IDENTIFYING SOIL RELAXATION FROM DYNAMIC TESTING

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Errata

Page 416 of this paper should be corrected as follows: second paragraph second line, replace “a reduction” with “an increase”.

The graphs on page 419 are missing labels and should be replaced with the ones below:

Figure 1: Force / Velocity and Wave-up / Displacement for Pile #13 (EOID)

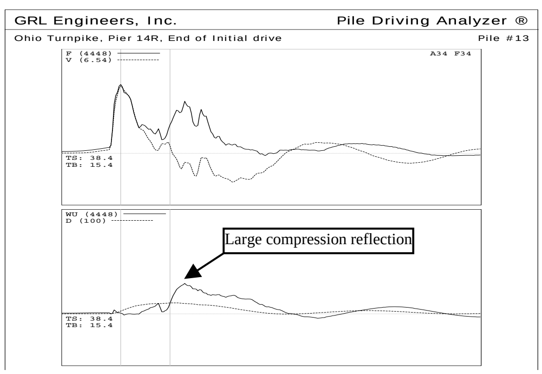
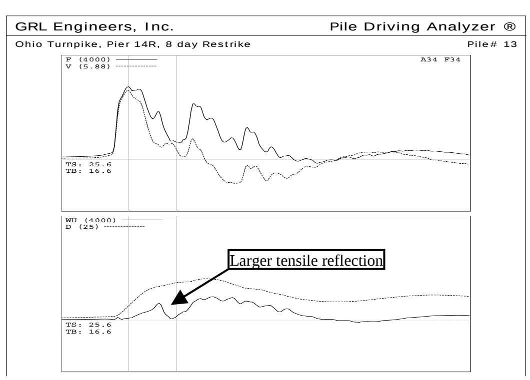


Figure 2: Force / Velocity and Wave-up / Displacement for Pile #13 (8-day Restrike)



IDENTIFYING SOIL RELAXATION FROM DYNAMIC TESTING

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ABSTRACT:

Dynamic testing of piles has been accepted worldwide and has proven to be a cost effective and reliable method of determining pile capacity. For driven piles, dynamic testing can be performed during initial driving to evaluate hammer performance, pile driving stresses, integrity and pile capacity at time of testing. However, the long term capacity can differ from that computed at the end of initial driving due to time dependent soil strength changes such as soil set-up (increase in capacity) and relaxation (decrease in capacity). To obtain a better estimate of the long term capacity, restrike testing is performed after an appropriate waiting period to identify soil strength changes.

Soil relaxation can occur in wet, dense to very dense sands resulting in a reduction in both skin friction and end bearing. Relaxation has also been observed to occur in weathered bedrock formations resulting in a potentially serious reduction in end bearing resistance. This paper presents examples of relaxation in both dense sand and weathered bedrock formations. Recommendations are given on how to perform a restrike test to obtain useful and reliable information and how to detect relaxation.

Keywords: Dynamic pile testing, soil relaxation, restrike testing

1. INTRODUCTION:

After almost four decades of research, development and field testing experience, high strain dynamic testing of piles has become the test of choice for evaluating hammer and pile performance during pile driving operations.Dynamic testing can be performed on both off-shore and on-shore environments on driven piles (steel, concrete or timber), in-situ piles (drilled shafts, auger-cast, etc.), micro-piles and also on sheet piles. The test method has been standardized by the American Society for Testing and Materials (ASTM, D 4945-96). Detailed derivations of the Case Method have been presented in a variety of publications including Rausche et al (1985).

While dynamic testing is only performed during pile driving, when real-time measurements are collected in the field, the complete dynamic testing process consists of three components. These components include 1) wave equation analysis, 2) field testing utilizing specialized equipment such as the Pile Driving Analyzer and 3) refined wave matching techniques such as CAPWAP analysis (Pile Dynamics, 2000) which, among other information leads to soil resistance and pile stress distribution. These three elements of testing and analysis lead to the most comprehensive evaluation of hammer performance, pile driveability and pile capacity determination.

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Dynamic testing is a relatively simple test which provides the engineer essential information on hammer, pile and soil performance. For driven piles, testing can be performed during initial driving or during restrike testing. Testing during initial driving is performed to evaluate the hammer performance, driving stresses, and pile integrity and capacity at time of testing. Restrike testing, performed after an appropriate waiting period, is essential to evaluate time dependent soil strength changes. These soil strength changes can occur from changes in pore water pressure or soil remolding once initial drive operations are stopped. Depending on the soil density and the soil's reaction to disturbance during initial driving, pore water pressure can either increase or decrease with time.

In loose to medium dense sands and silts, the pore pressure generally increases during pile driving operations due to soil densification. A reduction in pore pressure leads to a decrease in effective stresses which consequently reduces the soil strength. In wet, clayey soils, disturbance of the soil near the pile can occur which can greatly reduce the strength during initial pile driving operations. After pile driving ceases, increased pore water pressure will dissipate with time resulting in increased soil strength. This phenomenon is widely referred to as soil Aset-up@ in which the change in soil competency over time results in a higher capacity during restrike testing.

When driving into dense to very dense sands and sandy silts, the driving may disturb the tight structure increasing the pore volume (normally referred to as dilation). During this process, water may not infiltrate sufficiently fast to equalize the pore pressure and therefore a reduction in pore pressure occurs. This reduction in pore pressure increases the effective stresses which, in turn, increase the soil strength. However, this increased soil strength is temporary and only occurs during soil shearing. After pile driving is stopped, the pore pressures equalize resulting in reduced soil strength. This phenomenon is widely referred to as soil Arelaxation@. When relaxation occurs, a lower capacity is computed during restrike testing relative to the end of initial drive capacity. Soil relaxation can occur along the pile side surface (loss in friction) and/or at the pile toe (loss in end bearing) in coarse grained soils.

Relaxation can also be associated with weathered bedrock formations. Shale bedrock is the most susceptible to relaxation. After driving is stopped on weathered bedrock, water may seep along the pile surface and infiltrate the weathered bedrock, effectively softening the bedrock surface. The severity of the relaxation is generally dependent on the depth of the water influence. Generally speaking, the more weathered the bedrock formation, the higher the potential for relaxation. Relaxation can also be caused by rock fracturing from driving adjacent piles.

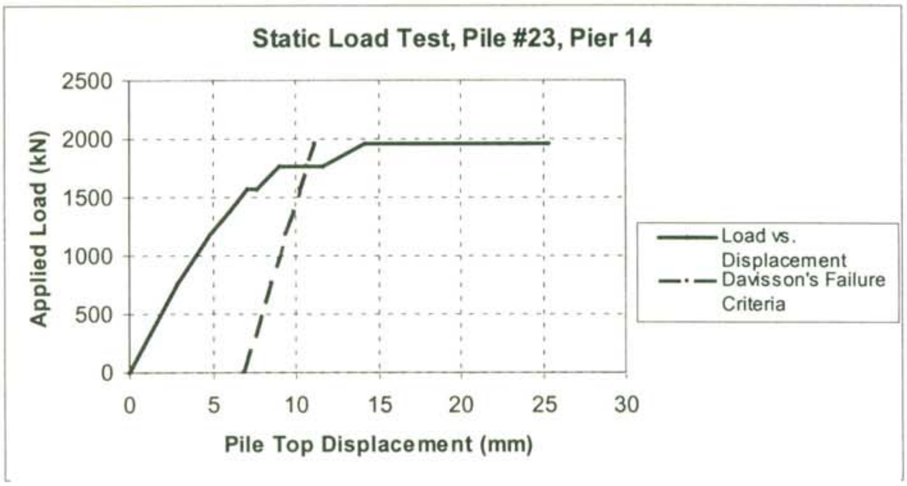
To clearly identify the relaxation potential, dynamic testing is performed both during initial driving and during restrike after waiting an appropriate time period (minimum 2 to 3 days preferable although the full relaxation may take up to 7 to 10 days). During the restrike test, close attention should be given to the results of the first few hammer impacts since relaxation (or soil set-up) may be evident only during these few early impacts. If the relaxation potential is not evaluated properly, or dynamic testing is performed only during initial driving operations, soil relaxation can cause unanticipated and potentially serious decreases in capacity relative to the end of drive.

2. CASE HISTORIES

2.1 Relaxation in Shale

Dynamic testing was specified during the reconstruction of twin bridges spanning over the Cuyahoga valley in Summit County, Ohio, USA. The piles were HP356x132 H-piles driven through stiff clay and clayey silt to bedrock which consists predominately of weathered siltstone and shale. Due to the bedrock's "weathered" state, dynamic testing was specified during both during initial driving and restrike to evaluate the potential relaxation of the bedrock.

After the series of dynamic tests at Piers 14R indicated potentially serious relaxation, it was decided to perform a static test for confirmation. The static test was performed on an undisturbed Pile (#23) which was also driven to 20 blows/25mm at end of initial driving. The results of the static test on Pile 23 using Davisson's failure criteria indicated a capacity of 1760 kN as indicated in Figure 3. This capacity was in line with the range of capacities measured from dynamic testing during the restrike sequences of nearby piles, confirming the conclusions and accuracy of dynamic testing.



Due to severe relaxation in the weathered bedrock, a larger APE D30-32 hammer was mobilized in order to drive the piles deeper into less weathered zones, and to a higher capacity at EOD therefore minimizing the effects of relaxation. Since all piles were driven with the smaller hammer at some piers, additional piles were added to account for the reduction in pile capacity due to relaxation.

2.2 Relaxation in Sand

Dynamic testing was originally specified during initial driving only for a bridge structure (State Route 129) over the Sevenmile River in Butler County, Ohio for the Ohio Department of Transportation. The piles driven were 406 mm O.D. steel pipe piles with a wall thickness of 11 mm. The piles were driven closed-ended through mainly loose to medium dense sand in the upper zones to dense to very dense sand in the lower zones. The required ultimate capacity was specified at 1504 kN. An ICE I-19 single acting diesel hammer was used to drive the piles.

The results of the dynamic testing of two piles during initial driving are summarized in Table 3. Note that Piles 129 and 123 were driven to final blow counts of 67 and 61 blows/0.3 m, respectively. At these blow counts and observed hammer performance, the mobilized capacities of 1713 and 1735 kN were significantly above the required ultimate capacity of 1504 kN. Based on these results, a driving criterion of 60 blows/0.3 m was utilized. Following the dynamic testing, a static test was performed on pile 129. The results of the static testing indicated a capacity of 1205 kN. Since this capacity was less than the minimum required and was significantly less than the capacity predicted from dynamic testing, relaxation in the lower dense sands was suspected.

Due to the potential relaxation, dynamic testing was requested to be performed during restrike on three other nearby piles after a 19-day waiting period. As shown in Table 3, Pile 114 was driven to a similar blow count to that of the static load test pile during initial driving. Piles 117 and 114, were driven to higher blow counts of 80 and 90 blows/0.3 m during initial driving. As anticipated, restrike testing of Pile 114 showed a relatively

Prior to pile driving, a preconstruction wave equation was performed to evaluate the adequacy of an ICE 42S to drive the HP356x132 piles to the required ultimate capacity of 1958 kN. The results of a wave equation analysis utilizing the GRLWEAP Program are shown in Table 1. In the driven pile practice, the GRLWEAP program is a very valuable tool in predicting pile driveability and the relationship between blow count and capacity (Rausche, 1995). The result of the analysis indicated the ICE 42S could mobilize the required capacity at a blow count of 397 blows/meter at compressive stresses within acceptable limits. At practical refusal, the analysis indicated the ICE 42S can mobilize 2670 kN. Based on the results of this analysis, the ICE 42S was approved.

Table 1: Results of Preconstruction Wave Equation Analysis

Ultimate Capacity (kN)	Maximum Compression Stress (Mpa)	Maximum Tension Stress (MPa)	Blow Count (Bls/m)	Stroke (meter)	Transferred Energy (kN-m)
890	148	0.4	137	2.4	15.7
1335	161	3.6	214	2.5	16.0
1780	187	2.9	320	2.6	16.9
2000	199	3.9	397	2.7	17.6
2225	210	7.5	491	2.8	18.3
2335	215	8.1	547	2.8	18.6
2445	220	9.4	611	2.8	18.9
2560	224	10.1	684	2.8	19.3
2670	226	10.4	800	2.8	19.2
2890	234	11.0	990	2.9	20.1

A summary of results from dynamic testing at Pier 14R on two piles is shown in Table 2. Both piles were driven to bedrock to practical refusal (20 blows/25 mm). Pile 13 was tested both during initial driving and restrike after waiting periods ranging from 1 to 8 days. Pile 18 was tested only during restrike after a waiting period of 8 days. As predicted by the wave equation analysis, the ICE 42S was able to mobilize capacities in the range of 2700 kN at the end of initial driving (EOD) or end of restriking (EOR). During restrike testing (BOR) after only one day, the capacity of Pile 13 already decreased to 1780 kN due to relaxation at the pile toe. After an 8-day waiting period, the capacity decreased further to a level as low as 1513 kN (a range in

Table 2: Case Method Results - Piers 14R - ICE 42S single acting diesel hammer

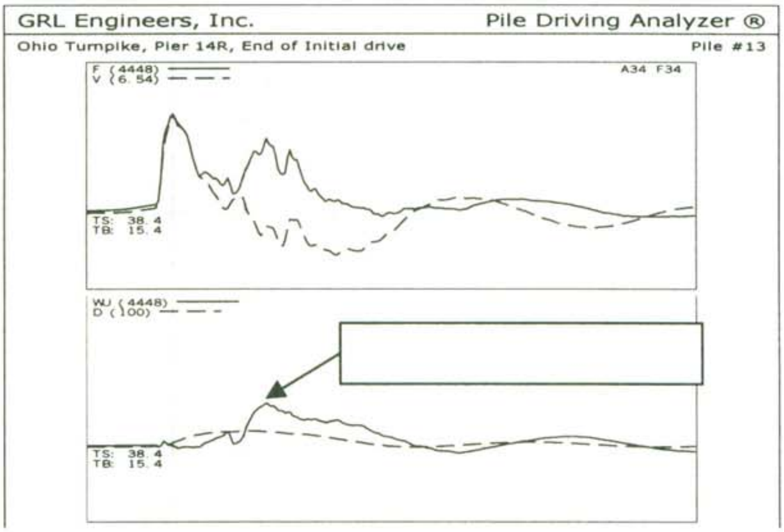
Pile No.	Test Type	Blow Count (Bl/25 mm)	Compressive Force (kN)	Hammer Stroke (meters)	Transferred Energy (kN-m)	Case Method Capacity (kN)
13	EOD	20	3010	2.8	21.8	2580
	BOR- 1 day	15	2545	2.6	16.3	1780+/-
	EOR- 1 day	20	3010	2.9	24.5	2400
	BOR- 8 day	10	2780	2.6	19.0	1513-1780
	EOR- 8 day	24	3355	2.9	25.8	2805
18	BOR- 8 day	7	3010	2.7	23.0	1535
	EOR- 8 day	27	3470	3.0	24.5	2940

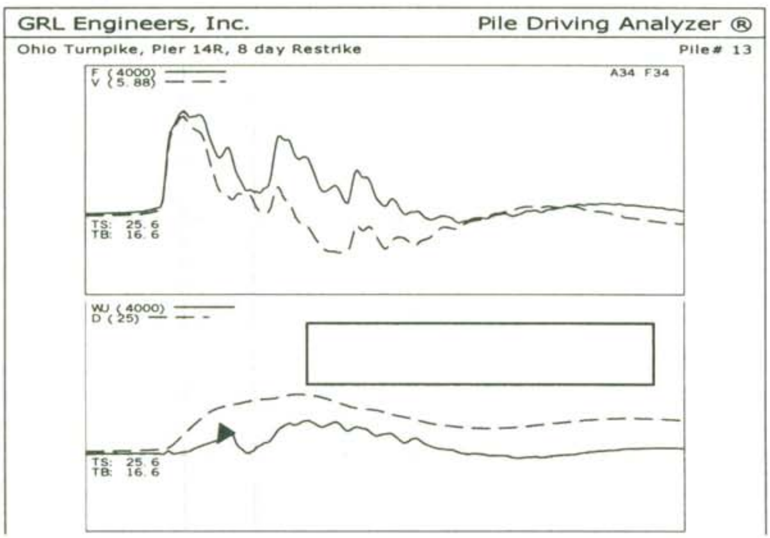
Notes:

Pile 13 drove an additional 15 cm during each restrike before again reaching 20+ blows/25 mm

Pile 18 drove an additional 46 cm during 8-day restrike before again reaching 20+ blows/25 mm capacity was given due to uncertainties in mobilized capacity at BOR due to low hammer energy input during the first few impacts). A restrike test after 8 days on Pile 18 indicated a similar capacity of 1535 kN. Note that the observed blow counts decreased from 20+ blows/25 mm at the end of driving to levels of 7 to 10 blows/25 mm during restrike. Interestingly, Pile 13 drove an additional 15 cm while Pile 18 surprisingly drove an additional 46 cm during the restrike sequences before they again reached practical refusal (20+ blows/25 mm). These relatively large pile sets during the restrike tests indicate that a relative thick zone of bedrock was influenced.

Figures 1 and 2 below shows typical records of the force and velocity (and wave-up/ Displacement) observed at the end of initial drive (EOID) and during the 8-day restrike, respectively, test for Pile #13. The EOID data (Fig. 1) shows a strong compression reflection from the pile toe indicating the pile is bearing on relatively strong, competent bedrock. The records from the 8-day restrike data (Fig. 2) show a smaller compression reflection from the pile toe in conjunction with a larger tensile wave indicating weaker, less competent bedrock. The larger tensile reflection is due to a larger pile toe displacement or set (lower blow count) as a result of relaxation.





low capacity of 1357 kN as compared to the EOD capacity of Pile 129 which was driven to a similar blow count. Pile 117, which was driven to 80 blows/0.3 m showed a higher capacity but still slightly less than the required 1504 kN. Only Pile 144 which was driven to 90 blows/0.3 m had sufficient capacity.

CAPWAP analysis was performed on EOD data for Pile 129 (static test pile) and on Restrike data from Pile 114 to compute and compare the skin friction and end bearing components. The CAse Pile Wave Analysis Program is an analytical wave matching procedure which requires measured data to be obtained by the PDA. The analysis computes the total soil resistance with the skin friction and end bearing components, along with soil damping and quake parameters during a representative hammer blow. As expected, the computed end bearing component for Pile 114 during restrike was substantially lower at 770 kN versus 1255 kN at EOD for Pile 129. In addition, the computed unit skin friction in the lower dense sands was 30 % lower during restrike testing. A slight increase in friction was computed in the upper loose to medium dense sands, which was attributed to soil set-up.

Table 3: Case Method Results - SR 129, Pier - ICE I-19 Single Acting Diesel Hammer

Pile No.	Test Type	Blow Count (Bls/0.3 m)	Compressive Force (kN)	Hammer Stroke (meters)	Transferred Energy (kn-m)	Case Method Capacity (kN)
Initial drive testing						
129	EOD	67	2890	2.6	26.9	1713
123	EOD	61	2890	2.6	27.8	1735
Restrike testing						
114	BOR- 19 day	63 @ EOD	2883	2.7	24.8	1357
117	BOR- 19 day	80 @ EOD	2930	2.8	27.1	1470
144	BOR- 19 day	90 @ EOD	3020	2.8	27.9	1885

Based on the results of the static and dynamic testing both during initial driving and during restrike, it was concluded that relaxation in the lower dense sands was a major factor and needed to be considered. To account for the relaxation, each pile was driven 2 to 3 ft deeper and to a higher blow count of at least 85 blows/0.3 m. This blow count is substantially higher than the original criteria of 60 blows/0.3 m although still within the capability of the ICE I-19 hammer.

3. CONCLUSIONS

When performing dynamic restrike testing for evaluation of potential relaxation, it is critical that the tester pay close attention to the first few impacts. Relatively low mobilized capacities during early impacts which are approximately equal to or slightly lower than the applied hammer peak force may indicate the ultimate capacity was not fully mobilized and not necessarily from relaxation. Therefore, difficulties in the evaluation process may surface when using diesel hammers if the stroke of the ram starts at relatively low levels. Therefore, it is imperative that when testing with a diesel hammer, the contractor operates the hammer at sufficiently high strokes as quickly as possible during start-up. This is generally not a problem for air or hydraulic hammers since they can typically be started at the maximum or rated stroke.

When severe relaxation occurs in bedrock, piles may need to be re-driven deeper into less weathered and therefore more competent bedrock. Alternatively, the design capacity may be reduced and additional piles added to account for the capacity short fall. Similarly, when relaxation occurs in dense to very dense sands, where a reduction in friction as well as end bearing occurs due to dilation, the piles will have to be Aover - driven@ to a higher capacity so as to account for the loss in capacity from relaxation. Again, an alternative solution is to reduce the design capacity and install additional piles.

If relaxation is anticipated, it is critical that the chosen hammer be sufficiently large so that, if necessary, the piles can be driven during initial driving to a level of capacity which, after relaxation, the soil resistance is still more than required. Wave equation analysis can be utilized effectively to aid the engineer in choosing the appropriate hammer. Based on local experience when testing piles driven into weathered shale, the hammer should be capable of mobilizing at least twice the anticipated end bearing component since experience has shown that up to 50% of the end bearing component may be lost from relaxation.

Dynamic testing was specified for two bridge projects in Summit and Butler counties, Ohio, USA. Concerns were raised early due to potential relaxation effects. The chosen hammers were approved based on a preconstruction wave equation analysis using the GRLWEAP program. The results from dynamic testing during initial driving correlated well to the hammer/pile performance predicted by the pre-construction wave equation analysis. However, restrike testing indicated relaxation in the weathered shale after as little as one day. However, dynamic testing after longer waiting periods indicated, as anticipated, that a 1-day waiting period for restrike testing was not sufficient to assess the long term capacity. Experience from many other projects shows that relaxation may take several days to fully develop (7 to 10 days). Results from static testing for both projects confirmed the relaxation and the adequacy of dynamic testing.

Dynamic testing was a very useful tool in evaluating the extent of the relaxation at these sites. It also aided the design engineer in the proper assessment of the foundation design during the pile driving sequences and was helpful in determining revised driving criteria to account for the relaxation.

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