

DYNAMIC ANALYSIS OF PILE DRIVING FROM VARIOUS HAMMERING LOCATIONS ALONG PILE SHAFT

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ABSTRACT

Large diameter piles are normally used for cases where soft deposits are present. In these situations, piles may normally be driven into the ground using hammer impact. This paper presents a numerical model based on Smith's approach for pile driving in cases where impact energy may be imparted to the pile by hammer from any location along the pile shaft. Smith's model is used to simulate pile, soil, and driving equipment. The soil is assumed to be elasto-plastic and the pile behaves elastically. The pile is assumed to be large diameter and made of steel. This facilitates to hammer the pile from any arbitrary location along the pile shaft. Analyses have been performed to account for energy release from four points along the shaft. The results have shown that when the pile embedment depth is low, by hammering the pile from the pile top sections high pile penetration is achieved. In addition, when the pile is about to fully embedded, the pile bottom hammering causes the pile to have greater permanent penetration (set). Moreover, generally speaking, the bottom hammering leads to lower driving stresses in the pile which is structurally on the safe side. This implies that by driving the pile from the bottom part, a reduction in driving time, reduction in driving energy, and reduction of the possibility of pile buckling may be achieved. Obviously, a reduction in noise is also warranted. Other advantages of anywhere hammering in pile driving will also be presented.

Keywords: Pile driving, Smith's model, hammering, driving stress, set.

INTRODUCTION

The earliest pile driving analyses, dating back to the nineteenth century, were carried out using empirical equations in which numerous uncertainties were involved. Engineers were never able to agree on which equation was the best, because no mathematical solutions were applied to solve the problems involved in pile driving analysis in a practical manner. Moreover, pile driving involves many complicating features such as the use of capblocks, pile caps, followers, cushion blocks, composite piles, step-taper and tapered piles, and more importantly, the modeling of the soil reaction to the pile motion. In addition, the manner in which energy is delivered from the hammer to the pile involves numerous uncertainties. Because of these uncertainties, dynamic formulae are partly empirical and thus only limited types and geometries of piles can be analysed. Numerous formulae are required to cater for all circumstances. Thirty eight pile driving

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formulae were listed by Chellis (1951) and four hundred and fifty such formulae were mentioned in the *Engineering News Record* (ENR). A more soundly based solution, the wave equation method, was subsequently employed. This involves the recognition of the mechanics of the transmission of energy from the hammer to the pile. Although the differential equation for axial waves in a longitudinal bar was formulated and solved by St Venant in the 1850's (Timoshenko and Goodier, 1951), the first recognition of the presence of axial compression waves in pile driving is attributable to Isaacs (1931), who found that the wave action occurred during the driving of piles and the energy was not transmitted to the pile tip immediately during impact. This was confirmed experimentally by E. N. Fox (Glanville et al., 1938). In 1938, a wave equation analysis reported by Glanville et al. (1938). However, many simplifying assumptions were required to facilitate solution by hand calculation, significantly lessened the solution's accuracy. As a consequence, empirical pile formulae remained in common use.

The earliest significant contribution to pile driving analysis using the wave equation method was made by Smith (1960) who derived a numerical finite difference algorithm. Since then, the wave equation method has become gradually more sophisticated, incorporating improved soil models. Finite element solutions have been applied to pile driving analysis. The first full finite element solution of the pile driving problem is attributed to Chow (1981). Choe and Juvkam-Wold (2002) studied pile driving analysis for top hammering and bottom hammering.

MODEL OF SMITH

In the pioneering work of Smith (1960), the pile-soil-driver system is discretised into a number of one-dimensional segments as shown in Figure 1. The hammer and the pile cap are modeled as rigid masses which are represented by the two weights W_1 and W_2 . The capblock is a short resilient object made of wood, plastic, or similar material, which is comparatively light. It is therefore assumed to be massless and is represented by a spring. The cushion is treated in the same way. The pile is modeled as a series of masses lumped at nodes and interconnected by springs. The soil reaction to the pile motion is modeled as a number of Winkler type springs and dashpots. The springs representing the stress-strain behavior of the soil are assumed to exhibit an elastic-plastic behavior. The elastic limit is defined by Q , the so called soil "quake" (maximum elastic deformation). The spring coefficients are determined by dividing the static ultimate resistance by Q . Since the ground will obviously offer greater instantaneous resistance to rapid motion than to slow motion, Smith introduced an additional "viscous damping" represented by dashpots. Generally supposed $Q = 2.54\text{mm}$.

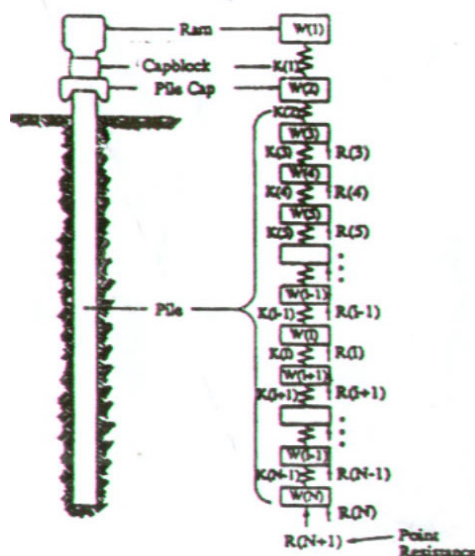


Figure 1. Model of Smith

This characteristic of soil behavior was initially discovered by Taylor (1942) in his studies on secondary consolidation. Smith suggested the soil resistance to the pile penetration be represented by a linear function of loading velocity defined by

$$R_{dyn} = (D_s - D'_s) K_{sm} (1 + J' V) \quad (1)$$

or

$$R_{dynamic} = R_{static} (1 + J' V) \quad (2)$$

where R_{dyn} is the dynamic soil resistance; R_{sta} is the static soil resistance; D_s is the total soil displacement from original position; D'_s is the total plastic deformation; K_{sm} is the soil stiffness, that is the soil spring coefficient; J' is the damping parameter for pile shaft resistance (J is used for pile toe resistance); and V is the velocity of the pile shaft (or the velocity of the pile toe for pile toe resistance).

Smith used finite difference technique for his pile driving model. The procedure of calculation starts with velocity of ram and continues by the following equation:

$$D(i, t) = D(i, t-1) + \delta t \cdot V(i, t-1) \quad (3)$$

$$C(i, t) = D(i, t) - D(i+1, t) \quad (4)$$

$$F(i, t) = K(i) \cdot C(i, t) \quad (5)$$

$$V(i, t) = V(i, t-1) + [F(i-1, t) - F(i, t) - R(i, t)] \cdot \frac{g \delta t}{W(i)} \quad (6)$$

where:

$D(i, t)$: displacement of segment i in time interval t

$D(i, t-1)$: displacement of segment i in time interval $t-1$

$C(i, t)$: spring compression i in time interval t

$F(i, t)$: force exerted by spring i in time interval t

$K(i)$: spring constant

$V(i, t)$: velocity of segment i in time interval t

$R(i, t)$: portion of ground resistance applicable to segment i in time interval t

$W(i)$: weight segment i

g : acceleration due to gravity

δt : time interval

Smith proposed time interval for steel and wood piles. These are 1/4000 sec. For concrete piles, this is 1/3000 sec.

The calculations are repeated until the pile velocity approaches zero and the tip displacement increment vanishes.

If a pile is driven from an arbitrary point, the formulation of segment $i=1$ which is for the ram, will be changed.

$$C(1, t) = D(1, t) - D(f, t) \quad (7)$$

$$V(2, t) = V(2, t-1) + [-F(2, t) - R(2, t)] \cdot \frac{g \delta t}{W(2)} \quad (8)$$

$$V(f, t) = V(f, t-1) + [F(1, t) + F(f-1, t) - F(f, t) - R(f, t)] \cdot \frac{g \delta t}{W(f)} \quad (9)$$

The values of J_c are listed in Table 1.

Table 1. Values J_c

| SOIL TYPE | CASE DAMPING FACTOR |
|-------------|---------------------|
| Clean sands | 0.10 to 0.15 |
| Silty sands | 0.15 to 0.20 |
| Silts | 0.20 to 0.40 |
| Silty clays | 0.40 to 0.70 |
| Clays | 0.70 to 1.00 |

STUDY OF PILE DRIVING FROM VARIOUS DRIVING POINTS ALONG PILE SHAFT

In this study a pile and driving system are assumed to have these details: length=12.6m, outer diameter=457mm, wall thickness=7.92 mm, mass density=7.75 ton/m³, ram weight=4.08 ton, ram impact velocity=4.08m/s. The soil friction angle is assumed to be $\phi = 35^\circ$. In this study, top hammering, quarter hammering, middle hammering, three quarter hammering, and bottom hammering are analyzed for various pile embedment in the soil.

Pile driving from various driving points along pile: Pile embedment=L/4

Figure 2 shows the pile tip set for driving points along the pile length. As seen, when a point of pile receives the impact wave, it starts to move. In the bottom hammering, the pile tip moves earlier than other points of pile, whereas in top hammering, the pile tip moves later than other points of pile. Therefore, in top hammering, the pile tip acceleration is greater than other points of the pile.

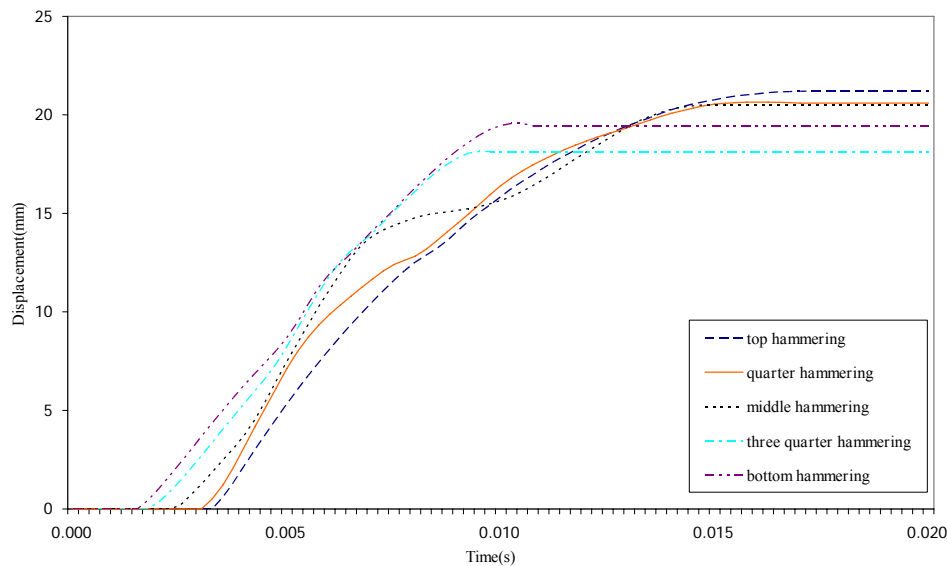


Figure 2. Variation of pile tip displacement versus time (pile embedment=L/4)

As observed in Fig. 2, in top hammering, the total pile settlement occurs after approximately 0.015 sec and in bottom hammering, this takes about 0.01 sec. It is also seen that due to the soil resistance in pile there is a difference between pile head displacement and pile toe displacement. This is elastic settlement. The least elastic settlement occurs in bottom hammering and the greatest value is produced in top hammering.

Table 2 shows some important information for this study. In driving the pile at any points except bottom hammering, compression stresses develop at the pile tip. In bottom hammering, tension stresses are produced. Therefore, in bottom hammering, residual stresses are lower than any other driving points.

Figure 3 shows driving stresses at the pile tip.

Table 2. Details of pile driving for L/4 pile embedment

| Driven point of pile | Residual stress (MPa) | Max acceleration (m/s^2) | Max velocity m/s | Elastic settlement (mm) | Set (mm) |
|----------------------|-----------------------|-------------------------------------|------------------|-------------------------|----------|
| Top | 58 | 6441.6 | 3.87 | 3.18 | 21.2 |
| Quarter | 56 | 4461 | 4.15 | 2.4 | 20.6 |
| Middle | 51 | 4163 | 4.1 | 1.4 | 20.5 |
| Three quarter | 45.6 | 4850 | 3.75 | 0.73 | 18.14 |
| Tip | 24 | 4824 | 3.65 | 0.49 | 19.44 |

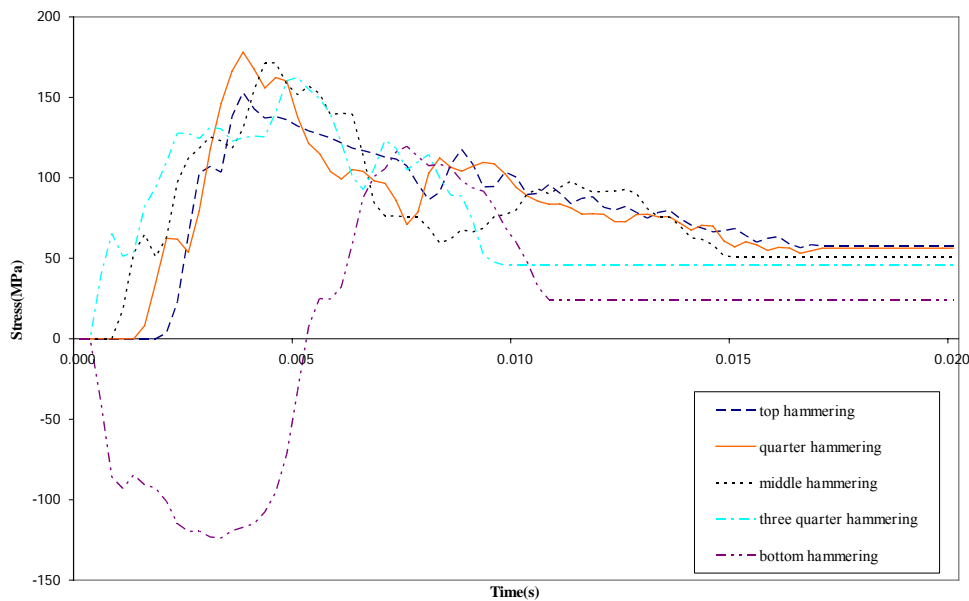
**Figure 3. Variation of driving stress in pile versus time (pile embedment=L/4)****Pile driving from various driving points along pile: Pile embedment=L/2**

Table 3 shows data for top and bottom hammering for the case in which half length of the pile is embedded in the soil. As seen, top hammering offers the greatest set other driving points. This is because the pile head is far from the soil and the impact energy dissipates later due to the soil damping. The bottom hammering gives the greatest set. Also, residual stress and elastic settlement are least in the bottom hammering.

Table 3. Details of pile driving for L/2 pile embedment

| Driven point of pile | Residual stress (MPa) | Max acceleration (m/s^2) | Max velocity m/s | Elastic settlement (mm) | Set (mm) |
|----------------------|-----------------------|-------------------------------------|------------------|-------------------------|----------|
| Top | 52 | 6138 | 3.65 | 3.75 | 17.39 |
| Quarter | 49 | 4315 | 3.71 | 2.36 | 16.96 |
| Middle | 51 | 4096 | 3.88 | 1.85 | 16.53 |
| Three quarter | 42 | 4850 | 3.48 | 1.19 | 15.71 |
| Tip | 38 | 4825 | 3.39 | 1.07 | 16.65 |

Pile driving from various driving points along pile: Pile embedment=3L/4

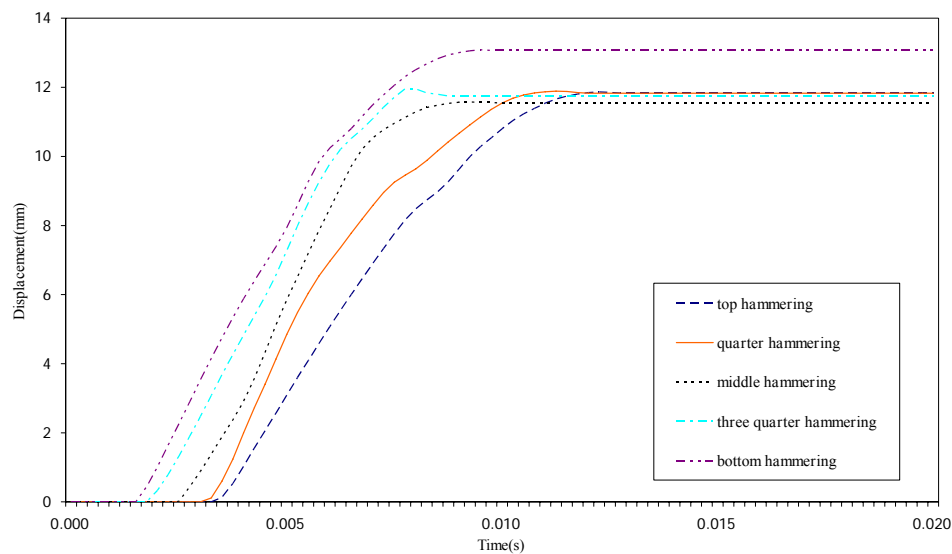
In this case, only a small upper length of the pile is not surrounded by the soil, therefore, the soil damping is not present for this part. The residual stress and elastic settlement are least in bottom hammering. Table 4 shows some important information for this case.

Table 4. Details of pile driving for 3L/4 pile embedment

| Driven point of pile | Residual stress (MPa) | Max acceleration (m/s^2) | Max velocity (m/s) | Elastic settlement (mm) | Set (mm) |
|----------------------|-----------------------|-------------------------------------|--------------------|-------------------------|----------|
| Top | 55 | 5837 | 3.44 | 4.12 | 14.38 |
| Quarter | 55 | 4172 | 3.41 | 2.86 | 13.89 |
| Middle | 52 | 4096 | 3.56 | 1.25 | 13.8 |
| Three quarter | 51 | 4850 | 3.23 | 1.2 | 13.72 |
| Tip | 19 | 4825 | 3.1 | 0.99 | 14.36 |

Pile driving from various driving points along fully embedded pile (pile embedment=L)

In this case, the soil offers its total damping to pile penetration. The bottom hammering produces the greatest set. Figure 4 shows the pile tip set for various driving points along the pile shaft.

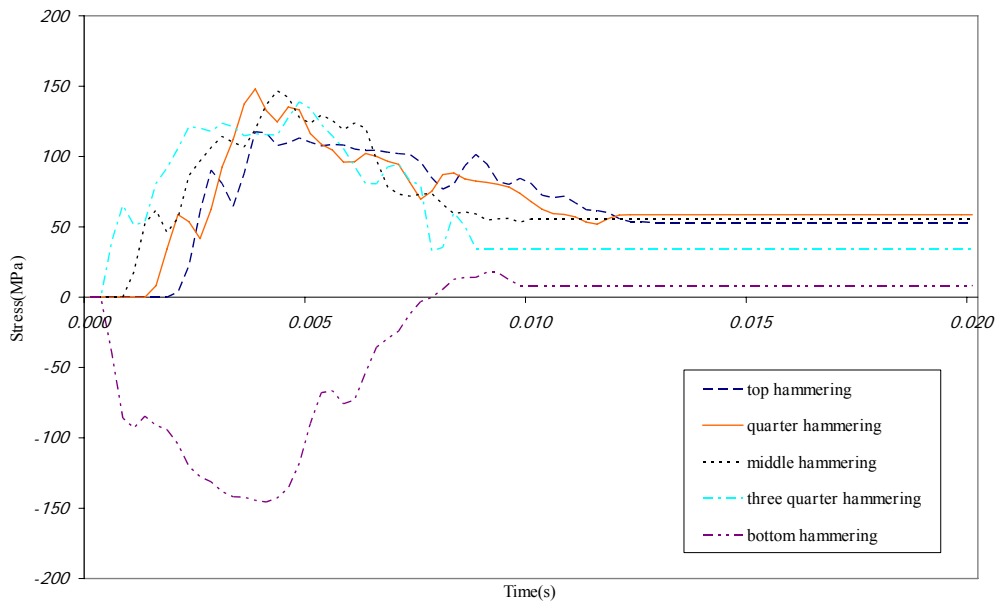
**Figure 4. Variation of pile tip displacement versus time (pile embedment=L)**

For fully embedded pile, in top hammering, the pile toe penetrates approximately after 0.01 sec and in bottom hammering. This takes about 0.008 sec. Table 4 shows some important information for this case.

Table 4. Some information for driven to any points of pile at pile length whole penetration

| Driven point of pile | Residual stress (MPa) | Max acceleration (m/s^2) | Max velocity m/s | Elastic settlement (mm) | Set (mm) |
|----------------------|-----------------------|-------------------------------------|------------------|-------------------------|----------|
| Top | 53 | 5526 | 3.23 | 4.23 | 11.83 |
| Quarter | 58 | 4172 | 3.03 | 2.31 | 11.82 |
| Middle | 55 | 3747 | 3.14 | 0.71 | 11.54 |
| Three quarter | 34 | 4850 | 2.87 | 0.6 | 11.75 |
| Tip | 8 | 4824 | 2.52 | 0.31 | 13.07 |

It is seen in Table 4 that the residual stress and elastic settlement are least bottom hammering. In the top hammering, the maximum acceleration occurs at the pile tip. In bottom hammering, the maximum acceleration occurs at the pile head. The residual stress and elastic settlement are least in bottom hammering. Figure 5 shows developed driving stresses in the pile around the pile toe.

**Figure 5. Driving stress versus time for pile tip in fully embedded pile**

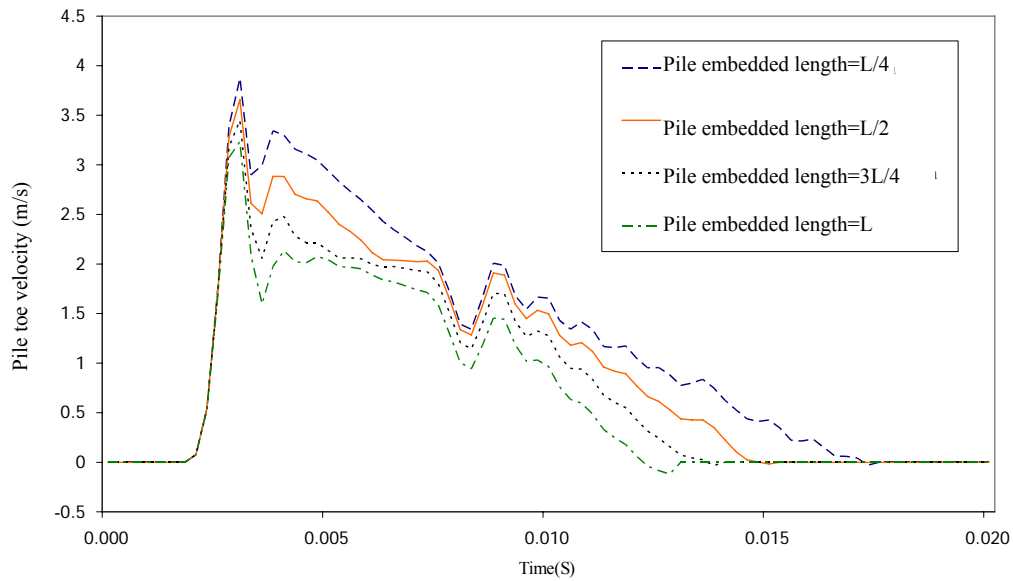


Figure6. Velocity of pile tip displacement for various pile penetration length at top hammering

PILE PARTICLE VELOCITY

In pile driving phenomenon, the soil damping is very important. Thus when the pile embedment increases, the pile particle velocity decreases. Also in top hammering, for a pile with $L/4$ penetration, the permanent pile penetration occurs for about 0.015 sec, however, for the fully embedded pile, the whole penetration occurs for about 0.01 sec. Figure 6 shows the velocity of the pile for various pile penetration in the soil at the top hammering.

MAIN RESULTS

Figure 7 compares the general conclusion extracted from analyses performed in this paper.

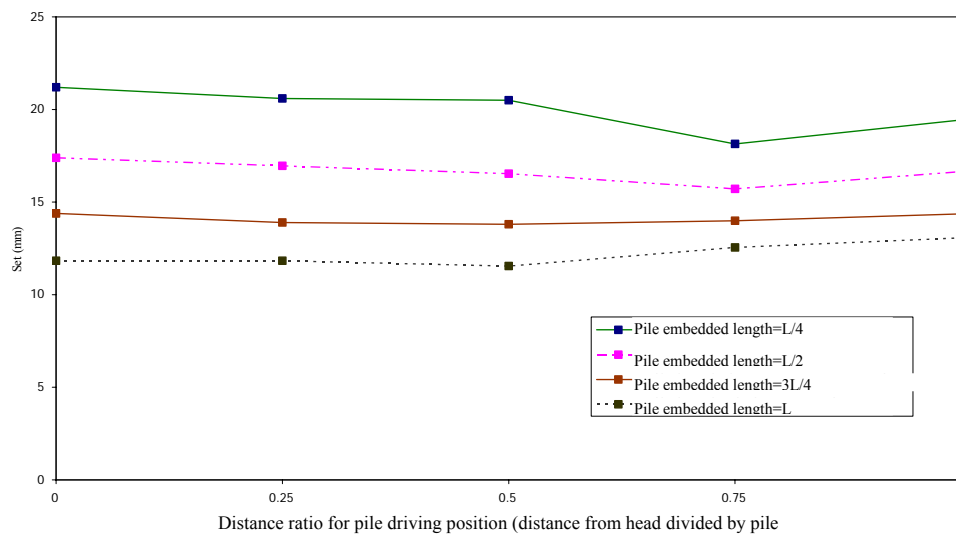


Figure 7. Comparison of pile set from various driving points along pile in

CONCLUSION

This paper investigates the effect of various driving points along the pile in pile driving phenomenon. Smith's model was used to simulate the pile, soil, and driving equipment. The results indicate that for low embedded length of the pile, the top hammering offers greater set than other point hammering. Moreover, for a fully embedded pile into the ground, the bottom hammering is more efficient from the quantity of the pile set. In addition, the bottom hammering, compared to other point hammering, generally converts compression driving stresses to tension stresses. From structural point of view, this is on the safe side for pile buckling. Considering these, together with a reduction of residual stresses and less noise made upon pile vibrations, the bottom hammering is more preferable than other point driving.

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