CASE HISTORIES OF PILE RELAXATION IN VANCOUVER

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ABSTRACT

The importance of re-striking driven piles subsequent to initial driving was highlighted on two, 100 m apart, projects at the east end of False Creek, Vancouver, B.C. On the first project (site "A") 340 mm diameter closed tip pipe piles were driven with a drop hammer, while on the second project (site B) similar piles were driven with an open-ended diesel hammer. On both projects the piles were initially driven to near refusal in dense fine to medium sand with silt layers. Upon re-striking, the piles exhibited a reduction in driving resistance by factors of 2 to 6.

On site "B" two load tests were conducted. A test pile driven to a end of initial driving (EOID) set of 14 blows/25 mm was load tested. One year later the load tested pile was re-struck and exhibited a beginning of re-strike driving resistance decreased by a factor of 5 (2.7 blows/25 mm). A second load test was conducted on another pile which had a low EOID penetration resistance similar to the BOR resistance of the initial test pile (3 blows/25 mm). The second load test indicated a similar pile capacity to the initial load test, indicating that the pile capacity is a function of the relaxed BOR driving resistance rather than the initial temporary high EOID driving resistance.

Soil information, pile installation procedures, driving records, and load test results are presented. The effects of relaxation are examined by wave equation analysis, and it is demonstrated that the relaxation is likely to be due to changes in pile capacity (real relaxation) rather than due to changes in hammer performance (apparent relaxation). An explanation for the behaviour is discussed.

INTRODUCTION

This paper describes interesting experiences during impact driving of closed-ended steel pipe piles on two separate but nearby projects in Vancouver. At both of the sites many of the piles exhibited a behaviour known as 'relaxation', wherein the driving resistance decreased dramatically upon

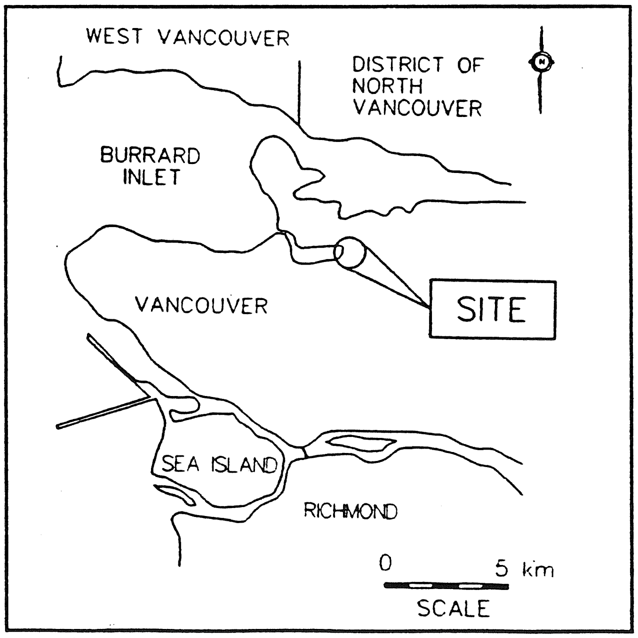

Figure 1 Keyplan

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being re-struck after an interruption in driving. Relaxation may be 'apparent', if due to a drop in hammer performance between end of initial driving (EOID) and beginning of re-drive (BOR), or 'real' if associated with time related decrease in the pile bearing capacity (Thompson and Thompson (1985)).

BACKGROUND

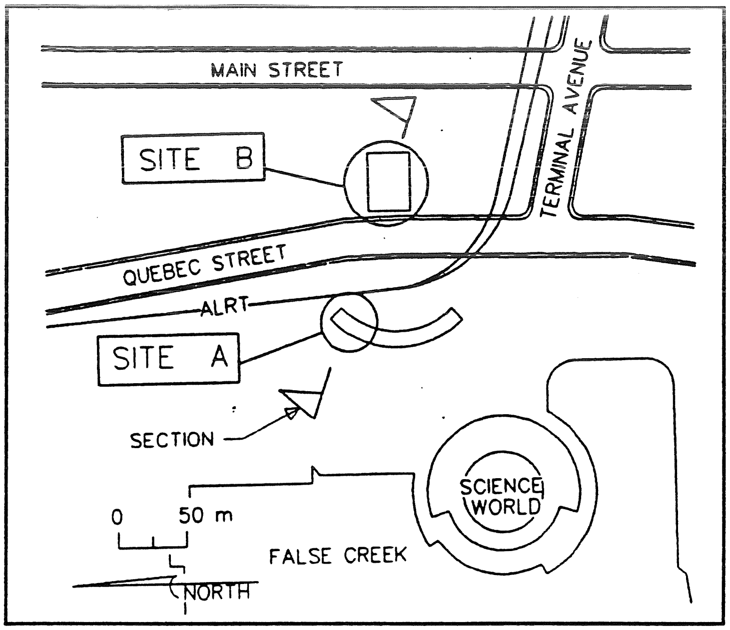

Figure 2 Location plan

The two subject sites are located at the east end of False Creek in Vancouver, B.C. as shown in Figure 1 and Figure 2. Ground surface in the area is approximately at elevation +4 m geodetic. The surficial soils at the two sites are shown in profile on figure 3. The upper soil unit consists of loose to medium dense fill of varied composition placed between 1910 and 1970. The depth of the fill is a maximum of approximately 10 m and is a function of dredging patterns prior to fill placement. The fill is underlain by a thin layer of soft clay/silt marine bottom sediments, which in turn are underlain by dense to very dense layered sand and sandy silt deposits, probably of glacio-fluvial origin. In places these deposits overly a very dense 'till-like' sandy silt with scattered gravel. Tertiary sandstone/siltstone/claystone bedrock occurs at a depth of 18 to 19 metres below grade.

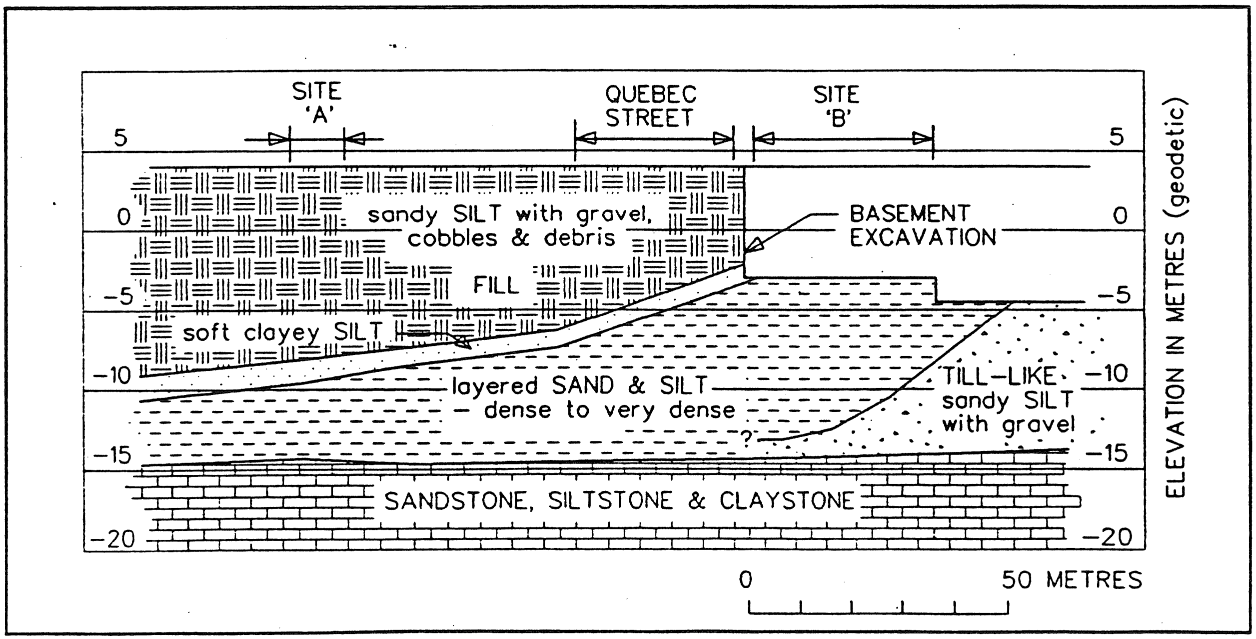

Figure 3 Soil profile for section indicated on figure 2

The pile relaxation behaviour discussed in this paper occurred when closed-tip pipe piles were being driven through the dense to very dense layered sand and silt.

SITE "A"

At site "A" piles were driven for construction of Gate 5 for the 1986 Expo'86 worlds fair. 18 m long pipe piles of 340 mm diameter, with a 12 mm wall thickness and with a 355 mm diameter x 25 mm bottom plate were driven with a 3,270 kg drop hammer. A 1.8 m drop was used for seating all the piles. The same hammer, leads, crane, and operator were used for driving all the piles at site "A". The piles had a 889 kN design load and were driven to a seating criteria of 120 blows for 300 mm or 10 blows for 12.7 mm, which ever occurred first. A soil log at site "A" is shown on figure 4 The piles were seated between 0.6 m to 2.5 m into the very dense layered sand/silt deposit. Typical grain size curves are given on figure 5. Final driving sequence of four typical piles is shown on figure 6. As shown on figure 6, some of the piles were re-driven up to three times and showed repeated relaxation.

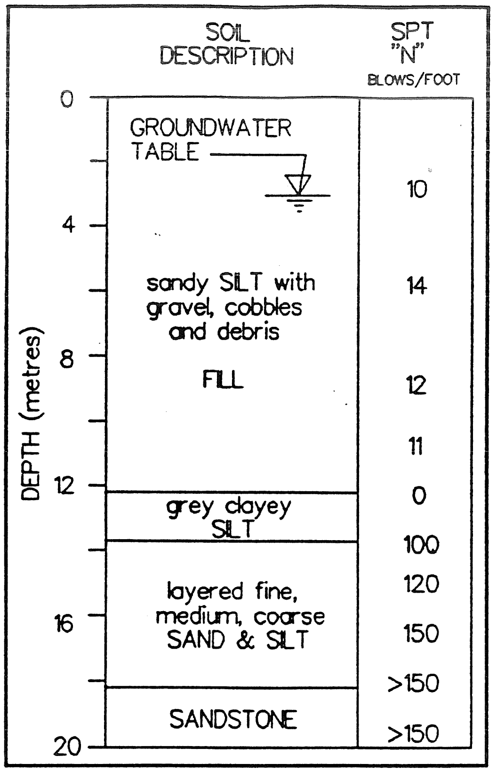

Figure 4 Site "A" soil log

All the piles shown in figure 6 were seated to approximately 20 blows per 25 mm at the EOID and when re-struck 6 to 24 hours later indicated BOR driving resistances of approximately 4 blows per 25 mm. Wave equation analyses were conducted to model the BOR and EOID conditions. For the BOR condition with 4 blows/25 mm and a transferred energy (ENTHRU) of 35.2 kJ (26.0 kip-ft) an ultimate capacity of 1,880 kN was calculated. In order to achieve the same ultimate capacity with the EOID driving resistance of 20 blows/25 mm the transferred energy (ENTHRU) dropped to 17.3 kJ (12.8 kip-ft). Blow count versus capacity for the two cases is shown on figure 7.

It is argued that it is unreasonable for the transferred energy (ENTHRU) of the drop hammer system to consistently drop by approximately 50% at the end of initial driving and thus it is concluded that the relaxation is not apparent but real. This is confirmed by data regarding the variability of transferred energy (ENTHRU) of drop hammer systems from dynamic (Pile Driving Analyzer) monitoring conducted on two other sites for the authors' company, and from a published case history by Hussein et al., (1992).

The data from these other sites also showed that an ENTHRU of 60% of the total potential energy was reasonable for the 3270 kg drop hammer system used. Figure 8 shows data for three drop hammer systems each with different ram mass, but the same total potential energy of 54 kJ, and approximately the same pile impedance. This data demonstrates that for a given potential energy and impedance, the driving efficiency of the drop hammer system increases with increasing ram mass.

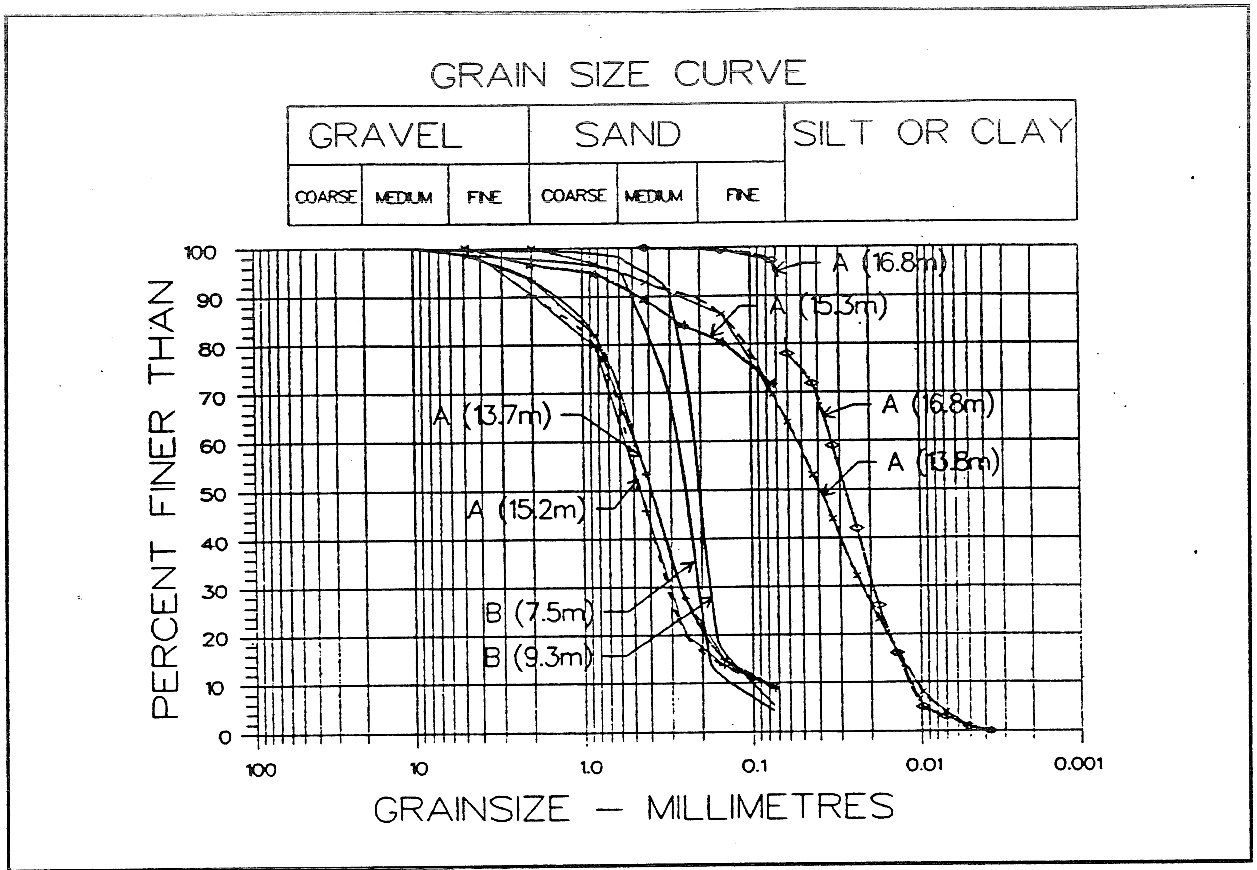

Figure 5 Grain size curves with site & depth of sample

SITE "B"

Site "B" is a commercial/residential high rise development with a 6.5 to 8 m deep basement. A typical subsurface log is shown on figure 9 and typical grain size curves are on figure 5. A test piling program was carried out in 1989, prior to excavation of the site. The test program included driving three 18 m long by 324 mm x 12.5 mm wall thickness closed tip pipe piles, one of which (test pile No. 1) was subjected to a static load test (load test No. 1) 10 days after driving. The driving record of the test pile No. 1 is shown on figure 10 and the load test results are on figure 11. The 1989 test piling was driven with a Kobe K25 open-ended diesel hammer. Load test No. 1 gave a Davisson offset limit load capacity of 2,300 kN.

The original design specified 324 mm diameter piles with 12.5 mm wall thickness, steel bottom plates and concrete infill. The contractor proposed an alternative pile section with a slightly smaller diameter of 298 mm (instead of 324 mm) and the same 12.5 mm wall thickness. The alternative was accepted, and 457 closed-end steel pipe piles with a design load of 1,220 kN were installed in July and August, 1990. All piles were driven with tip plates, and were subsequently filled with concrete. The production piling was driven after the site had been excavated to a depth of between 6.5 and 8 m for the building basement (figure 3). Two diesel hammers were used:

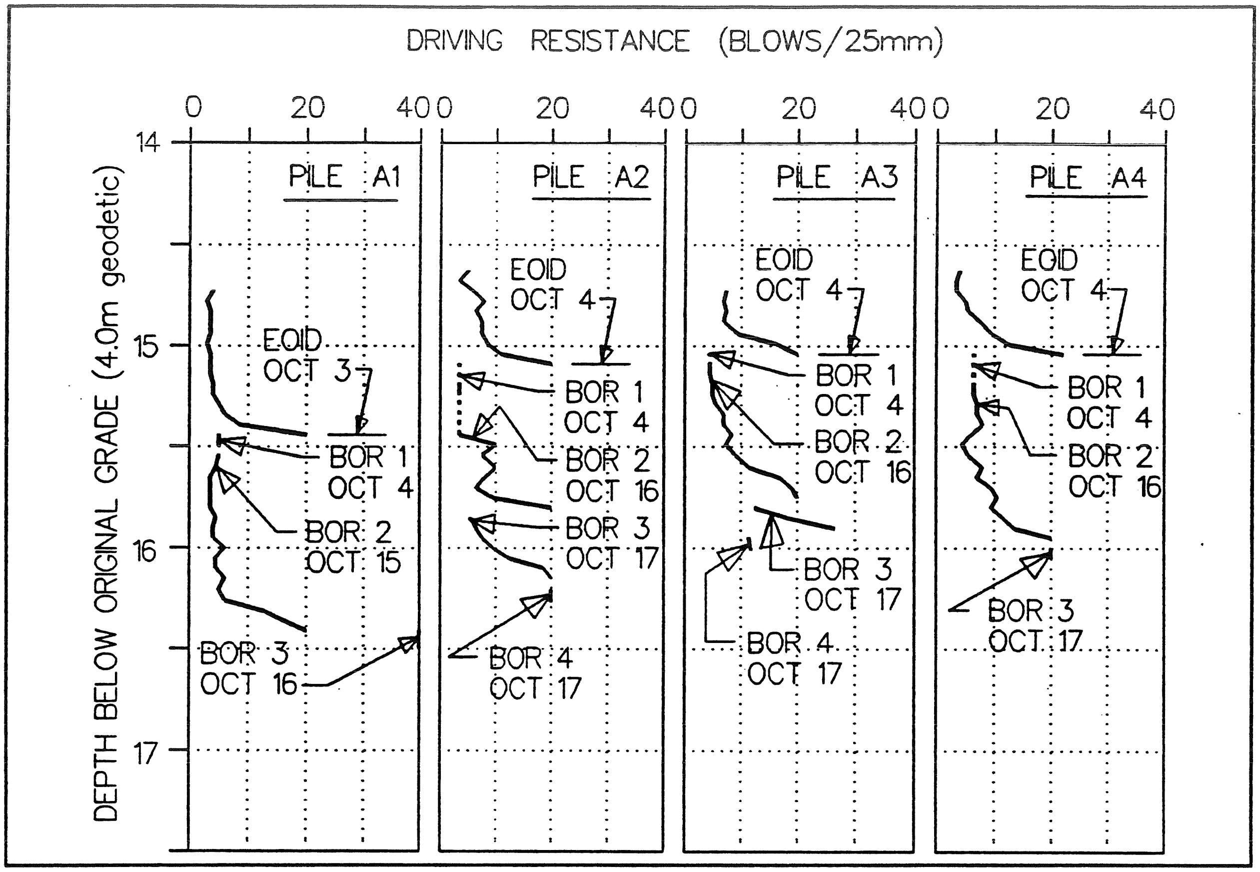

Figure 6 Typical site "A" pile seating records
EOID = end of initial driving, BOD = beginning of redrive

a Kobe K25 with a ram weight of 2,500 kg (5,500 lbs) and a manufacturer's rated energy of 74.8 kJ (55,000 ft-lbs), and a Delmag D30-13 with a ram weight of 3,000 kg (6,600 lbs) and a manufacturer's rated energy of 90.0 kJ (66,000 ft-lbs). Initial specifications required that the piles had to be driven with either the K25 or D30-13 hammer to practical refusal. Practical refusal was defined as a penetration rate of 10 blows or more per 25 mm penetration.

Of the 457 production piles many penetrated to bedrock prior to meeting the stipulated refusal and upon being re-struck one to three days later confirmed the refusal set. However in a zone

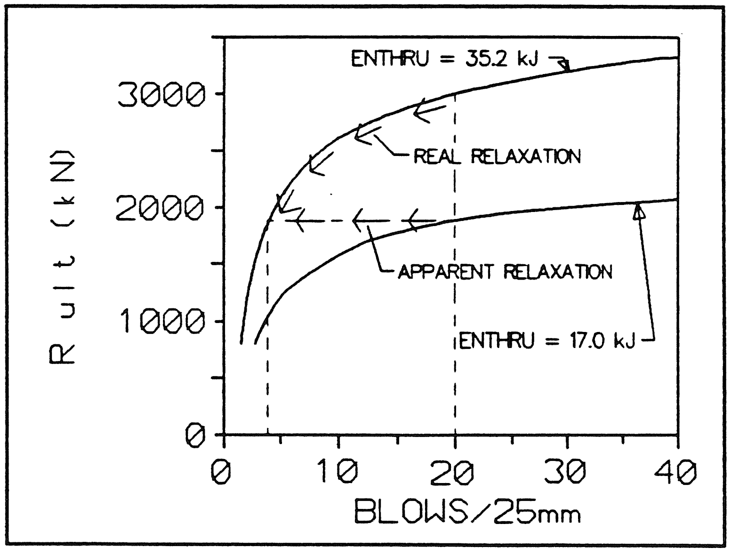

Figure 7 Site "A" wave equation bearing graph for varying ENTHRU

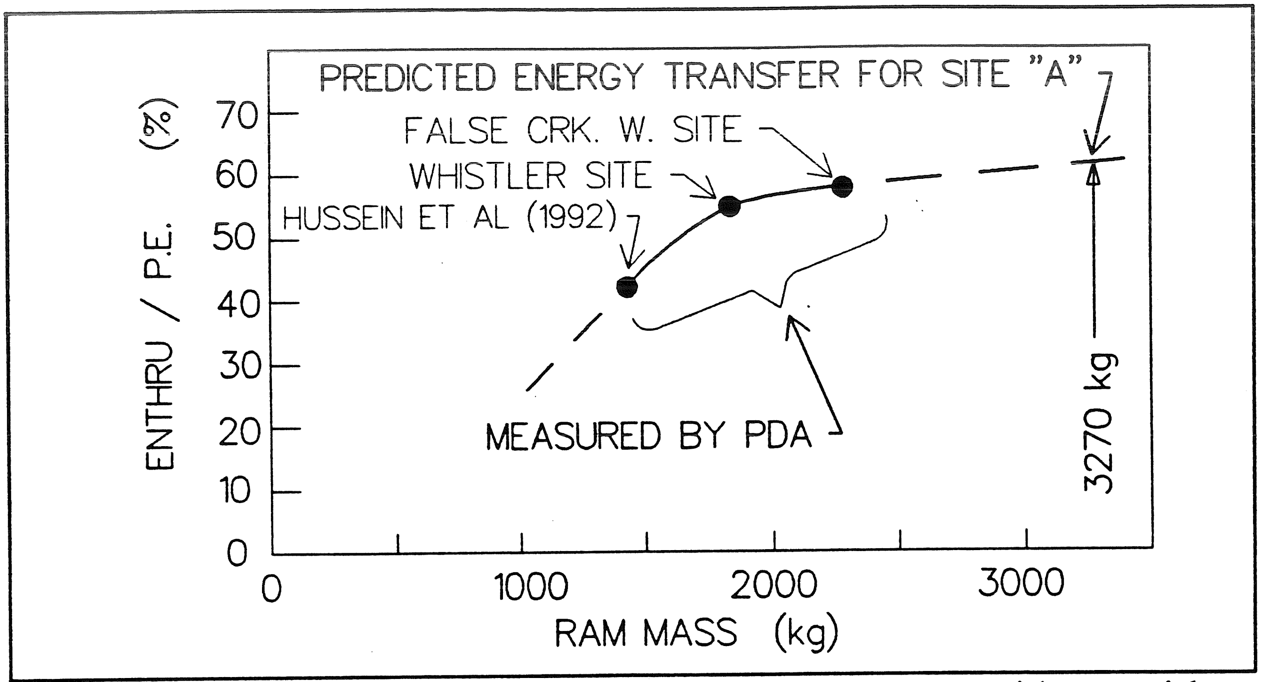

Figure 8 Energy transfer versus ram mass for drop hammers with potential energy of 54 kJ

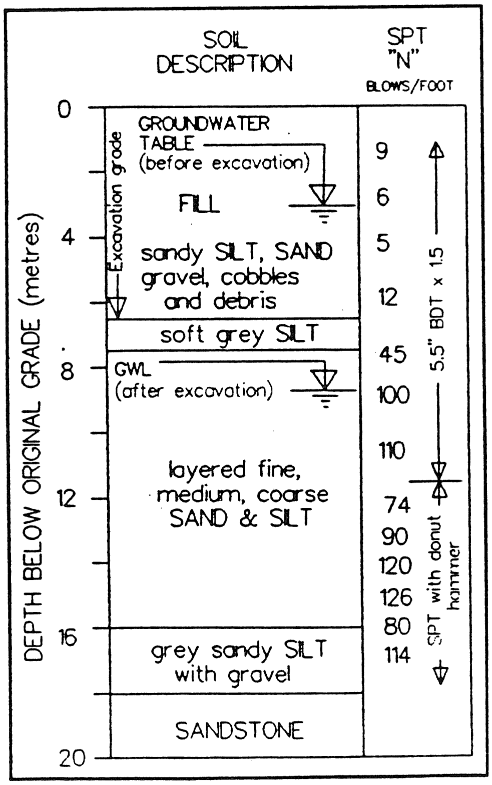

Figure 9 Site "B" soil log

adjacent to the westerly boundary of the site, in the vicinity of test pile No. 1, it was found that the piles encountered refusal within the dense to very dense layered sand and silt and upon being re-struck many piles showed a drastic reduction in penetration resistance, typically by a factor of 2 to 4 (figure 12).

At this time it was initially proposed to continue driving all the piles until they penetrated to the bedrock. However, because of schedule and cost implications, it was decided to further investigate the long term (relaxed) capacity of the piles by driving and static load testing a second test pile (test pile No. 2) and by re-striking Test pile No. 1. The Kobe K25 hammer was used for these tests.

The penetration resistance of test pile No. 2 was relatively low, at approximately 3 blows/25 mm (see figure 10), similar to BOR resistance of the most severely relaxing piles. The static load test was performed a few days later. A Davisson offset limit failure load of 2,400 kN was achieved. This was essentially equal to the capacity of test pile No. 1 which had a EOID penetration resistance approximately 5 times greater.

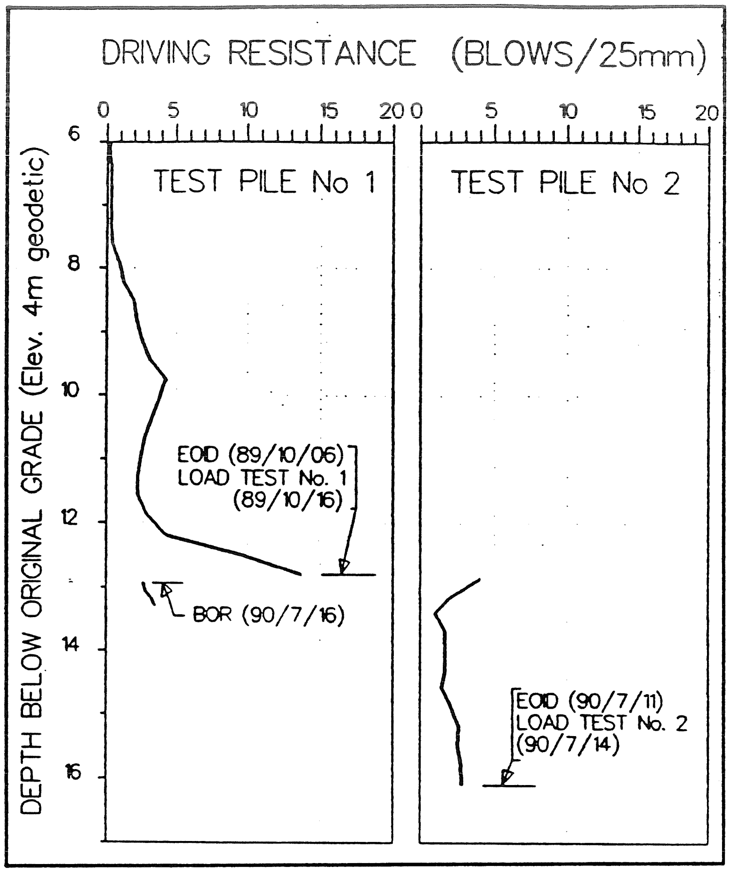

Figure 10 Driving records for Site "B" test piles

Test pile No. 1 was re-driven a total penetration of 0.47 m with the K25 hammer. Penetration resistance at BOR was 2.7 blows per 25 mm reduced by a factor of 5 from the resistance at EOID. It should be noted that since the initial driving and pile load test, grade around the pile had been lowered by 6 m and the pile had been filled with concrete, both of which should increase the penetration rate of the pile. However calculations and wave equation analyses indicated that these two factors could not account for the dramatic reduction in driving resistance and the cause was attributed to pile relaxation. Based on the load test and re-driving of test pile No. 1 it was demonstrated that the piles seated in the very dense layered sand and silt had sufficient capacity in their relaxed state and that driving to bedrock was not necessary.

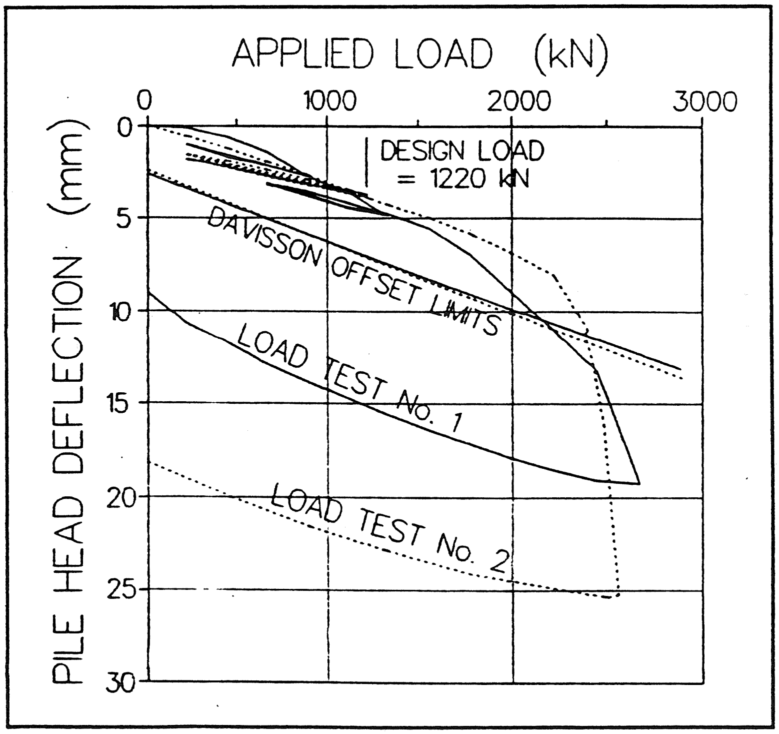

Figure 11 Site "B" load test results

Figure 13 shows the results of wave equation analyses for various transferred energies (ENTHRU) from the diesel hammer. It is shown that the ENTHRU would have to decrease by about 32% in order to cause the observed three-fold reduction in driving resistance. A reduction in ENTHRU of this order does not normally occur. For example all reductions in ENTHRU values for open-ended diesel hammers given by Thompson and Thompson (1985) were less than 22% and averaged 14.6%. Based on the above,

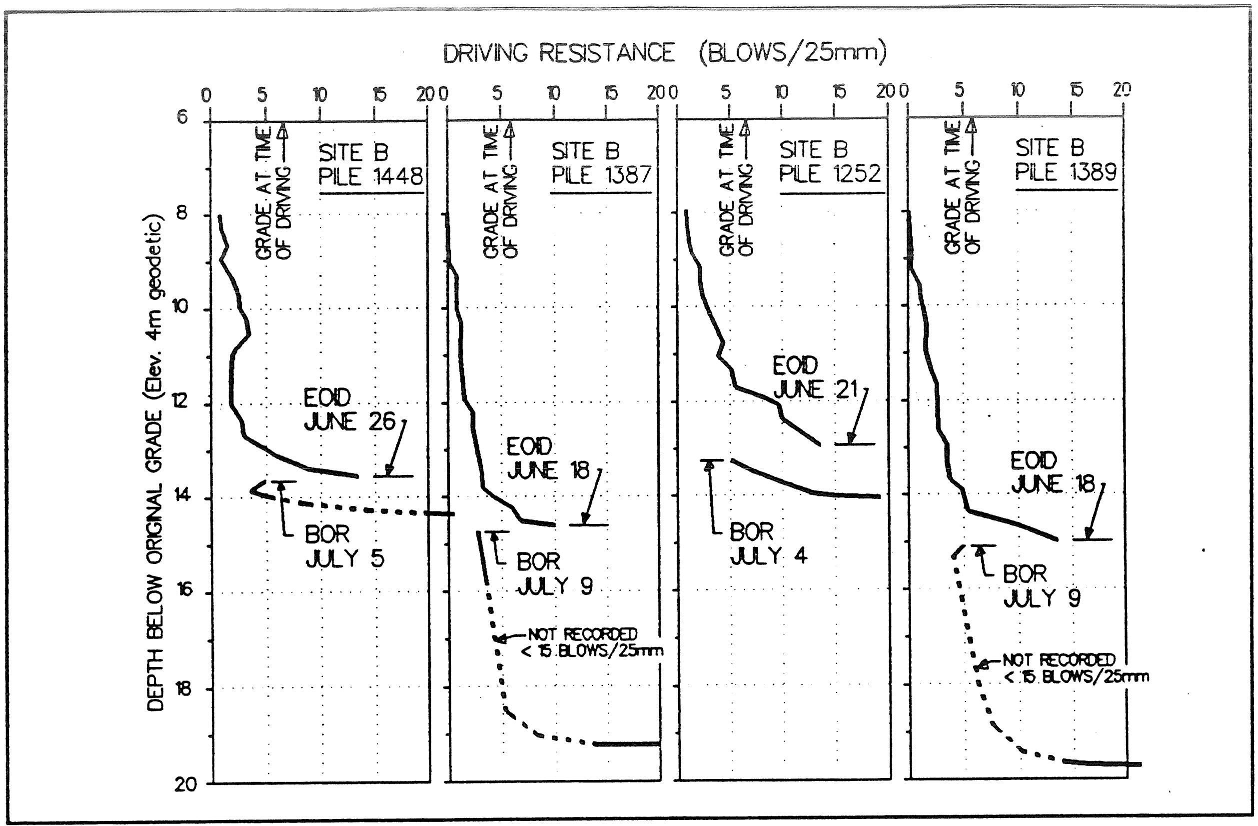

Figure 12 Pile driving records for site "B"

the relaxation is believed to be due to a reduction in pile bearing capacity (real relaxation) rather than reduction in ENTHRU (apparent relaxation).

DISCUSSION

Previous documentation of pile relaxation has been given by Parsons (1966), Yang (1970), Thompson et al (1985), Samson and Authier (1985) and has been mentioned in several textbooks including Terzaghi & Peck (1967), Peck Hanson and Thornburn (1974), and the Canadian Foundation Manual (1992). One commonly accepted theory explaining relaxation is that given by Yang (1970). He proposed that when a pile is driven into saturated dense fine sands and silts that the soil dilates, causing generation of reduced (negative) pore pressures and therefore increased effective stresses, which temporarily increases the bearing capacity and penetration resistance of the pile. After driving has ceased, these reduced pore pressures stabilize with time causing effective stress, bearing capacity, and energy required to advance the pile to decrease.

The occurrence of reduced (negative) pore pressures, as discussed by Yang, is demonstrated during penetration of electric piezocone (CPTU) soundings in dense fine sands and sandy silts. The CPTU is in effect a miniature pushed-in pile and would be expected to experience a similar pore pressure regime around it as would a driven pile. CPTU were not conducted at the sites "A" & "B" discussed in this paper, however, negative pore pressures have been measured on other sites when pushing through dense fine sands and silts.

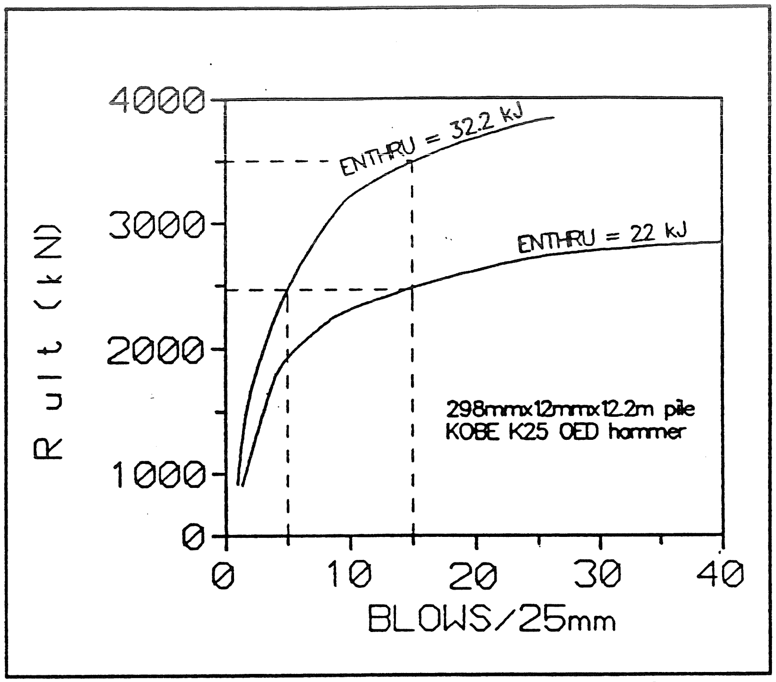

Figure 13 Wave equation bearing graph for typical site "B" pile with varying ENTHRU

The effect of temporary low (negative) pore pressures on pile bearing can be shown by normal effective stress pile design calculation procedures such as those by Fellenius (1988). The effective stress analysis procedure show the pile capacity to be directly proportional to the effective stresses around the pile. This being correct, an upper bound of increase in pile bearing capacity would occur when the pore pressure around the pile approaches minus one atmosphere. For the piles at sites "A" & "B" this is calculated to result in an increase in pile capacity by a factor of approximately 3.5. From the wave equation bearing graphs in figures 7 & 13 it can be seen that a temporary increase in pile capacity over approximately 1.5 would result in essential refusal of the pile, demonstrating that real relaxation of the piles could be accounted for by the theory presented by Yang.

CONCLUSIONS

Two case histories are discussed where the pile driving resistance of closed-tip pipe piles decreased between the end of initial driving (EOID) and the beginning of re-drive (BOR) when the pile tips were being driven through layered very dense sands, fine sands and silts. It is demonstrated by wave equation analysis that this change in driving resistance is due to real pile relaxation, a decrease in pile capacity with time. A theory explaining this behaviour has been given by Yang, (1970). He proposes that the initial driving of the piles into the dense soils causes them to dilate, this causes reduced pore pressures which result in a temporary increase in pile capacity. When the pore pressures return to static values the pile capacity reduces. The two case histories, CPTU data, and effective stress analyses support the theory postulated by Yang.

In the two case histories the relaxation behaviour was associated with a layered deposit, including very dense fine sand and inorganic silt layers which would be expected to behave in a dilative manner when penetrated by the piles. Relaxation was observed under driving by both a drop hammer (site "A") and diesel hammers (site "B"). The extent of relaxation, expressed as a ratio between the driving resistance at EOID to the resistance at BOR was dramatic - up to a factor of six in extreme cases, and typically two to four. This is too dramatic a ratio to be caused by changes in hammer performance. Wave equation analysis indicate a drop in ENTHRU of 30 to 50% is required in order to achieve increases in driving resistance of this order, whereas data from other sites show measured variations in ENTHRU for diesel and drop hammers were less than 22%.

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