Multiple Blow Analysis for Bottom-Hammering Piles

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1. INTRODUCTION

Pile driving has ~~been used for platform foundations and offshore structures. In the early stage of development~~ of the pile driving practice, Newton's laws were applied to pile driving analysis on the assumption that the energy delivered by the hammer would be immediately transmitted to the tip of the pile at impact. However, the results from this method were highly variable in reliability because of elastic and plastic behaviors of the pile and soil. Smith[1)] developed a mathematical ~~solution to the wave equation that could be used to~~ solve ~~complex pile driving problems~~.

Lowery *et al.*[2)] have done intensive pile driving analysis studies and have developed several versions of wave equation analysis programs. However, their models are limited to a maximum of 70 pile elements which usually corresponds to 210-m pile length. Their models always include the gravity effect, whereas Edwards' program[3)] has an option to include the gravity effect. Another model has been developed by Holloway *et al.*[4-5)] and they also provided a good review of a number of wave equation analysis programs. Their model incorporates residual stresses in the solution. However, their ~~model is only valid for hammering at the top of the~~ pile ~~(top-hammering). Commercial~~ wave equation analysis programs such as the GRL program[6)] are also available. Although the GRL program can handle long piles, it is not valid for analysis of multiple hammering at the bottom of the pile (bottom-hammering).

All the models above are designed for single blow analysis (SBA) except for the Holloway *et al.*'s model, and can not simulate multiple bottom-hammering. This paper presents numerical analysis results on the effect of multiple blows for a bottom-hammering

2. ALGORITHM OF WAVE EQUATION ANALYSIS

Smith[1)] developed a mathematical solution to the wave equation. The solution was based on a discrete element idealization of an actual hammer-pile-soil system. The hammer-pile system is represented as a series of weights and springs. All springs are assumed perfectly elastic, whereas the soil is modeled as a spring and a dash-pot. The calculation of the wave equation analysis program starts with an initial ram velocity at the beginning of impact at time zero. The action of each ~~weight and~~ each ~~spring is calculated in each time interval to determine pile~~ displacement, force, and ground displacement per hammer blow for the specified soil resistance.

The method for hammering at the top of the pile can be applied to analyze pile driving by hammering at the bottom of the pile. In general, the hammering point can be any part of the pile and the same method can be applied to analyze the hammer-pile-soil system. All equations and descriptions are available from Choe & Juvkam-Wold.[7)]

During a hammer blow, the pile will move downward initially, then rebound, and then converge to a final position. At its final position, ~~the residual stresses in the pile are not zero because relative movements of~~ adjacent pile elements are not the same. Holloway *et al.*[4)] showed the importance of series of hammer blows rather than a single hammer blow for top-hammering. No multiple blow analysis (MBA) is available for bottom-hammering that is quite different from that of top-hammering. In this study, residual stresses are calculated from relative displacement of adjacent pile elements from the preceding blow and become initial stresses in the pile for the next hammer blow analysis for multiple blow analysis.

Validation of the Model. **Fig. 1** shows a comparison of driving resistance versus total static soil resistance with Lowery *et al.* model.[2)] As can be seen in Fig. 1, it shows a good match between the two models for the wide ranges of soil resistance. Other good matches are achieved with different damping constants.

3. FURTHER ANALYSES AND DISCUSSION

Top-Hammering and Bottom-Hammering. **Table 1** shows all input data with soil strength data. **Fig. 2** shows net pile penetration versus number of iterations at three different depths below the sea floor. This is a single blow analysis for top-hammering. For top-hammering, the pile penetration at the pile tip is considerably less than that of the pile top. Note that the pile penetration rapidly decreases as pile driving depth increases.

Key Words: Pile Driving Analysis, Multiple Blow Analysis, Bottom-Hammering

Fig. 3 shows net pile penetration for bottom-hammering by a single blow analysis. If the pile is being driven 90-m below the sea floor, a depth that represents low soil resistance, it shows a similar trend as that of top-hammering. In other words, hammering location does not affect pile penetration if soil resistance is low. If the pile is being driven 150-m below the sea floor, the penetration increases initially and then decreases, and then converges to its final penetration value. Also note that predicted pile penetration at 210-m is unreasonably high (4.3 cm) compared to that of top-hammering (0.048 cm) in Fig. 2, because the pile is pulled down from the bottom of the pile resulting in large pile penetration near the pile tip. This is one of major limitations for single hammer blow analysis for bottom-hammering.

Single Blow Analysis and Multiple Blow Analysis. Multiple blow analysis is applied to see the effect of residual stresses. From 10 consecutive blows for top-hammering and bottom-hammering, MBA for both top-hammering and bottom-hammering becomes almost linear after 4 or 5 consecutive blows. Therefore, an average net penetration of last 5 blows out of 10 consecutive blows is logical and used in this study.

Fig. 4 shows a comparison of pile driving resistance between SBA and MBA for top-hammering. The pile sinks about 58-m below the sea floor due to its own weight of 127 tons. SBA reaches practical refusal beyond 200-m, whereas MBA reaches more than 250-m below the sea floor. MBA gives better penetration per blow than SBA as penetration depth increases.

Fig. 5 shows a comparison of pile driving resistance between SBA and MBA for bottom-hammering. Compared to Fig. 4, pile driving resistance for SBA for bottom-hammering does not decrease much for deep depth where top-hammering indicates a refusal. This is unrealistic and results from the fact that the tip part of the pile can move even a fraction of a centimeter, regardless of soil strength and the movement of the top portion of the pile. This is one of disadvantages for single blow analysis for bottom-hammering at high soil resistance. As expected, MBA gives a close result to that of SBA for low soil resistance where the effect of residual stresses is negligible. As soil resistance to pile driving increases, MBA for bottom-hammering predicts less penetration than SBA because the tip part of the pile bounces back while the top part of the pile moves downward. In these cases, the pile will have a significant amount of residual stresses, especially at deep depth of penetration. Therefore, MBA should be used for bottom-hammering analysis at high soil resistance.

4. CONCLUSIONS

The following conclusions have been drawn from this study.

1. A wave equation analysis program has been developed and it can handle long piles for top-hammering and bottom-hammering. It simulates multiple blow analysis as well as single blow analysis.
2. If a single blow analysis is used, it predicts refusal early for top-hammering and predicts unrealistically high pile penetration for bottom-hammering, especially for high soil resistance.
3. Multiple blow analysis which takes into account the effect of residual stresses in the pile should be used for more realistic pile driving analysis and prediction.

REFERENCES

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TABLE 1 - DEFAULT INPUT DATA WITH A SOIL STRENGTH DATA

31,000	total pile length, cm
60.96	outer diameter of the pile, cm
55.88	inner diameter of the pile, cm
610.2	hammer energy, kJ
36.3	weight of the ram, tons
0.85	hammer efficiency, fraction
133.4	weight of pile cap, kN
76.2	diameter of capblock, cm
24,756	spring constant for capblock, kN/cm
0.5	coefficient of restitution for capblock
0.254	Max. elastic ground deformation (quake), cm
0.0049	damping constant at the point of pile, sec/cm
0.0016	damping constant along the side of pile, sec/cm

Remolded miniature vane shear strength vs. depth:

Depth, m	kN/sq. m	kips/sq. ft
0	0.00	0.00
213	71.82	1.50
305	88.38	1.85

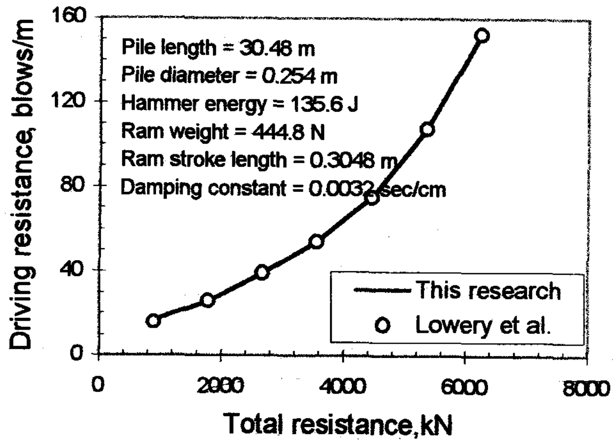

Fig. 1 Model comparison with Lowery et al.'s model.

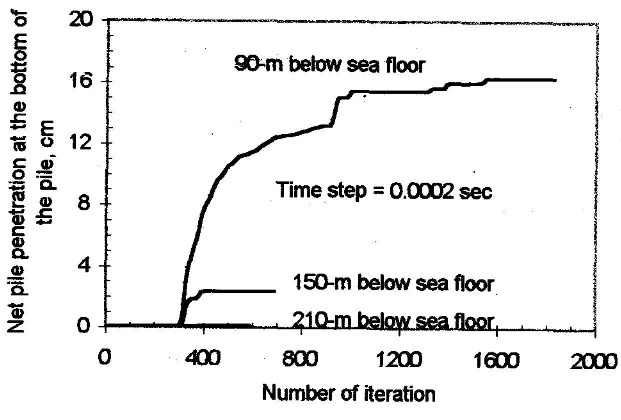

Fig. 2 Net pile penetration for top-hammering.

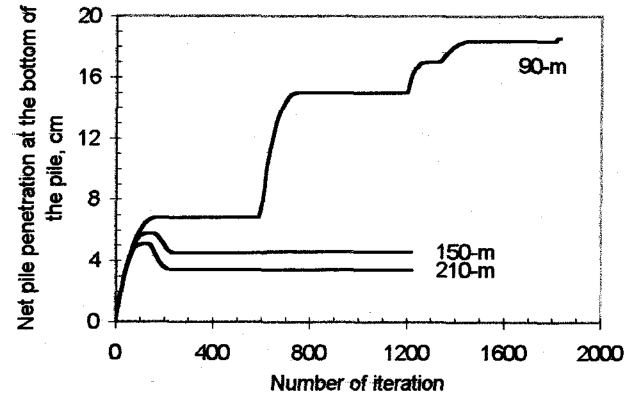

Fig. 3 Net pile penetration for bottom-hammering.

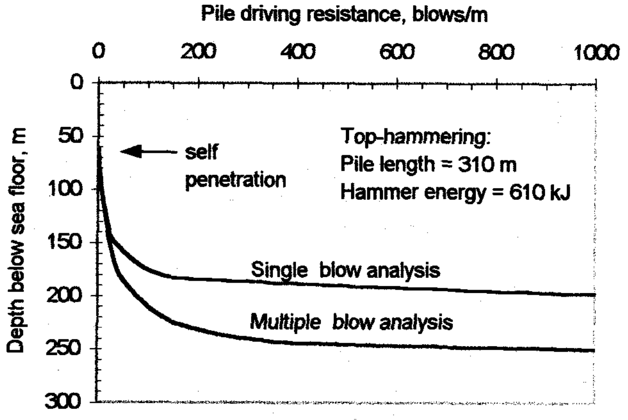

Fig. 4 Comparison of single blow and multiple blow for top-hammering.

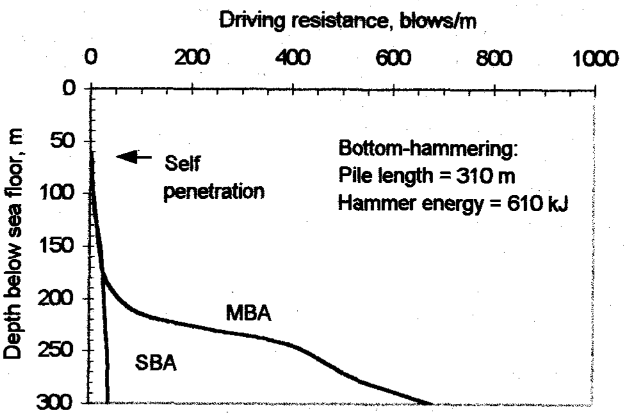

Fig. 5 Comparison of single blow and multiple blow for bottom-hammering.