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Dynamics of pile driving as a function of ram drop height

M. Hussein
Goble Rausche Likins and Associates, Inc., Orlando, Fla., USA

F. Rausche
Goble Rausche Likins and Associates, Inc., Cleveland, Ohio, USA

G. Likins
Pile Dynamics, Inc., Cleveland, Ohio, USA

ABSTRACT: The effectiveness of pile driving depends largely on the proper choice of hammer size. For a constant ram weight, the dynamic behavior of the hammer, pile, and soil are related to the ram drop height. Dynamic pile top records of force and velocity on three 25 ft (7.6 m) long prestressed concrete piles were obtained with a Pile Driving Analyzer™ (PDA) under impacts of a drop hammer of 3.14 kips (14 kN) weight. Each pile was subjected to 15 impacts with ram drop heights ranging from 1 to 15 ft (0.3 to 4.6 m) with one foot (0.3 m) increments. The effects of ram drop heights and ram impact velocity variations on the dynamic behavior of the hammer, pile, and soil are investigated.

1 BACKGROUND

Impact pile driving is an integrated process through which various components interact in a dynamic manner under a hammer blow. The energy rating of any given hammer is dependent upon its ram weight and drop height; this, however, is only an overall index. For a particular application, the hammer must transfer a sufficient portion of this energy through the driving system and pile to the soil in order to cause pile penetration at acceptable stress levels. Both the ram impact velocity and the driving system (hammer cushion, pile top cushion, and pile cap) affect maximum driving stresses. The pile must have sufficient strength to withstand driving forces which are sufficiently large to overcome soil resistance. The soil, in turn, has intrinsic properties and a dynamic behavior that is influenced by the nature of loading. Dynamic soil behavior affects hammer performance, while pile size and stiffness affect soil behavior, and the hammer and driving system affect both pile forces and soil loading. Thus, energy generation, transmission, and dissipation are interrelated.

All other factors in the hammer system being relatively constant, the ram drop height has a profound effect on the pile driving operation. This paper considers a case study where pile top dynamic data were obtained on three piles under the impacts of a drop hammer. The effects of varying ram drop height on the behavior of the pile and soil are investigated.

2 SITE DETAILS

The final stage of a research project to study the feasibility of using fiberglass to prestress concrete piles was the driving of three piles. The drop hammer had a ram weight of 3.14 kips (14 kN) and the pile cap weighed 0.32 kips (1.4 kN). Sheets of plywood were used for both hammer and pile top cushions with thicknesses of 2.25 and 4 inches (55 and 100 mm), respectively. The piles were 25 ft (7.6 mm) long with 10-inch (250 mm) square prestressed concrete sections and are referred to as Piles A, B, and C. Pile A had steel strands and spirals, Pile B had fiberglass strands and steel spirals, and for Pile C both strands and spirals were made of fiberglass. After the end of installation, each pile was then subjected to an additional 15 hammer blows with drop heights ranging between 1 and 15 ft (0.3 to 4.6 m). The findings of the research into prestressing concrete piles with fiberglass have been published elsewhere (Sen, Issa, Iyer 1992).

Pile top dynamic measurements using a PDA were obtained during the entire installation of all three piles. The data was analyzed in the field according to the Case Method (Rausche, Goble, Likins 1985). Figure 1 presents a summary of the soil conditions and measurement results from initial driving as a function of depth. A hammer drop height of 8 ft (2.4 m) was used throughout pile driving. Generally, subsurface conditions were dense to very dense sand. End of driving pile penetrations were 21 ft (6.4 m) at driving resistance of 29 blows per foot (29 blows/300 mm), and calculated pile static capacities averaging 200 kips (890 kN). During driving, pile top compressive stress and transferred energy averaged 3.5 ksi (24 MPa) and 10.5 kip-ft (14.3 kJ), respectively. Pile tension stresses averaged 0.45 ksi (3 MPa).

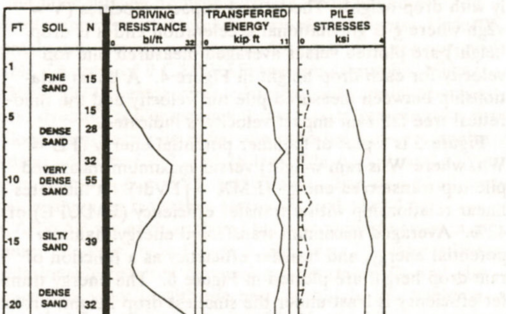

Fig. 1 Typical pile installation history

3 RESULTS

After the end of driving, each pile was subjected to 15 additional blows with increasing drop heights up to 15 ft (4.6 m). Figure 2 shows pile top force and velocity (multiplied by pile impedance) records from three blows of Pile A with drop heights of 2, 7, and 15 ft (0.6, 2.1 and 4.6 m), respectively. Averaged Case Method results of pile top velocity, compressive force, transferred energy, and maximum pile top displacement for each blow on all piles as a function of drop height are presented in Figure 3.

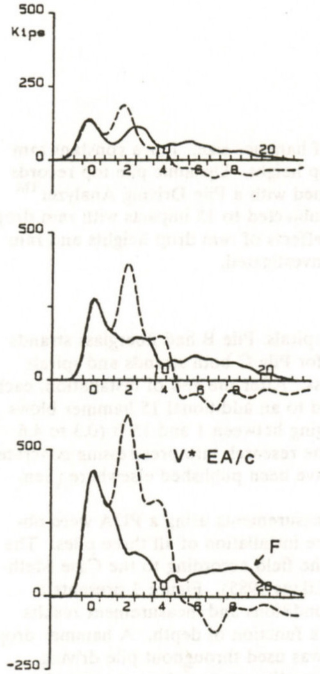

Fig. 2 Measurements for Pile "A" at drop heights of 2, 7 and 15 ft

3.1 Hammer performance and energy transfer

As indicated in Figure 3, pile top maximum transferred energies and displacements increased approximately linearly with drop height. Theoretical impact velocities ($V = \sqrt{2gh}$ where g is gravitational acceleration and h is drop height) are plotted versus averaged measured pile top velocity for each drop height in Figure 4. A linear relationship between measured pile top velocity and the theoretical free fall ram impact velocity is indicated.

Figure 5 is a plot of hammer potential energy (PE = Wh, where W is ram weight) versus maximum measured pile top transferred energy (EMX = $\int FVdt$). It indicates a linear relationship with a transfer efficiency (EMX/PE) of 42%. Averaged maximum transferred energy, hammer potential energy, and transfer efficiency as a function of ram drop height are plotted in Figure 6. The energy transfer efficiency is least under the smallest drop height, probably because of certain energy losses which are independent of drop height. For example, initial friction losses on the hoist drum when it begins to spool are significant and

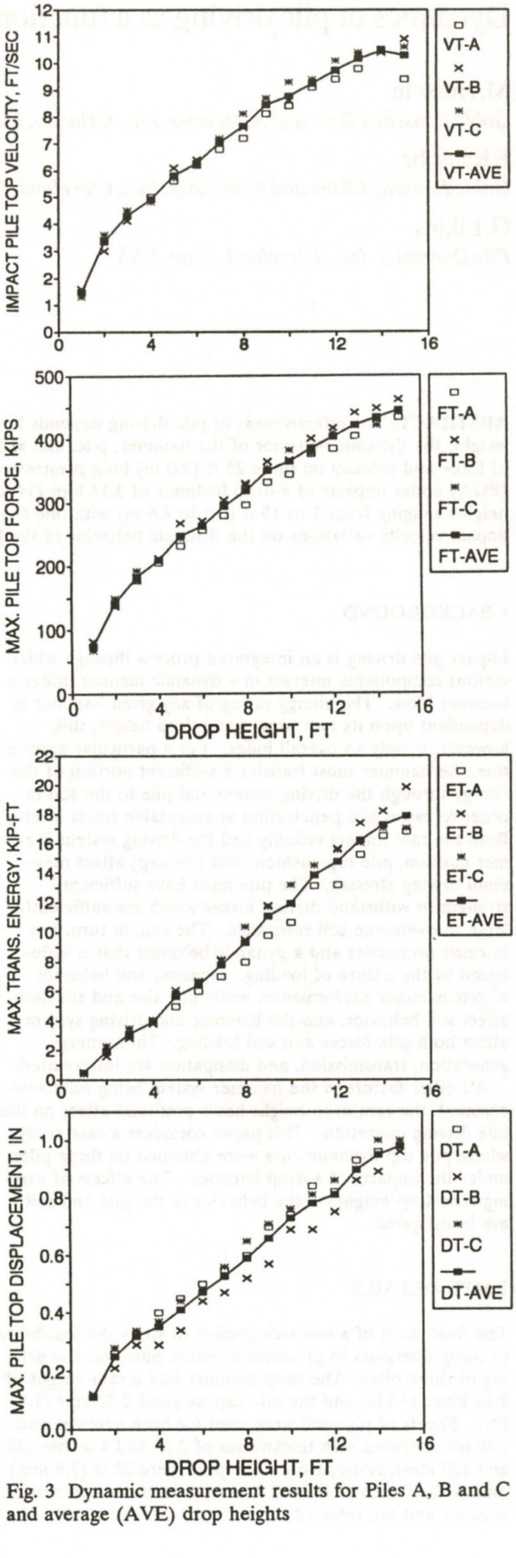

Fig. 3 Dynamic measurement results for Piles A, B and C and average (AVE) drop heights

equal for all ram falls. It is also observed that the transfer efficiency reaches an approximately constant level above drop heights of 5 ft (1.5 m).

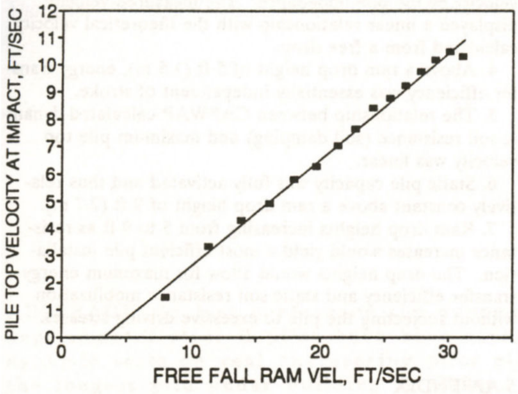

Fig. 4 Measured pile velocity versus theoretical free fall velocity

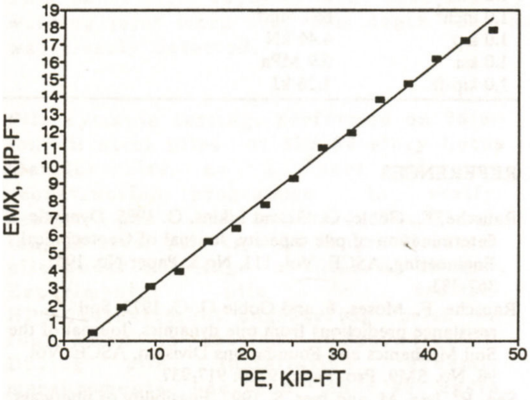

Fig. 5 Measured transferred energy EMX versus ram potential energy PE

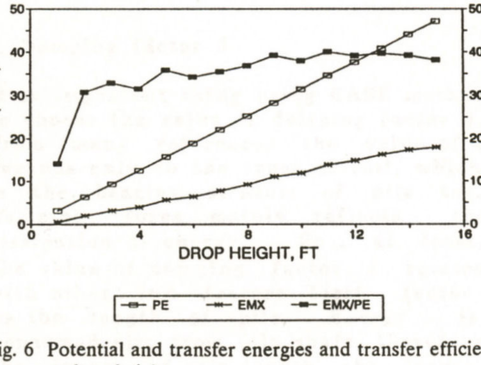

Fig. 6 Potential and transfer energies and transfer efficiency versus drop height

3.2 Pile performance

All three piles responded in similar manner both during initial installation and under the 15 variable hammer blows. Maximum compressive stress ranged between 0.6 to 4.7 ksi (4 to 32 MPa). Pile tension stresses were negligible during the added hammer blows due to then sufficient soil resistance. Dynamic measurements did not indicate any pile structural damage; however, Pile C suffered minor pile top spalling under the maximum drop which was attributed to hammer-pile misalignment.

Averaged pile top velocities at impact plotted versus averaged pile top forces at impact in Figure 7 indicate a linear relationship with a slope equal to the pile impedance, Z. This indicates good dynamic data quality since the theoretical relationship $F = Zv$ is verified. Assuming the normal concrete density, the stress wave speed can be computed to be c = 12674 ft/sec (3864 m/sec) from $Z = \rho cA$ (where ρ is the mass density, c is the stress wave speed, and A is the pile cross-sectional area). Thus, Z = 41 kips/ft/s (599/kN/m/s). The wave speed was confirmed by the measured wave reflections from the pile toe at time 2L/c, where L is the pile length below the point of gage attachment. There was no appreciable difference in the performance of all three pile types.

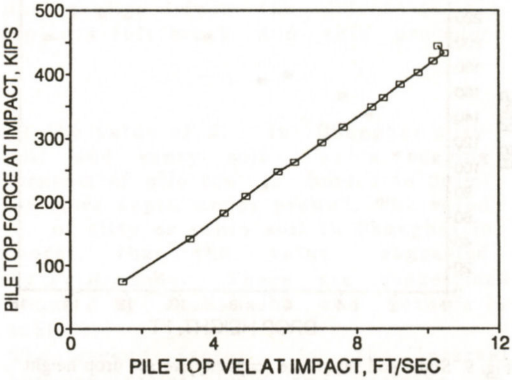

Fig. 7 Averaged pile top force versus average pile top velocity

3.3 Soil behavior

The piles showed a linear increase in maximum pile top displacements with increasing ram drop heights. Unfortunately, pile net set readings under each blow are not available. A total of 9 CAPWAP analyses (Rausche, Moses, Goble 1972) were performed to compute static capacities and dynamic soil resistance forces. Data representing three blows from each pile at varying drop heights were analyzed (drop heights of 2, 7, and 15 ft of Pile A; 3, 9, and 13 ft of Pile B; and 4, 6, and 12 ft of Pile C). The sum of all maximum damping resistance forces, R_d, calculated by CAPWAP for each analyzed blow, is plotted versus maximum pile velocity in Figure 8. The data indicates a linear relationship between dynamic soil resistance R_d and pile maximum velocity with the best fit straight line having a slope of $J_v = 10.3$ kip-sec/ft (150 kN s/m). Dividing this value by the pile impedance yields the nondimensional Case Method soil damping factor of 0.25 which is in the

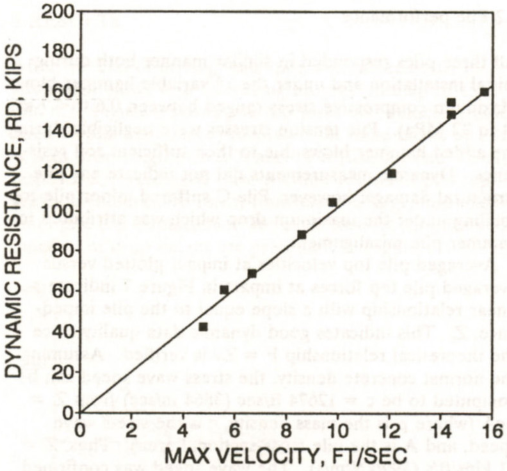

Fig. 8 Dynamic soil resistance (obtained from CAPWAP analysis) versus maximum pile velocity

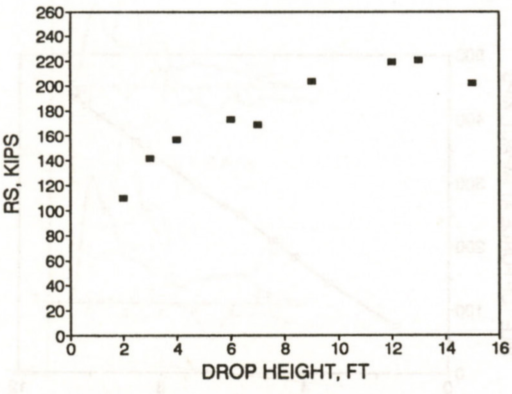

Fig. 9 Static soil resistance (capacity) versus drop height

range of accepted values for the sandy soil type at the site. Similarly, a Smith damping factor can be calculated by dividing J_v with the average static resistance of 177 kips (790 kN) yielding 0.06 s/ft (0.19 s/m) again a value in good agreement with the usually recommended 0.050 s/ft (0.165 s/m).

Static pile capacities plotted as a function of ram drop heights in Figure 9 are essentially constant (in other words they are fully activated) above a ram drop height of 9 ft (2.7 m). However, pile top compressive stresses continue to increase from 3.2 to 4.5 ksi (22 to 31 MPa) with increasing drop heights from 9 to 15 ft (2.7 to 4.6 m), respectively, demonstrating that the calculated capacity is independent of drop height or maximum pile top force.

4 CONCLUSION

Dynamic pile top measurements and analyses performed under 15 hammer blows with varying ram drop heights on three piles support the following conclusions:

1. All three pile types performed in a similar manner, regardless of material used for prestressing.
2. Pile top displacements, and transferred energies increased almost linearly with increasing ram drop heights.
3. Pile top forces were proportional to measured pile top velocity by the pile impedance. The measured velocity displayed a linear relationship with the theoretical velocity calculated from a free drop.
4. Above a ram drop height of 5 ft (1.5 m), energy transfer efficiency was essentially independent of stroke.
5. The relationship between CAPWAP calculated dynamic soil resistance (soil damping) and maximum pile top velocity was linear.
6. Static pile capacity was fully activated and thus relatively constant above a ram drop height of 9 ft (2.7 m).
7. Ram drop heights increasing from 5 to 9 ft as resistance increases would yield a most efficient pile installation. The drop heights would allow for maximum energy transfer efficiency and static soil resistance mobilization without subjecting the pile to excessive driving stresses.

5 APPENDIX

English	SI
1.0 ft	.308 meter
1.0 inch	25.4 mm
1.0 inch^2	654 mm^2
1.0 kip	4.46 kN
1.0 ksi	6.9 MPa
1.0 kip-ft	1.36 kJ

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Edited by
FRANS B.J. BARENDS
Delft Geotechnics & Technical University Delft

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