DYNAMIC ANALYSIS OF FOLLOWER DRIVEN PILES FOR THE VENICE FLOOD GATE PROJECT

Frank Rausche, Principal, GRL Engineers, Inc., Cleveland, United States; Giorgio Pezzetti, Technical Director, Field S.r.l., Lallio, Italy; Christian Jannacci, Technical Manager, Stone S.p.A., Milan, Italy; Anna Klesney, Research Engineer, GRL Engineers, Inc. , Cleveland, United States

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Without doubt, driven piles are the most economical deep foundation element for a nearshore environment, providing for high bearing capacities and stiffness, quick installation times, assured quality by simple monitoring and inexpensive dynamic load testing during restrike testing. However, when the pile top elevation is several meters below water surface, questions often arise as to the most reliable and economical pile installation method. Frequently encountered, yet relatively expensive, solutions include driving inside a dewatered cofferdam, driving long piles that are later cut off below water surface, or using an underwater hammer. Arguably, the most economical solution is driving the piles with a follower or chaser. However, many foundation engineers shy away from this solution because of the uncertainty associated with the transfer of energy through the interface between follower and pile, the associated potential driveability problems and maybe the limited fatigue life of the follower.

This paper will demonstrate how the driveability of a hammer-follower-pile-soil system should be analyzed prior to installation and how to model the pile-follower interface both for steel and concrete piles. As an example, results will be presented which were obtained for both steel pipe piles and precast concrete piles, driven by a single-acting diesel hammer through a steel follower for a pre-construction test pile program in Venice, Italy. While analysis of the steel pile-follower system was straightforward, for the concrete piles, the presence of a soft cushion material whose material properties changed continuously posed some difficulty. Pile Driving Analyzer® measurements and CAPWAP® analysis yielded not only realistic stresses and transferred energy values in the pile, but also reasonable model parameters for further use in a pure wave equation analysis.

As a side note for clarity, the dynamic measurements and analysis results herein presented are based on the GRLWEAP and CAPWAP software. GRLWEAP is commonly used all around the world for the preparation of pile driving jobs. The program either yields a bearing graph that relates bearing capacity and pile stresses to blow count or set per blow or it predicts blow counts and pile stresses as a function of pile penetration. These results allow the contractor to estimate driving time and select an economical hammer and driving system for a safe and efficient installation. CAPWAP on the other hand is the analysis of choice once a pile has been installed and records of pile top force and velocity have been acquired during installation or during a restrike test. CAPWAP is a signal matching program which calculates for one particular impact (for example at the end of driving) the static and dynamic soil parameters. Its final results include the calculated resistance distribution, the complete stress history in the pile and also a simulated load set curve. The CAPWAP calculated dynamic soil parameters can also be used in a Refined GRLWEAP analysis to generate a calibrated bearing graph."

Introduction

Underwater foundations of bridge piers, locks, dams and other water structures can either be constructed in the dry by building and evacuating a cofferdam or by driving the piles through water. If the pile tops have to be driven to within a short distance from the mudline, either an underwater hammer must be employed or the piles must be driven through a follower or chaser which can be taken away from the pile top once the pile has reached the necessary depth.

While underwater pile driving makes for a very elegant solution, underwater hammers are more expensive than standard diesel or hydraulic hammers. This factor often makes follower driving more desirable. The follower is in general reused for the driving of many piles of the same size and thus has to withstand an even more punishing abuse than the piles themselves. Great care must therefore be exercised when designing a follower.

The literature describes the dynamics of follower pile driving (e.g. Rausche and Webster, 2003) and several case studies have been investigated. For example, Rausche, 1977 showed that analysis of installation records of large diameter offshore piles driven with followers could be done successfully with the CAPWAP approach (PDI, 2000). Stacy et al. (1996) described a project for which large prestressed concrete piles were successfully driven with followers by matching the impedance of the follower to that of the pile.

Considerable uncertainty exists among pile driving professionals about the proper dynamic analysis of the pile driving process to determine (a) the energy transmission from follower to pile, (b) the stresses in follower and pile and (c) the fatigue life of the follower.

However, modern software such as GRLWEAP (PDI, 2005) and CAPWAP (PDI, 2000) provides a convenient analysis tool. The following discussion should give foundation engineers the information necessary to use these tools to realistically simulate follower installations.

Behavior and Modeling

Several combinations of follower and pile materials exist; however, the most commonly encountered cases involve a steel follower on a steel pile and a steel follower on a concrete pile. The latter situation requires insertion of a cushioning material between follower and pile top. This added material complicates the modeling and adds uncertainty thanks to the variable nature of the cushioning material. However, this uncertainty is not unlike that encountered in the analysis of a concrete pile directly driven through and protected by a pile cushion.

Impedance matching of pile to follower helps to reduce reflection of energy from the follower-pile interface and reduce stresses in either follower or pile. Obviously, a very heavy follower would impose high stresses on the pile while a very light follower would itself suffer high stresses. In both cases energy reductions in the pile must be expected. Impedance is defined as

$$Z=A\sqrt{E^*rho} \qquad (1)$$

where A is cross sectional area, E is Young's modulus and rho is mass density of the material of pile or follower.

Unless the interface between follower and pile is executed with well-matching surfaces, in addition to stress wave reflections, energy losses must be expected due to an inelastic collision. Tools available to model the non-ideal follower-pile interface are (a) reduced impedance, (b) tension slack, (c) compression slack and (d) coefficient of restitution or slack efficiency less than 1.0. Both GRLWEAP (PDI, 2005) and CAPWAP (PDI, 2000) offer these model components. Details on their physical meaning and mathematical representations can be found in the background information of the software.

Details of the Venice pile tests

A total of 29 test piles were driven to within a short distance of the mudline. All piles were follower driven through approximately 12 m of water.

Subsurface information obtained in the vicinity of the reported installation locations indicated 1 m silty sand, underlain with silty clay to 4 m depth. Fine sand was reported beginning at 4 m depth, continuing until reaching a layer of interbedded clayey silt, sandy silt and silty clay at approximately 9 m depth below seabed. The interbedded layers there continued to the boring terminations, with a layer of fine sands consistently encountered beyond an approximate 80 m depth.

The steel follower was a pipe of 406 mm diameter, 16 mm wall thickness and 16 m length (as shown in Fig. 1).

Fig. 1. Follower to steel pile connection

Follower bottom was closed off by an 80 mm thick steel plate which was heavily reinforced by gussets. A sleeve aligned follower and piles. Fig. 2 shows the bottom bell of the follower. Fig. 3 shows installation of the strain sensors and accelerometers on the follower, 15 m above follower bottom plate.

The first phase of testing involved the driving of 13 steel piles. Like the steel follower, the steel piles were made of 406 mm outside diameter pipe with a 16 mm wall thickness. Piles had a length of 18 m, for a combined pile and follower length of 34 m for 12 of 13 test piles. The follower was gravity connected to the piles, i.e. there was no tension connection. The thirteenth test pile was twice extended by splicing reaching a final pile length of 41 m and a combined length of 57 m.

Fig. 2. Bell of follower

Fig. 3. Instrumenting the steel follower

The second phase of testing involved the driving of 16 concrete piles with various follower arrangements. All concrete piles were of 18 or 20 m length, 406 mm outside diameter and 195 mm void. Since these regularly reinforced piles were cast in a form, their internal void was variable in shape, making the cross sectional area slightly larger than nominal. All concrete piles were cast with a 5 m long taper which reduced the outside diameter from 406 to 250 mm. The pile bottom was solid. The follower arrangements were as follows.

- Two concrete piles of 18 or 20 m length were installed with a Type 1 arrangement which consisted of a concrete follower of 420 mm outside diameter and 170 mm inside diameter. The concrete follower was fitted with a steel plate and short steel sleeve at its bottom which was welded to the pile top. Follower top cushioning consisted of 80 mm softwood.

- Thirteen concrete piles of 18 m length were driven with the steel pipe follower in the Type 2 arrangement. An 80 mm softwood cushion was inserted between follower bottom and pile top. This type was the standard arrangement with gravity connector that has no tension connection to the pile.

- One concrete pile of 18 m length was driven with two steel followers of 16 m length each in the Type 3 arrangement. Thus, the final combined follower and pile length was 50 m.

Concrete wave speeds, determined from force and velocity records, yielded dynamic elastic moduli for the concrete that ranged between 31 and 45 MPa. This very large range of elastic modulus values has been attributed to micro-cracking caused by the pile driving process. Micro-cracks reduce the wave speed and therefore the apparent dynamic elastic modulus. In general these micro-cracks can be expected to "heal" due to cement hydration with time after installation.

Hammer and Driving Systems

Both Delmag D30-32 and D46-32 single-acting diesel impact hammers were utilized in the test pile program. The D30-32 has a 29.4 kN ram weight and a maximum rated energy of 102 kJ at a rated ram stroke of 3.5 m. The D46-32 model is manufactured with a 45.1 kN ram and has a maximum rated energy of 165.7 kJ at a rated ram stroke of 3.7 m. The contractor reported a steel cable reel as hammer cushion. The pile cushion, a protection for the concrete pile top from either helmet or steel follower, consisted of 80 mm thick softwood.

Instrumentation

Dynamic measurements were obtained with pairs of strain transducers and accelerometers attached to opposite sides approximately 1 m below the follower top. Analog signals from the sensors were conditioned, digitized, processed and stored with a Pile Driving Analyzer (PDA). Selected output from the PDA typically included values such as the measured force and calculated stress maxima, transferred energy, hammer operating rate and a Case Method calculation of mobilized soil resistance.

For two test piles, measurements of force and velocity were additionally taken on the pile, 1 m below its top. This layout required underwater sensors which were removed by diver after the testing was finished.

Measurement results

The force and velocity measurements, taken at the follower top, include information of reflections from below. If a follower-pile interface is imperfect or if there is a change of impedance, force and velocity will show a reflection of the impact wave at a time that is equal to twice the distance to the interface from the sensor location divided by the wave speed. Fig. 4 (refer to paper end) shows a record taken on the Type 3 double steel follower on concrete pile configuration. Below the force velocity record a sketch shows the impedance variation that has been used to generate the CAPWAP match (see Fig. 5, refer to paper end) and the associated results. The length scale of the impedance plot has been obtained by multiplying the time scale of the force-velocity record with the pile material wave speed (which is variable along the pile length). This sketch also shows time lines which are set roughly at the end of the associated event. For example, at the time of the first major force and velocity peak, the impact event is finished. The compressive reflection of the first steel follower bottom is finished at the second time line with the label "steel-on-steel follower".

A few additional items are noteworthy:

- The steel follower impedance is 788 kN/m/s and the concrete pile impedance is 1004 kN/m/s. This is a good impedance match and falls in the usually recommended range of 50 to 200% of the pile impedance.
- As described, the bottoms of the steel followers have been fitted with steel plate, gussets and sleeve. The associated reflection is compressive, i.e. the force increases relative to the velocity.
- The impedance sketch in Fig. 4 shows an impedance increase where the compressive reflection from the bottom of the upper follower. The impedance increase was determined by signal matching. The sleeve does not participate in the transfer of the stress wave and therefore only has a mass but no stiffness effect. However, the mass effect is not exactly proportional to the weight of the sleeve because of phase shifts and bending effects.
- Below the lower followers steel plate, the presence of the wood cushion has been represented by an impedance reduction. The associated reflection is a very strong velocity increase relative to the force. Obviously, this effect is much greater than the compressive reflection from the steel on steel follower interface.
- Not shown in the impedance sketch is the presence of tension and compression slacks. The tension slacks prevent transmission of tension waves. The compression slacks delay the onset of full compressive force transmission (reduced stiffness). Alternatively, the CAPWAP slack models were sometimes used with force limitation, i.e. the tension and compression

slacks would only transmit a tension or compression force less than the slack limit.

- The velocity record is positive throughout the record and this indicates that the soil resistance was rather low allowing for tension forces which would be partially filtered at the follower-follower and follower-pile interfaces.

Obviously, this follower-pile system and therefore also its CAPWAP model are rather complex and explains why the reflections in the measured force-velocity plots are not very clear at the time of the expected pile toe reflection.

Analysis results

For each pile test, at least one and often multiple records were analyzed by CAPWAP. Multiple records were analyzed where restrikes were performed or significant interruptions in pile driving occurred. During the interruptions strong increases of bearing capacity occurred with setup factors (ratios of end-of-driving to restrike capacities) reaching a magnitude 10. The Case Method, i.e. the simplified method of bearing capacity assessment which has been derived under the assumption of a uniform pile, was only of limited value because of the significant pile non-uniformities.

CAPWAP not only calculates the soil resistance activated during the hammer blow but also the stress and transferred energy values occurring along the pile and over time. Standard CAPWAP output shows maxima of tension and compression stresses and transferred energies. The present project provided a unique opportunity to explore the energy transfer and the stresses in follower driven piles.

Fig. 6 (refer to paper end) shows, corresponding to the record and signal match of Figs. 4 and 5, the transferred energy and compressive stresses vs. depth. The compressive stresses show a distinct increase immediately above the follower bottoms. This is due to the impedance effect of follower bottom plate and sleeve. The transferred energy graph indicates no loss at the interface of the two followers. On the other hand at the cushion protected pile top, the energy transfer shows a definite reduction. The stress reduction at that point is naturally due to the increased cross sectional area of the pile top relative to the steel follower.

Figs. 7 and 8 (refer to paper end) show, respectively, CAPWAP calculated transferred energy values along comparable 10 follower-steel pile and 11 follower-concrete pile combinations, respectively. The analyzed situations differ by the amount of soil resistance along the piles and therefore by the way energy is being dissipated in the soil below the follower-pile interface.

The heavy, circle-marked line shows the average energy transfer curve for all results. At the follower-pile interfaces, a reduction in transferred energy is apparent, particularly in the steel follower-concrete pile situation which is primarily caused by the soft cushion. It can be concluded from these summaries that there was an energy loss of less than 2% in the steel pile and less than 11% in the concrete pile situation.

Comparison of pile calculated and measured forces

To confirm the realism of the pile variables calculated from follower measurements by CAPWAP, measurements were simultaneously taken on both the follower and the concrete pile, 1 m below the pile top. A standard CAPWAP analysis was then performed with the follower measurements and the force calculated below the follower-pile interface. For the first concrete test pile, Fig. 9 (refer to paper end) shows a comparison of the calculated and measured forces in the pile, suggesting that good results can be obtained by follower measurements and analyses that include a model of the follower-wood cushion-pile interface.

Wave equation simulation

As a check on the realism of the wave equation analysis and to develop a recommendation for proper simulation of follower driven piles, a typical situation was analyzed with the GRLWEAP program. Since the follower-pile interface is located above grade, the differing soil resistance situations of the individual piles did not materially affect the energy transfer. The calculations for both steel and concrete piles were done with standard compressive slacks of 3 mm and unlimited tension slacks (99 mm).

For the steel follower, surprisingly a much lower coefficient of restitution of 0.25 had to be chosen than normally recommended (0.85) for steel-steel interfaces. Possibly this reduction was the result of an imperfect alignment. With the 0.25 COR a transfer energy reduction of 3.5% was calculated, similar and conservative compared to the average value of the average CAPWAP result of 3.1%.

For the concrete follower, the simulation included a standard coefficient of restitution of 0.5 (standard for wood) and an elastic modulus of 500 MPa which would normally be recommended for plywood cushions at the end of driving. In the present case all comparison analyses involved end of driving situations. The average CAPWAP and GRLWEAP simulated energy reductions at the cushioned steel follower-concrete pile interface were both 11%.

Fatigue

While piles are driven only once, typically with 1000 to 10,000 hammer blows, the follower is potentially subjected to a huge number of hammer blows during the driving of a large number of piles. Follower fatigue damage, particularly at welded components, is therefore a real possibility. The records collected by the PDA help to assess the number of stress cycles to which the follower is subjected. Positive-negative stress cycles have to be expected in the center of the follower while the top and bottom where welding may occur are only subject to compressive stresses. Fig. 10 (refer to paper end) shows for the third steel pile, at the end of driving, the force-time diagrams for follower top (i.e. the measured force at the sensor location 1 m below top), middle (CAPWAP calculated at a location 8 m below the top) and bottom (CAPWAP calculated 1 m above the follower bottom). The heavy line is the middle force and it shows the same maximum compression magnitude as the pile top force; however, it has higher tension forces than the other curves. The plotted record is 200 ms long and after that time no significant forces remain. It would be safe to conclude that for each hammer blow there are two cycles of compressive and tensile forces, with the second cycle of much lower intensity. It should be mentioned that forces calculated by the wave equation analysis generally indicate a much less dampened behavior and would therefore lead to a much more conservative assessment of the fatigue life of the follower. Another important parameter in the consideration of fatigue is the soil resistance. While higher soil resistance usually results in a higher compressive force, it also produces a more dampened record (exceptions are pure end bearing piles). In the present example the soil resistance at the end of driving was extremely low resulting in a penetration of 50 mm per blow.

Summary and Conclusions

The measurements and analyses acquired at and performed for Venice Flood Gate project, have shown the feasibility of taking measurements on followers and subsequently achieving reasonably accurate results of pile performance and soil resistance without resorting to the more complex underwater measurements on the piles. Energy losses in the steel follower-pile interfaces were somewhat higher than normally expected. However, in the steel follower-concrete pile the losses were very similar to those expected by standard simulation of softwood cushions and also similar to those normally expected in pile top cushions.

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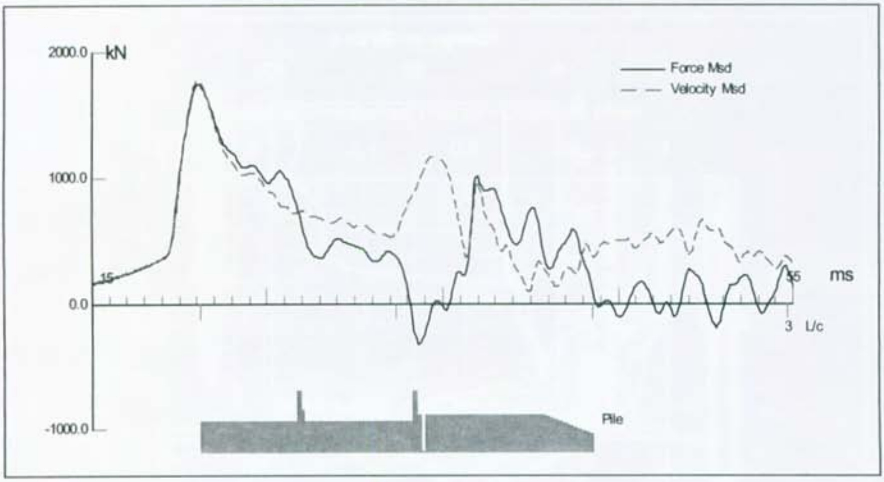

Fig. 4. PDA record of 2 steel followers driving a tapered concrete pile

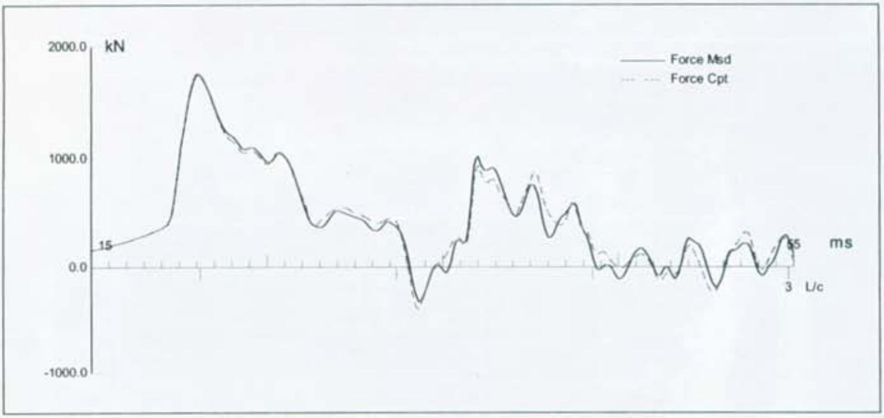

Fig. 5. Force match from CAPWAP for the record of Fig. 4

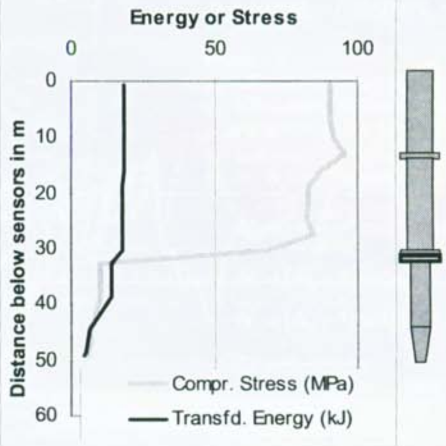

Fig. 6. Transferred energy and compressive stress vs. depth

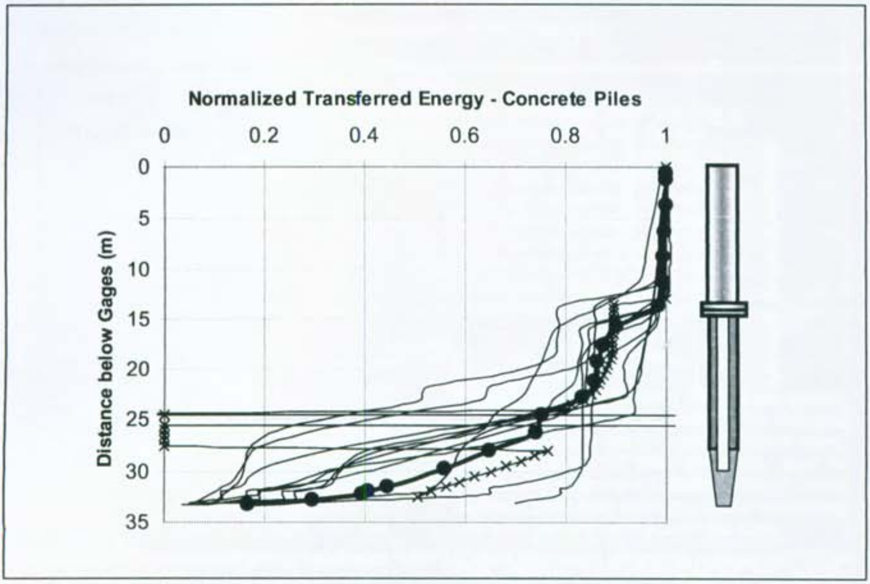

Fig. 7. Energy transfer of comparable concrete piles, average (•) and simulation (x)

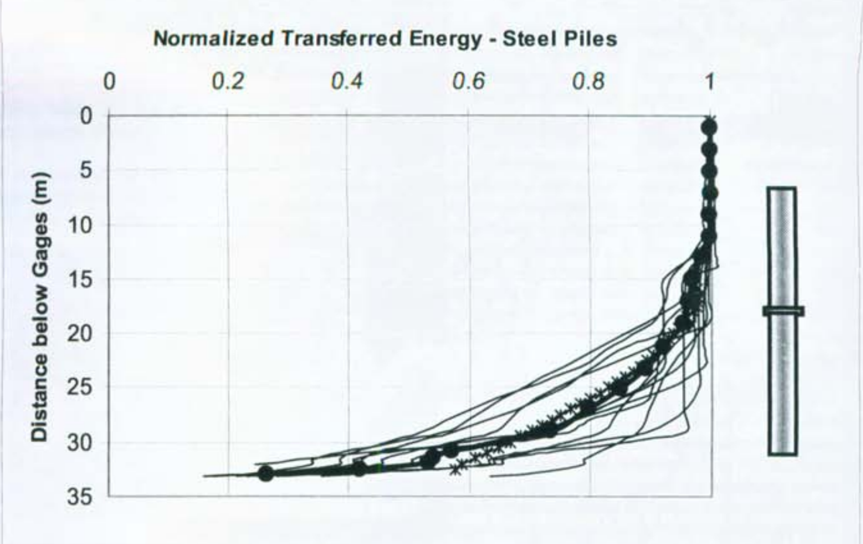

Fig. 8. Energy transfer of comparable steel piles, average (•) and simulation (x)

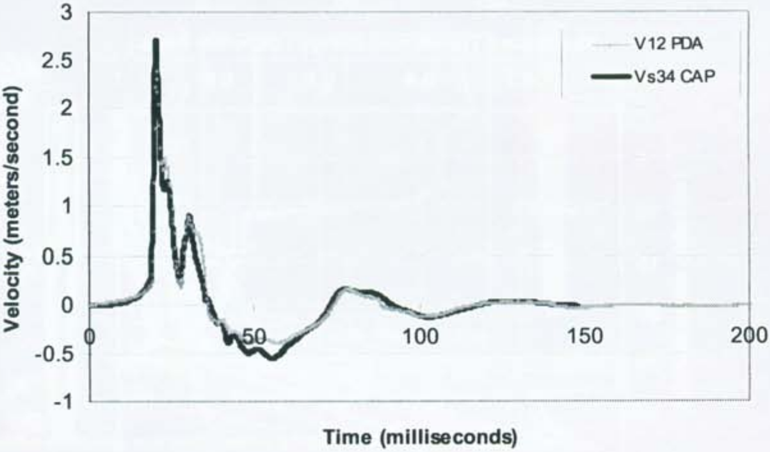

Fig. 9. Comparison of directly measured and CAPWAP calculated (using follower top measurements) pile top forces.

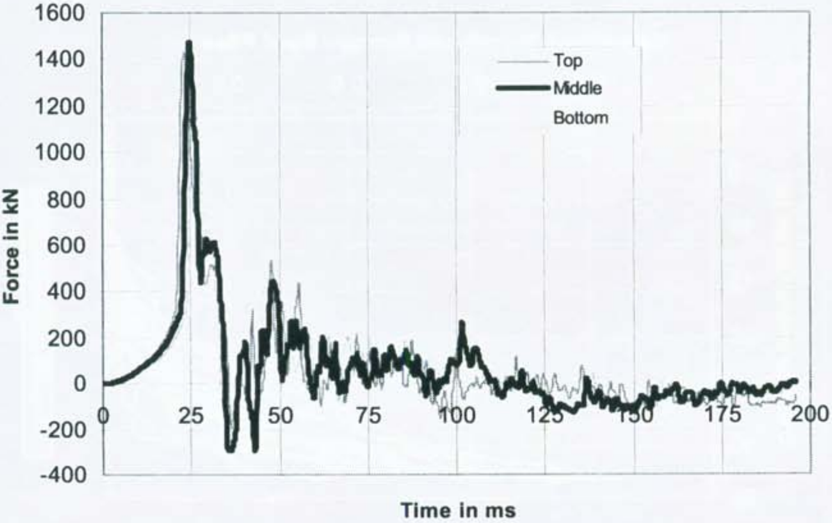

Fig. 10. Forces at follower top, middle and bottom; 3rd steel pile