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Pile Evaluation by Dynamic Testing During Restrike

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SYNOPSIS: Since pile driving causes dramatic changes (mostly temporary) in the state of stress of the surrounding soil, piles are sometimes restruck to assess their "long term" bearing capacity. Pile driving resistance (i.e., blow count) during restrike, some time after installation, is often compared to the end of initial driving blow count to estimate changes in pile behavior with time. Dynamic pile testing provides means to quantify this pile assessment taking into consideration potentially misleading factors that are not readily apparent without pile instrumentation. This paper presents four case histories where piles were evaluated by testing during restrike.

INTRODUCTION

Pile foundations are routinely installed by impact driving. During installation, the pile is repeatedly driven into the ground to the desired penetration, causing dramatic alterations in the original stress condition of the surrounding soil. The shape of the pile (i.e., displacement or non-displacement type, tapered or uniform) influences the soil behavior and degree of disturbance. The changes are mostly temporary, but can also be permanent.

The effect of pile driving on the soil, however, is dependent on the type of soil. The effects of driving piles into clays may be grouped into four main categories: remolding, alteration in the state of stress, change in pore pressure, and time dependent gain in strength (de Mello, 1969). The effect of time after installation is an important practical consideration since it dictates the "long term" behavior of the pile. It is well established in many localities that piles driven into clays gain capacity over time, a phenomena commonly called soil "set-up". Pile driving causes an increase in pore water pressure which causes a reduction in effective stress thereby reducing the pile capacity and blow count during driving. As these pore pressures dissipate, the soil resistance acting on the pile increases as does the pile capacity. Conversely, dense fine cohesionless soils can develop negative pore pressures when the pile is driven. In these cases, the effective stresses at the pile toe are temporarily higher than the long term conditions. As negative pore pressures dissipate, the axial pile capacity decreases with time. This capacity reduction phenomena is referred to as "relaxation". The reduction in bearing capacity with time of piles rounded in shale is generally attributed to relief of high locked-in lateral stresses (Thompson and Thompson, 1985). The period of time needed for assessment of the effects of changes in soil condition on pile capacity varies from hours to months depending on the soil characteristics. While it is generally agreed that set-up is advantageous, it can be a hinderance to pile installation in cases where it occurs quickly and pile driving have to be temporarily interrupted for reasons such as pile splicing, hammer maintenance or changing cushions. Relaxation is always considered problematic.

Pile penetration resistance (blow count or set per blow) during restrike is often compared to that observed at the end of initial installation to assess pile static capacity changes with time. Dynamic pile testing during driving and/or restrike provides means to take into consideration potentially misleading factors that are not readily apparent without instrumentation. Of primary importance is that the hammer energy during restrike is adequate to mobilize maximum soil resistance and is similar to that during initial installation. Since changes in hammer energy transferred through the pile into the soil will affect the pile driving blow count, dynamic testing provides information that allow for a separation of hammer performance and soil resistance effects.

DYNAMIC PILE TESTING

Dynamic pile testing is routinely performed on thousands of projects annually around the world for the purposes of improving pile installation procedures.

foundation design assessments, and quality control. The following are the main objectives of dynamic pile monitoring: (a) evaluation of pile static capacity (shaft friction and toe bearing) and assessment of time dependent soil strength changes (Rausche, Goble and Likins, 1985), (b) determination of dynamic pile stresses (high forces required to overcome soil resistance may produce potentially damaging stresses in the pile) under hammer impacts (Hussein and Rausche, 1991), (c) assessment of pile structural integrity (Rausche, Likins and Hussein, 1988), and (d) investigation of hammer and driving system performance (Likins, 1982). The most widely adapted testing and analyses procedures are the Case Method which is conveniently applied in the field for every blow in real time by a specialty computer/data acquisition device called the Pile Driving Analyzer™ (PDA). The Case Method utilizes the measurements of force and velocity records of the pile under a hammer blow. Force is calculated from reusable strain transducers and velocity is obtained by integrating the measured acceleration from accelerometers.

The same dynamic pile records of force and velocity may be further analyzed by the CAPWAP® method (Rausche, 1970) to determine soil resistance forces (static and dynamic) and their distribution along the pile shaft and under its toe. The analysis procedure consists of signal matching pile force or velocity records given one measurement as input and the other as a boundary condition by manipulating values in the soil model. Analysis results include: pile static capacity, shaft resistance distribution and toe bearing, soil quake and damping values, and simulated pile head and toe static load versus displacement relationships.

The mobility, speed, ease of application and low cost of dynamic pile testing allow for practical and rational evaluation of pile analysis, particularly assessment of soil strength changed with time. The following case histories illustrate the applicability and advantage of dynamic pile testing during restrikes.

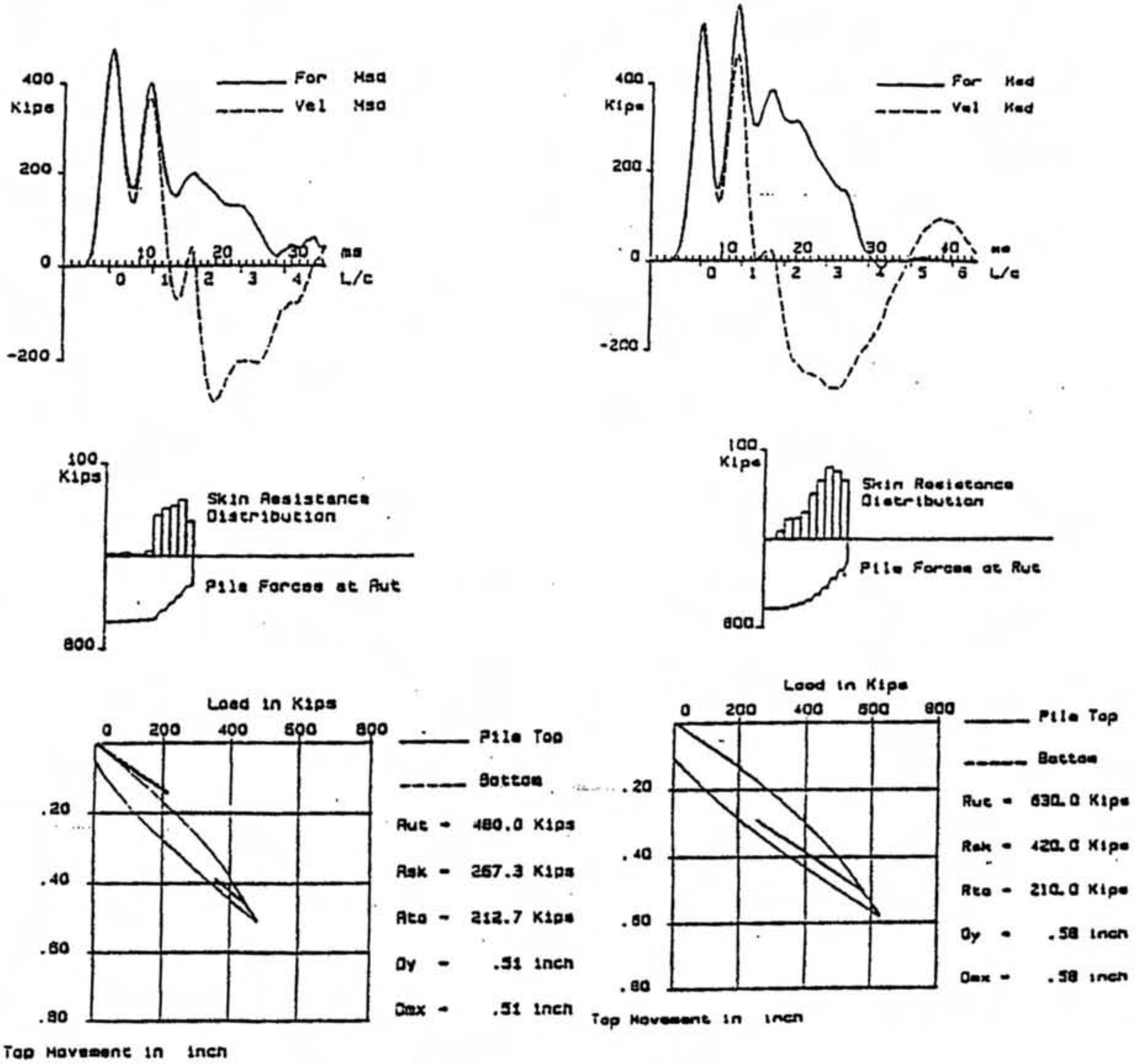
CASE 1 - SOIL SET-UP AND PILE CAPACITY INCREASE

A pile driving test program was undertaken to evaluate installation procedures, assess pile capacity, and provide foundation design parameters for a hospital and medical office building. Square prestressed concrete piles (area = 0.126 m^2) were driven. Preliminary design loads were 900 kN per pile (required capacity of 1800 kN incorporating a safety factor of 2). Pile driving was accomplished with a differential acting air hammer having a ram weight of 36 kN and a rated energy of 33 kJ. Typically, ten sheets of plywood were used as pile top cushions. Subsurface conditions were generally uniform consisting of 24 m of primarily loose silty fine sand with SPT N-values less than 15. Below and at the pile tip elevations was either very dense fine sand or limestone. The water table was approximately 5 m below ground surface. Past experience in the same city indicated an increase in pile capacity after installation. The piles were restruck one day and also six weeks after initial installation. Dynamic pile testing using the PDA was performed during the installation and restrikes of all test piles to monitor pile driving and soil strength changes with time. Two proof static loading tests were also performed.

During installation of all test piles, maximum pile top compressive stresses averaged 17.6 MPa and maximum pile tensile stresses ranged between 7 and 10 MPa. Averaged maximum transferred energy ranged between 11 and 15 kJ depending on whether one or two compressors were used to power the hammer. Dynamic data did not indicate pile damage. End of driving static pile capacities (computed by the PDA and CAPWAP) average 1850 kN. The structural engineer and owner asked if pile ultimate capacities could be increased by 10 percent. Restrike testing on three of the piles one day after installation showed average pile capacities of 2000 kN, confirming the 10 percent increase. A proof static loading test was performed on one pile to verify pile bearing capacity. Approximately six weeks after installation, several piles were restruck (and dynamically tested) for pile capacity determination. Restrike capacities then averaged 2750 kN. Plots of pile top force and velocity histories along with CAPWAP analysis results are presented in Figure 1 including soil resistance distribution with simulated static loading test graphs of one day and six week restrikes of test pile 6. The engineer designed the foundation with an ultimate capacity of 2725 kN per pile and a proof static loading test was carried out for verification. This case illustrates the use of dynamic pile testing to quantify and use the soil set-up effects to improve the foundation design.

CASE 2 - RELAXATION AND DECREASE IN PILE CAPACITY

An extensive pile driving and loading test program was part of the design for a major highway project. Four test sites along the project route were used to assess the driveability and bearing capacity of various pile sizes and to assess time effects on pile capacity. At one site, fifteen steel H-piles of different sizes were driven and restruck. Dynamic pile testing was performed during installations and restrikes. Seven



1 Kip = 4.45 kN, 1 ft = 0.3048 m, 1 inch = 25.4 mm

FIGURE 1: Case 1 - CAPWAP results of one day and 6 week restrikes.

piles were also subjected to static loading tests. Two closed ended diesel hammers were used to drive and restrike the piles; a ICE 520 (ram weight 23 kN) and a ICE 640 (ram weight of 27 kN) with respective rated energies of 40 and 52 kJ. Soil borings indicate 8 m overburden consisting of 1 m clayey silt and rock fragments (N-values 7 over) with some ash, sand, gravel and brick fragments (N-values between 1 and 6) over a layer of weak decomposed shale bedrock (N-values from 5 to 8) that was soft enough to be sampled as soil. This case study discusses results of testing for one of the piles involved.

Pile A was initially driven with the Link Belt 520 hammer to a depth of 10 m. The driving resistance gradually increased from 18 to 39 blows per 25 mm during the last half meter of penetration. Towards the end of driving, the compressive stress averaged 150 MPa, transferred energy averaged 13 kJ, and the pile capacity was 1950 kN. Two month after initial driving, the pile was subjected to a static loading test that indicated a failure load of only 1090 kN suggesting substantial relaxation. Two and a half months after the static test, the pile was dynamically tested during restrike, using the larger Link Belt 640 hammer. The restrike consisted of driving the pile an additional 0.25 m with driving resistance of 8, 7, 9, 10, 10, 11, 12, 13, 15 and 21 blows per 25 mm, respectively. During the restrike process, compressive stress again averaged 150 MPa and transferred energy for the larger hammer increased to 15.5 kJ. At the beginning of restrike (low blow count compared to the end of drive), the computed pile capacity was 962 kN; the capacity increased to 1950 kN at the end of restrike as the blow count also increased. The low initial blow count and low capacity confirmed the relaxation.

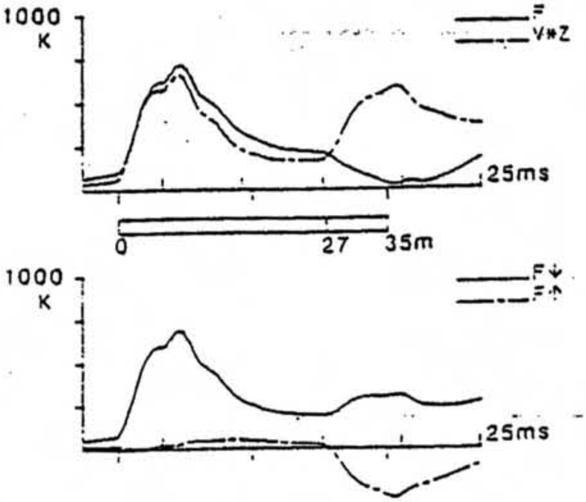
Similar pile relaxation were found on the other piles, however, the degree and rate of decrease in pile capacity seemed dependent on pile size, penetration into the shale, and driving resistance at the end of driving. Based on several restrike with varying wait times, most of the reduction in pile capacity occurred in the first few days following pile installation.

CASE 3 - RESTRIKE TESTING REVEALS UNEXPECTED PILE DAMAGE

Subsurface conditions and structural requirements dictated that a new bridge be founded on driven piles. A few test piles were initially driven to establish driving criteria and penetration depth to develop the required 2270 kN capacity. Dynamic testing, performed during pile installations and also during restrikes, indicated an increase in strength with time which was then incorporated into the pile design process. Production piles were driven to a depth that, with time, would develop the required capacity. Routine dynamic testing during restrike of random production piles was specified for quality control to verify pile capacities.

Under consideration is a square (area = 0.209 m^2) prestressed concrete pile with a length of 35 m. Pile driving and restriking were accomplished with a Delmag D46-32 open ended diesel hammer with a rated energy of 115 kJ at fuel pump setting #2. Subsurface conditions can generally be described as layers of loose and medium dense slightly silty and clayey fine sand. These sands were underlain by clayey fine sand and weathered limestone and very dense shells. The pile was initially driven to a penetration of 34 m and a final driving resistance of only 23 blows per meter. Throughout its installation, the pile driving resistance did not exceed 65 blows per meter and was similar to that of other neighboring piles. End of drive blow counts in this area of the site were generally lower than those at other locations.

The pile, along with a few others, was tested during restrike for quality control and capacity verification. Figure 2 presents plots of dynamic testing records of the first blow during restrike. The data indicates that the supposed 35 m pile is broken (Beta factor = 33) at a location 27 m below the pile top. Incidentally, testing on other piles indicated that required capacity was not reached and pile splicing was necessary.



1 K (Kip) = 4.45 kN

FIGURE 2: Case 3 - 35 m pile showing damage at 27 m.

CASE 4 - ENERGY CONSIDERATION IN RESTRIKES

Square prestressed concrete test piles with lengths varying between 23 to 32 m were driven, and dynamically instrumented, at a bridge construction site. Subsurface investigations indicated 21 to 35 m of mostly silty sand and sandy clay overburden over a bearing stratum of dense cemented sand. Required pile capacities were 1350 kN. Pile driving was accomplished with a single acting air hammer (ram weight of 30 kN and rated energy of 27 kJ).

One pile, 30.5 m long, was initially driven to a penetration of 26 m and a driving resistance of 120 blows per meter. During installation, maximum pile tension stresses reached 8.3 MPa and towards the end of driving, maximum pile top compressive stresses averaged 13 MPa, maximum pile top transferred energy averaged 10.8 kJ, and CAPWAP computed a capacity of 370 kN. A restrike was performed to assess time dependent changes in pile capacity. During this restrike, maximum compression stress and transferred energy were similar to end of drive results. The PDA computed pile capacity was only 585 kN so it was decided to splice the pile and continue driving until the bearing stratum was reached.

An additional 10 m section was spliced to the pile and pile redriving with dynamic testing resumed two weeks after initial installation. The pile redriving resistance was very high with no permanent set under the first twenty blows. The very high blow counts led both the contractor and the engineer to believe that the pile had acquired significant added capacity in the two weeks waiting period since initial driving, and according to analysis (i.e., wave equation) should now have adequate capacity. Dynamic measurements, however, indicated that maximum pile top transferred energy averaged only 4.7 kJ (less than half what was observed at the end of driving) and maximum pile top compressive stress of only 6.2 MPa (much lower level than that during installation). The computed pile capacity was still 590 kN. Further investigation revealed that the plywood pile top cushion was very wet and that the hammer needed maintenance. After installing a new pile top cushion and repairing the hammer, redriving was resumed and the blow count dropped to less than 200 blows per meter. The maximum pile top compressive stress, transferred energy, and capacity were 12.8 MPa, 10.8 kJ and 590 kN, respectively. The pile was driven an additional 8.8 m to a final blow count of 400 blows per meter (maximum energy transfer of 12.1 kJ) and to a PDA computed pile capacity of 1350 kN. A restrike test performed one hour after end of drive indicated a pile capacity increase to 1500 kN.

This case history illustrated the importance of incorporating hammer performance into the evaluation of restrikes for evaluating pile capacity and assessment of soil strength changes with time.

CONCLUSIONS

Pile driving causes great disturbance to the surrounding soil. The extent and magnitude of change in the soil's state of stress depends largely on the type of soil and subsurface conditions and to a lesser extent on pile and hammer types. Restrikes are often performed on driven piles some time after initial installation to assess time dependent soil strength changes and their effects on pile bearing capacity. Dynamic pile testing during restrikes provides an inexpensive, fast, and accurate mean to rationally evaluate restrike data taking into account potentially misleading factors that are not readily apparent without pile instrumentation. This paper included four case histories that illustrate the necessity and usefulness of dynamic pile testing during restrikes.

REFERENCES

de Mello, V.F.B. (1969). Foundations of buildings on clay, state-of-the-art report: 49-136. Proceedings of the Seventh International Conference S.M.&F.E., Mexico City, Mexico.

Hussein, M. and Rausche, F. (1991). Determination of driving induced pile damage. Foundations Profondes, L'Ecole Nationale des Ponts et Chaussees, Paris, France.

Likins, G. (1982). Evaluating the performance of pile driving hammers. Fourth PDA Users Day Seminar, Amsterdam, Holland.

Rausche, F. (1970). Soil response from dynamic analysis and measurements on piles. Ph.D. Dissertation. Case Western Reserve University, Cleveland, Ohio, USA.

Rausche, F., Goble, G., and Likins, G. (1985). Dynamic determination of pile capacity. Journal of Geotechnical Engineering, ASCE, Vol. 111, No. 3, Paper No. 1951: pp. 367-383.

Rausche, F., Likins, G., and Hussein, M. (1988). Pile integrity by high and low strain impacts. Proceedings of the Third International Conference on the Application of Stress Wave Theory to Piles, Ottawa, Canada.

Thompson, C.D. and Thompson, D.E. (1985). Real and apparent relaxation of driven piles. Journal of the Geotechnical Engineering Division, ASCE, Vol. 111, No. 2, pp. 225-237.

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