Pile Driving Resistance and Load Bearing Capacity
Resistencia Al Hincado y Capacidad Portante en Pilotes

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Abstract

Pile driving resistance, often expressed simply by blow count, has long been used as a convenient indicator of pile bearing capacity. Accurate assessment of capacity based on blow counts, however, requires an understanding of the mechanics of the hammer system, pile, soil, and dynamic interaction of these physical parameters. Correct evaluation of a pile driving blow count log can only be done with factual consideration of the specifics in each situation. Otherwise, erroneous conclusions regarding pile load bearing capacity and driveability may be drawn. This paper considers some of the parameters that contribute to driving resistance and the real and apparent bearing capacity suggested by observed blow counts. Quantitative results from numerical computer analyses and dynamic field measurements are used to illustrate the characteristic effects of the various components involved in the pile driving process. Important performance parameters of the hammer system, pile and soil are delineated and discussed.

Resumen

La resistencia a la hinca de pilotes, a menudo expresada simplemente por el conteo de golpes por longitud de penetración, ha sido utilizada como un indicador conveniente de la capacidad portante del pilote. La evaluación exacta de la capacidad portante basada en el conteo de golpes requiere entendimiento de la mecánica del sistema de martillo, pilote y suelo y la interacción mecánica de estos parámetros físicos. La evaluación correcta del registro del conteo de golpes en la hinca sólo puede hacerse con consideración objetiva de las condiciones específicas en cada situación. De otra manera, se pueden obtener conclusiones erróneas acerca de la capacidad portante de los pilotes y su hincabilidad. Este artículo considera algunos de los parámetros que contribuyen a la resistencia a la hinca y la capacidad portante real y aparente sugeridas por el conteo de golpes observado. Los resultados cuantitativos de análisis numéricos hechos por computador y de las mediciones dinámicas efectuadas en pilotes hincados son utilizadas para ilustrar los efectos característicos de los varios componentes envueltos en el proceso de hinca de pilotes. Parámetros importantes de desempeño del sistema del martillo, el pilote y el suelo son enumerados y discutidos.

1 INTRODUCTION

Structural loading and settlement requirements, geotechnical conditions, specific site and project characteristics, and economic considerations often dictate the use of deep foundations. Piles are commonly used with load carrying capacities from a few to several thousand tonnes. Driven piles are made of wood, steel (pipe or H-shape), concrete (pre-stressed or post-tensioned), or a combination of these materials (e.g., concrete-filled steel pipe). They typically range in size from 250 to 750 mm in diameter and 10 to 50 m in length. Impact pile driving hammer ram weights typically range from 1 to 10 tonnes and drop heights from 1 to 3 m. Several hundred to thousands of hammer blows are typically needed to install each pile. Although pile driving by hammer impacts appears to be old-fashioned and destructive, this installation process in itself provides a test of the constructed pile.

Counting the number of hammer blows it takes to advance the pile a unit distance into the ground (i.e., recording a blow count log) has long been used as construction control and quality assessment method. The resulting blow count (e.g., blows/ft, blows/m), is a convenient indicator of soil resistance and, therefore, pile bearing. The relationship between blow count and capacity is commonly known as a "Bearing Graph", with typical shape characteristics as shown in Figure 1. This graph can be used in two ways: (a) for a specified pile capacity, it shows the associated blow count (for driving criterion specification or driveabilty analyses); (b) for an observed blow count, it indicates the corresponding pile capacity.

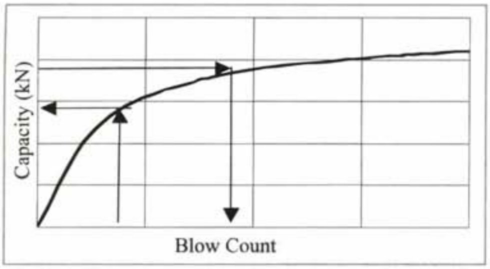

Figure 1 The Bearing Graph

Originally, bearing graphs were constructed based on impact energy considerations, incorporating simplifying assumptions. This obsolete type of analysis should be applied to pile driving analysis, Terzaghi (1943). The advent of digital computers in the 1950s made it possible to apply the principles of one-dimensional elastic stress-wave propagation for rational and practical analysis of pile driving dynamics, Smith (1960). In today's practice, bearing graphs are generated by computer programs such as (GRL)WEAP (Goble and Rausche, 1976). Clearly, a bearing graph is a simple, convenient, and effective tool to control pile driving. However, it is generally recognized that there are a number of reasons why the bearing graph can lead to erroneous results:

Input parameters are average experience values; they may not reflect accurately enough a particular situation.

The observed blow count is oftentimes inaccurate.

The soil resistance changes after installation.

Equally important, a realistic prediction of pile driveability or an accurate assessment of bearing capacity requires an understanding of the fundamental characteristics of the mechanics and dynamic interaction of all components involved in the pile driving process. The following discussion attempts to aid in the understanding and proper interpretation of dynamic analysis results.

2 DYNAMICS OF PILE DRIVING

The pile driving process generally involves the hammer, capblock, helmet, pile cushion, pile, and soil. The falling ram impacts and compresses the hammer cushion, accelerating the helmet, compressing the pile top cushion, and eventually moving the pile top. The suddenly applied impact generates an elastic compression wave causing strain and motion of the pile. The pile motion is opposed by the soil resistance. Permanent pile set is achieved following elastic rebound after maximum displacement. Subsequent hammer blows produce cumulative pile penetration. In addition to axial forces, piles are subjected to bending and torsion.

The length and initial intensity of the stress-wave in the pile are functions of: ram weight, stroke, efficiency, diesel hammer combustion pressure, hammer and pile cushion stiffness and coefficient of restitution, helmet weight, and pile weight and stiffness; soil resistance effects and wave reflections at the tip also influence the characteristics of the stress wave in the pile. The stress level in the traveling wave has to be high enough to overcome soil resistance (dynamic and static) forces, and the motion has to be maintained for a sufficiently long duration to overcome elastic deformations and cause permanent pile set. The pile should have sufficient structural strength, stiffness, and mass to withstand and transmit the dynamic driving stresses and motions caused by the hammer impact.

3 DYNAMIC MEASUREMENTS

Bearing graphs generated by wave equation analysis can only be as accurate as the degree of realism and correctness achieved in representing the actual field conditions. The model and analysis necessarily represent "normal" conditions and "average" performance. Modern dynamic testing methods and analyses, primarily conducted with a Pile Driving Analyzer® (PDA) as described by Hussein et al. (1995), provide information about actual driving conditions, however, only when a pile is actually driven. Likins et al. (1988) discussed other, more direct measurement techniques. Additionally, it should be noted that the pile capacity indicated by the blow count reflects the conditions at the time of driving or restriking. Soil setup or relaxation effects, occurring with time after pile installation, cause, respectively, increases or decreases of pile bearing capacity with time.

4 HAMMER SYSTEM PARAMETERS

Pile driving hammers come in a variety of models, all with their own characteristics. To the pile driving contractor, the hammer is a tool that installs the pile. To the engineer, each hammer impact applies a test load and helps to judge the quality of the installed pile. It is, therefore, important to accurately determine the hammer efficiency for economic production of pile driving operations and reliable engineering evaluation of foundation quality. The performance of pile driving systems may be assessed by the ratio of energy transferred to the pile, as measured by the PDA, and the rated hammer energy. This transfer ratio (or transfer efficiency or global efficiency) is quite variable, generally ranging between 20 and 80%, Rausche et al. (1985). The transfer ratio expresses energy losses in the hammer and also in the driving system (hammer cushion, helmet and pile cushion) whose parameters also play a major role in the overall driving system performance and, therefore, in the development of pile bearing capacity, blow count and pile driveability.

4.1 Example 1: Effect of Impact Velocity

Figure 2 shows two bearing graphs for a 25 m long steel pile (cross sectional area = 100 cm^2) considering two hammers with almost identical rated energies (65 kJ), however, with different ram masses and drop heights (1.8 tonnes x 3.6m, and 5.3 tonnes x 1.2 m). The lighter hammer has a higher impact velocity and therefore generates a higher amplitude shorter duration stress wave.

The bearing graph for the lighter hammer first indicates lower capacities for the same blow count but when driving gets hard it indicates that this hammer becomes more efficient. The reason is that the longer stress wave with its lower pile velocities is more effective for low capacities, because it causes less dynamic soil resistance. However, as the soil resistance increases, the higher forces of the sharper stress wave can overcome higher soil resistance forces and generate permanent pile set.

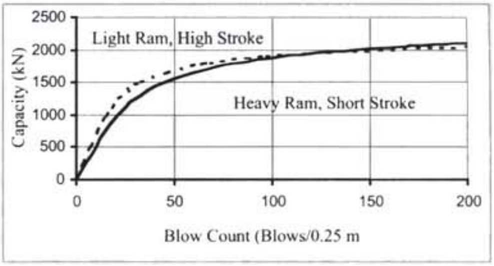

Figure 2 Hammers with Identical Rated Energies

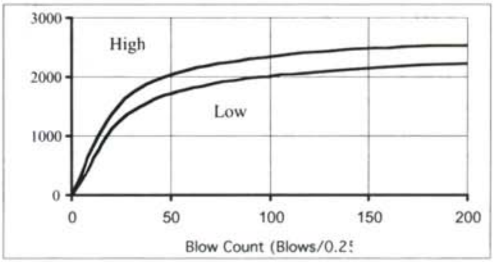

Figure 3 Effects of Different Hammer Efficiencies

4.2 Example 2: Hammer Efficiency

Figure 3 presents bearing graphs for a steel pile (25m long, 140 cm^2 area) and an air hammer (ram mass of 4.6 tonnes and drop height 1.5m), analyzed with reasonable efficiency values that were 15% of the "normal" value of 0.67. Such a difference in hammer efficiency is normally not noticeable by routine inspection, without dynamic measurements. The effect can be significant: for example, at 2000 kN capacity the required blow count could differ by as much as 100% (an increase from roughly 50 to 100 blows/0.25m). On the other hand, at lower resistances, say below 25 blows/0.25 m, the blow count differences at a given capacity value approach the difference in efficiency, i.e. at lower blow counts there is a nearly linear relationship between hammer energy and blow count.

4.3 Example 3: Cushion Stiffness

This example illustrates the effect of cushion stiffness variability on the characteristics of the bearing graphs. The analysis was done for a 30m long concrete pile (cross sectional area 2100 cm^2) driven with a 3.6 tonnes hammer and 1.5 m stroke. According to Figure 4, the blow counts at, say, 2000 kN capacity, would decrease from 100 to 75 blows/0.25m for a three-fold increase in cushion stiffness (due to a decrease of cushion thickness to 1/3 of its original size). In the case of a plywood cushion, such thickness reduction can easily happen when driving a concrete pile with more than 1000 hammer blows. Obviously the stresses in the pile would significantly increase as the pile cushion becomes more compressed. This important matter can easily be checked with the wave equation analysis, however, stress considerations are beyond the scope of this paper.

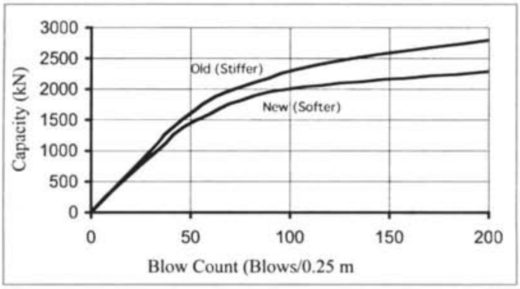

Figure 4 Cushion Stiffness Effect

5 PILE PARAMETERS

There are several aspects to pile design: structural strength, geotechnical capacity and serviceability, and driveability. The pile has to be of sufficient strength, stiffness, and impedance (function of unit weight, elastic modulus, and section area) to withstand and transmit dynamic driving stresses against soil resistance forces to attain permanent penetration under each hammer blow. Pile physical and mechanical properties play important roles in pile driveability.

5.1 Example 4: Open vs Closed-Ended Pipe

Evident in Figure 5 is the difference in the bearing graphs of an open-ended pile (low displacement-type) and closed-ended (displacement -type) 35m long, 600x30 mm (diameter x wall thickness) steel pipe pile driven with a hammer (11.4 tonnes ram and 1.75m stroke). The driveability of the two pile conditions is markedly different at higher capacity values; e.g., at 7000 kN, the blow counts are 55 and 95 blows/0.25m for the open and closed-ended piles, respectively. The main reason for the difference is the higher amount of end bearing (60% instead of 20% of total capacity). End bearing of a displacement pile has a higher flexibility than a non-displacement pile (quake for the closed-ended pile is 10 mm instead of 2.5 mm for the open one) or a pile with more shaft resistance. A resistance with a higher quake requires more energy for overcoming the soil resistance. Larger displacement piles tend to "bounce" which means they return a large amount of energy which has elastically compressed the soil at the pile toe, but which was not dissipated by pile penetration.

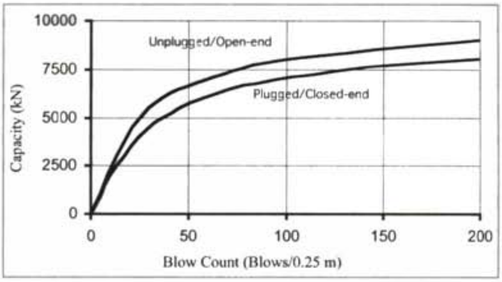

Figure 5 Pile Characteristics Effects

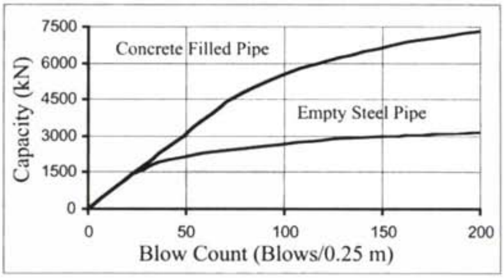

Figure 6 Pile Impedance Effects

5.2 Example 5: Pile Impedance

Figure 6 shows the dramatic effect of pile impedance on the capacity-blow count relationship. Considered here is a 25 m long pipe pile, 600x10 mm, empty (as would be expected during initial installation) and concrete filled (as may be the case during restrike) impacted with a hammer having a ram mass of 3.5 tonnes with a drop height of 1.5 m. The analysis indicates that the capacity that can be achieved at the same blow count may be twice as high after making the pile stiffer and heavier.

6 SOIL RESISTANCE EFFECTS

Under hammer impacts, the instantaneous soil resistance acting along the pile shaft in skin friction and at the pile tip in end bearing have two components: dynamic velocity-related, and static displacement-dependent forces. Cohesive soils (e.g., clay) have higher damping (i.e., provide more dynamic resistance) than cohesionless (e.g., sand) soils. According to Smith, a damping factor has to be chosen to consider the dynamic resistance in the wave equation analysis. Furthermore, the flexibility of pile and soil influence the elastic-plastic pile/soil behavior (i.e., maximum displacement, rebound, and net penetration) under a hammer blow. The soil stiffness is inversely proportional to the so-called quake (an input parameter), which actually quantifies, how much rebound is caused by the soil. The quake only varies substantially at the pile toe, primarily as a function of the volume of soil displaced, i.e., as a function of pile size.

As mentioned earlier, long-term pile load bearing capacity may be different than the static soil resistance during driving. Estimates of these time dependent changes should be made in addition to estimates of damping and quake.

6.1 Example 6: Plugging Of A Pipe Pile

Steel pipe piles may be driven open-ended or closed-ended, depending on geotechnical conditions and structural requirements; with each type having advantages under certain conditions. Under static conditions, open-ended piles often behave like closed-ended piles. However, driving through hard layers may be practically impossible with closed-ended pipes. Under certain conditions, primarily in very dense soils of sufficient depth, smaller diameter open-ended pipe piles and also H-piles tend to develop a soil plug during driving which moves with the pile and thus makes the pile behave like a displacement pile. Figure 5, already discussed in relation to open and closed-ended pipe pile, can also be considered to study the effect of pile soil plugging effects.

6.2 Example 7: Damping Effects

Figure 7 presents bearing graphs for a 45 m long concrete pile (area=5000 cm^2) and hammer with ram mass of 13.5 tonnes and a stroke of 1.5 m, illustrating the difference in required blow counts for the same static pile capacity in different soil types (with relatively "high = 0.65s/m" and "low = 0.16 s/m" damping factors). For example, for a 7000 kN static capacity, blow counts are roughly 50 and 100 blows/0.25m, for the cohesionless and cohesive soil, respectively and thus differ by a factor of two. Alternatively, for a blow count of 100 blows/0.25 m, the bearing graph indicates a static pile capacity of either 7000 (cohesive) or almost 9000 kN (cohesionless).

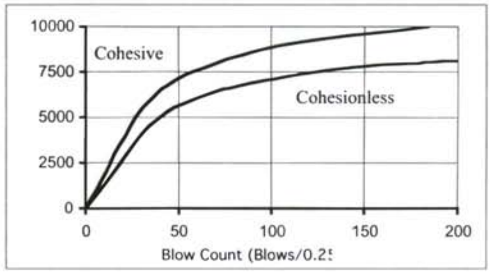

Figure 7 Effects of Soil Damping on Bearing Graphs

6.3 Example 8: Calculated Quake Effects

Actually, this example is related to Examples 4 and 6 (open-ended/closed ended or plugged piles). However, depending on the density and the degree of saturation of the soil at the pile toe, smaller or larger toe quakes (D/120 or D/60) are standard recommendations for displacement piles of diameter D. Figure 8 illustrates the effects of soil quake (i.e., maximum soil elastic deformation) on bearing capacity or pile drivability. Shown are two bearing graphs for a concrete pile (30 m long, 3600 cm^2 area) and a diesel hammer with a ram mass of 6 tonnes and 2.5 m maximum stroke. Again, a significant difference between the two bearing graphs can be observed with the lower one pertaining to the larger quake case.

Figure 8 Quake (Soil Rebound) Effects

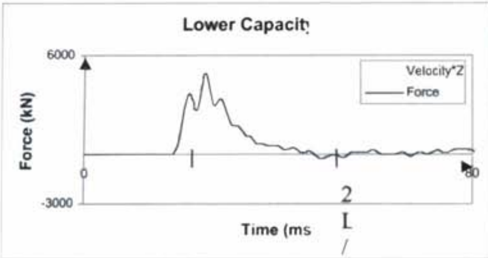

Figure 9 Force and Velocity, Lower Capacity

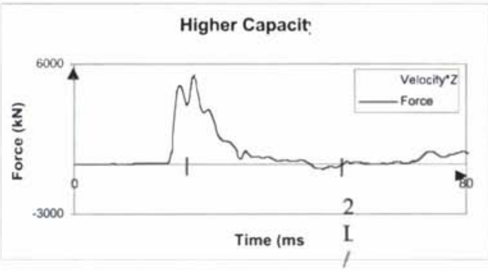

Figure 10 Force and Velocity, Higher

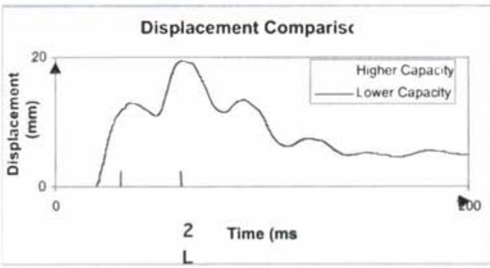

Figure 11 Displacements vs Time From Pile Top Measurements

6.4 Example 9: Measured Quake Effects

This example is from a job where tests were made during pile installation using a Pile Driving Analyzer on a 50 m long, 600 mm square concrete pile, driven with a hydraulic hammer (10 tonnes ram and 120 kJ rated energy). Presented in Figures 9 and 10 are plots of measured pile-top force and proportional-velocity records obtained under two different hammer blows from different pile penetrations (30 and 38 m), but at equal blow counts (50 blows/0.25m). The Pile Driving Analyzer determined different bearing capacities of 1880 and 2440 kN, even though the blow counts and transferred energies were similar. Figure 11, showing the pile displacement records for the two blows, which explains the apparent pile capacity/blowcount discrepancy. The blow indicating lower capacity actually exhibited twice as much pile rebound as the other blow; the rebound (i.e., difference between maximum displacement and net set) was 7 mm in one case and 14 mm in the other. Furthermore, the test records show similar initial (i.e., at time of impact) pile-top displacements, but with increased displacement due to a tension wave reflection from the pile toe (caused by a large quake) in the case of "lower capacity" data, which resulted in the greater difference in rebound between the two situations. This case history shows the effect of elastic rebound (i.e., quake) on pile driveability (i.e., blow count) and static capacity. This effect has already been reported by Likins (1983) among others.

7 CONCLUSIONS

The Bearing Graph, expressing the relationship between pile capacity and blow count by computer wave equation analysis is a common method to assess pile driveability and evaluate static capacity. It is conveniently applied for design, construction, and inspection purposes. However, the analyzing engineer often assumes "normal conditions" or "average performance", which in some cases do not represent actual field conditions. Many of the parameters are not easy to predict accurately, or even observe during routine inspection. It is therefore reasonable to perform several analyses both with high and low conservatism to generate upper and lower bound predictions. Unfortunately, these uncertainties contribute to uneconomical conservatism in pile foundation design.

It is, therefore, recommended to perform dynamic pile testing (conventionally, or remotely by utilizing cell-phone technology), to quantify the performance of hammer, driving system, pile, and soil. Test results can then be used to refine the prediction of pile driveability and the determination of a pile's load carrying capacity. Modern technology has made it possible to economically and routinely test and evaluate each and every pile on a job. Widely available methods of quality control and assurance make it possible to advance pile foundation design to a reliable level consistent with modern civil engineering practices, eliminating the need for overly conservative design factors of safety and allowing for a more economical utilization of pile foundations.

REFERENCES

Goble, G. G., Likins, G., and Rausche, F. (1975). *"Bearing Capacity of Piles from Dynamic*

Measurements" Final Report, Case Western Reserve University, Cleveland, Ohio.
Goble, G. G. and Rausche, F. (1976). *"Wave Equation Analysis of Pile Driving – WEAP Program"* Federal Highway Administration Implementation Package 76-14.1, Vols. I, II, and III, Washington, D.C.
Hussein, M. and Likins, G. (1995). *"Dynamic Testing of Pile Foundations"* Proceedings of ASCE Structures Congress XIII, Boston Massachusetts.
Likins, G.E. (1983). *"Pile Installation Difficulties in Soils with Large Quakes", Proceedings,* ASCE Specialty Conference, Philadelphia.
Likins, G.E. and Rausche, F. (1988). *"Hammer Inspection Tools",* Proceedings of the 3rd International Conference on the Application of Stress-Wave Theory to Piles, Ontario, Canada.
Rausche, F., Likins, G. E., Goble, G.G., and Miner, R. (1985). *"The Performance of Pile Driving Systems"* Final Report in 4-volumes, FHWA Office of Research and Development, Washington, D.C.
Smith, E. A. L. (1960). *"Pile-Driving Analysis by the Wave Equation"* ASCE Journal of the Soil Mechanics and Foundations Division, vol. 86, no. SM4, pp. 35-61.
Terzaghi, K. (1943). *"Theoretical Soil Mechanics"* John Wiley & Sons publishers, New York.