in bias weights investigated. It is likely that the bias weight has a more dramatic influence on penetration rate in granular soils below the water table where vibrations may produce liquefaction of the soils around the pile.

### Driver Frequency

The centrifugal force, $F_c$, of a vibratory driver is proportional to the frequency squared ($F_c = me\omega^2$), so the effect of operating frequency is coupled with driving force. Two sets of analysis were carried out: 1) where the frequency was varied while the centrifugal force was held constant and equal to 405 kN ($F_c$ at $\omega = 20$ Hz ), and 2) where the frequency was varied while the eccentric moment was held constant so that the centrifugal force varied. The results of these simulations are presented in Figure 5. For the first case, the penetration rate increase as the frequency decreases. This occurs because at lower operating frequencies the downward force is applied for a longer duration, and therefore, more energy is transmitted during penetration. For the second case, the penetration rate increases with frequency due to the increase in applied force.

### Pile Embedment

The response for pile embedment depths of 5, 10, and 15 m are shown in Figure 6. The results are approximately linear and if extrapolated show refusal for a pile embedment of 16 meters.

### In-Situ Lateral Earth Pressure

The in-situ lateral earth pressure coefficient ($K_0$) depends on the strength and stress history of a soil deposit and has a large influence on the driving results. A common assumption used for normally consolidated soils is $K_0 = 1 - \sin\phi$ which was adapted from the work of Jaky (1948). This leads to $K_0 = 0.56$ and 0.36 for the "loose" sand and "dense" sand cases investigated, respectively. The dense soil would have a lower lateral earth pressure than the loose soil; however, the interface friction is expected to be higher. For $\delta \approx 0.75\phi$, the dense case has only a slightly lower penetration rate than the loose case because these two factors offset as shown in Figure 7.

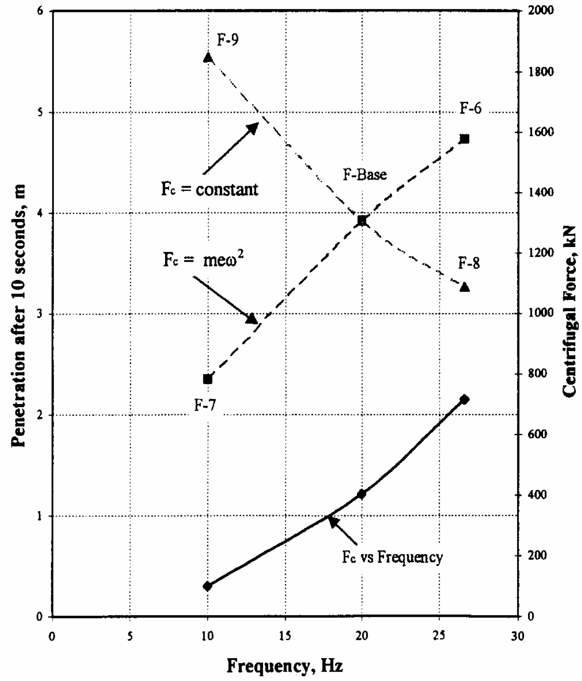

Figure 5 Effect of frequency on penetration for Group 1 $F_c$= constant= 405 kN and Group 2 $F_c = me\omega^2$

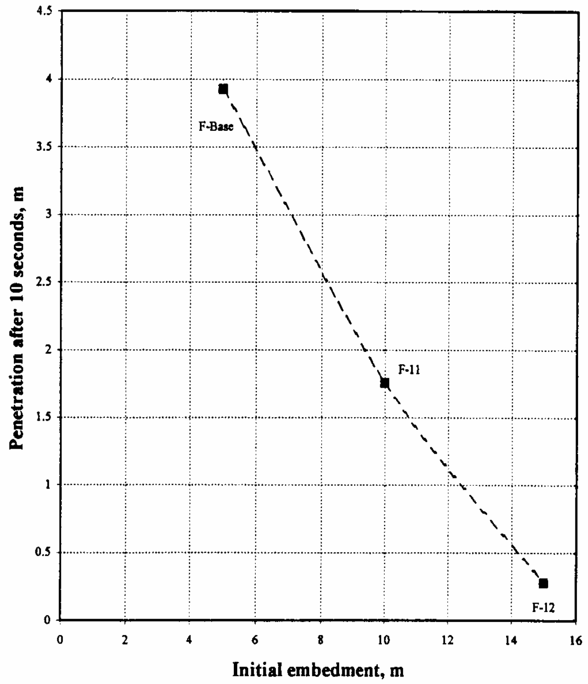

Figure 6 Effect of initial embedment (20 Hz)

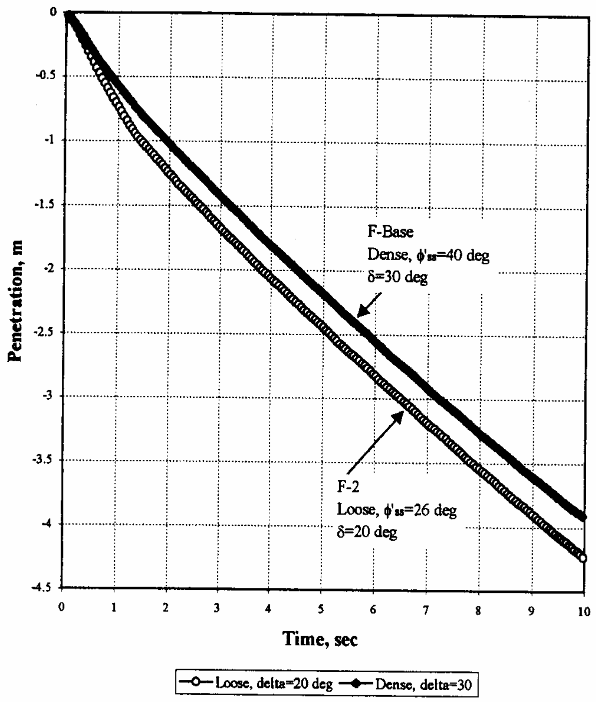

Figure 7 Penetration profiles of dense and loose soil with different δ values

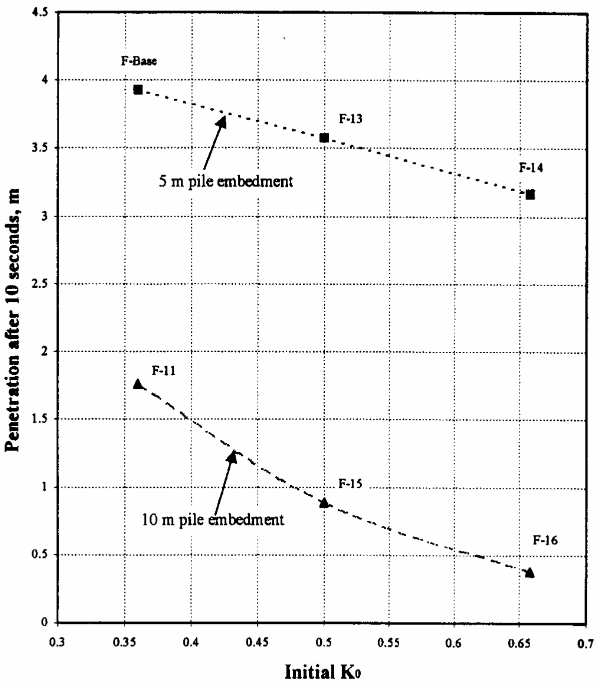

Figure 8 Influence of $K_0$ on penetration, $\delta = 30°$

The influence of $K_0$ on penetration rate at a constant interface friction of 30° is shown in Figure 8 for the dense sand with $\phi'_{ss} = 40°$. The static resistance of friction piles would be ≅ 83% larger for a $K_o$ of 0.66 compared to 0.36; however, the penetration rate during the first 10 seconds is reduced by only 20% at a 5 m embedment and more than 75% at an embendment of 10 m. The influence of $K_o$ has a relatively larger influence on penetration rate at greater pile embedments.

## Soil Model

A comparison was made between results obtained using the Mohr-Coulomb (MC) and hyperbolic (HY) soil models described previously. The elastic modulus used in the MC model was adjusted to obtain similar stress-strain responses for triaxial compression conditions as shown in Figure 9. Figure 10 illustrates that the penetration rate is only slightly effected by the stress strain response for non-displacement sheet piles.

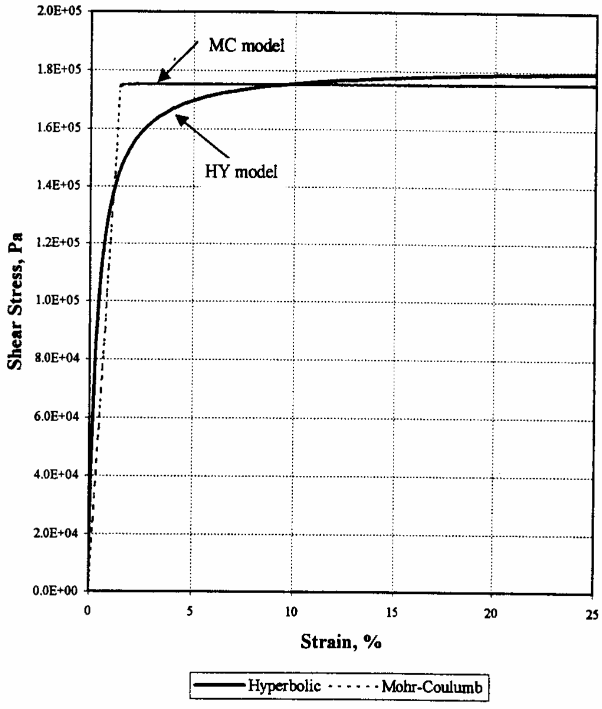

Figure 9 Stress vs. strain results of the models used

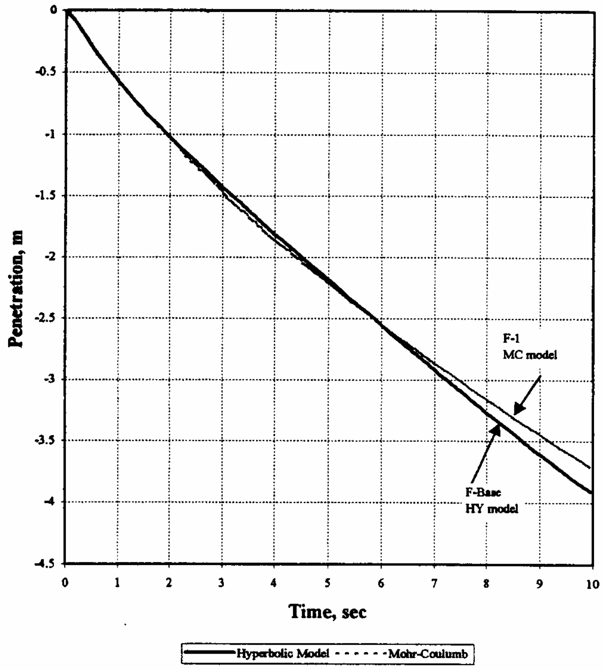

Figure 10 Penetration profiles using the hyperbolic and Mohr-Coulomb models

## CONCLUSIONS

The vibratory installation of piles is a very complex process with many variables involved including pile, driver, and soil characteristics. A two dimensional numerical simulation was used to assess the relative influence of several variables under simplified conditions.

The penetration rate of non-displacement "sheet" piles was primarily influenced by the driver operating frequency and soil/pile interface strength. A variation in operating frequency of 50% produced similar changes in the penetration rate for the ranges in frequency investigated.

A reduction in interface strength of 33% led to an increase in the penetration rate of 90% when the same lateral earth pressure was assumed. However, when the lateral earth pressure was varied with the soil strength in a consistent manner the variation in penetration rate was less influenced by interface strength.

The magnitude of $K_o$ has a relatively greater influence on penetration rate with increasing pile embendment.

Bias weight had a small influence on penetration rate for the conditions modeled. It is expected that bias weight would have a much greater influence in granular soils below the water table.

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