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Driveability Analysis Techniques for Offshore Pile Installations

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ABSTRACT

Pile driveability analyses for offshore platforms require a unique set of criteria, which may not normally be associated with other pile foundation installations. The selected hammers, pile makeup details and soil profile must be carefully reviewed, as these factors will determine if pile installations will be successful. The most important of the variables to establish is the expected Soil Resistance to Driving (SRD). Common practice is to relate the SRD to the Static Soil Resistance (SSR) which is normally provided based upon the American Petroleum Institute (API) methods of calculation or some variance based upon local site conditions and experience. In addition, due to the substantial use of hydraulic hammers hammer operating energies must be selected such that pile driving can be accomplished while avoiding pile damage.

Current procedures used for driveability analysis will be provided and the methods of parameter selection discussed in detail. These procedures, which have been used on several offshore projects in various offshore fields around the world, will be presented with the original driveability analysis and the recorded pile installation records. A method to determine the expected SRD will be discussed based upon the experience collected from these sites which are in numerous offshore fields worldwide. Four Case Studies are shown to validate the described methodology.

1 INTRODUCTION

Wave equation analysis has become the standard method of evaluation for pile driving systems, with GRLWEAP the most widely used wave equation program. Standard bearing graph analyses provide a thorough evaluation of the pile and hammer system, while predicting the expected blow counts, pile stresses and hammer performance. However, these types of analyses may only be provided for a selected pile penetration, and the prediction of blow count versus pile penetration is not possible. The driveability analysis option can be used to provide detailed predictions of blow count versus depth as well as predictions for the expected pile stresses and hammer performance. The driveability option is the preferred analysis technique for piles driven to support offshore structures as these piles often have deep penetrations with large required pile capacities. As such, a major concern is being able to drive the pile to the required pile penetration to achieve the ultimate pile capacities.

Wave equation program models were developed based upon the original studies conducted by E.A.L. Smith (1960). The model simulates what is happening in the hammer, pile and soil during and immediately after the ram impact. It does this by modeling the system's components with masses, springs and dashpots and calculating the displacements and velocities of the masses and the forces in the springs. Stresses are determined from forces divided by cross sectional area at points that are roughly one meter apart. This method of calculating the pile movements and stress is an accurate solution of the wave equation, a differential equation.

Over the past 50 years several practitioners have used the available wave equation programs to perform driveability analyses for offshore piles. Originally, these analyses could only be accomplished by performing the so called bearing graph analysis to determine the relationship between soil resistance (pile capacity) and blow count. The user would then need to determine the soil resistance to driving (SRD) based upon the soil conditions or the geotechnical report, and then plot the predicted blowcount determined from the SRD over the pile penetration depths. This technique is less than ideal as the pile penetration for each plot along the SRD curve should be analyzed based upon the planned pile length and soil resistance distribution. This would result in multiple bearing graph analyses needed to accurately model offshore piles. Therefore, the driveability analysis option in the GRLWEAP program was developed to automatically perform these multiple bearing graph analyses and plot the results.

A partial literature review provides several experiences where engineers have used driveability analyses to predict or match the observed pile blow counts for offshore pile installations (Stevens, et al., 1982, Alm and Hamre, 1998, and Dutt, et al., 1995). Most of these experiences are for local soil conditions specific to a single or few similar sites. In addition, the proposed driveability model has usually been adjusted after pile installations to provide a match of the observed blow counts and perceived SRD. The primary purpose of this paper is to provide a guideline on how to perform driveability analyses such that the results will provide a clear prediction of the expected performance and driving conditions. It should be noted that the proposed method is not intended to predict the exact blow counts but is intended to provide a conservative assessment of the proposed hammer/pile combination. Of course this method may need to be modified for site specific conditions but is provided as a guideline that should result in a reasonable approach for most soil conditions.

2 GRLWEAP PROGRAM

The latest version (2010 Offshore) of the GRLWEAP program includes several new options which enhance the use of the program with regards to driveability analysis. Most of these improvements have been provided based upon our experiences with performing driveability analyses and also those of other engineers who routinely do these analyses. The improvements and their importance are discussed below:

Unit End Bearing Input – Previous versions required that the total end bearing resistance be input for each soil layer rather than the unit end bearing value. This required calculation of the end bearing was usually based upon the unit end bearing values provided in the geotechnical report which is of course redundant. More importantly however, it required the user to decide which layers would behave as plugged or un-plugged when calculating the end bearing resistance. The user now specifies both the unit end bearing and the pile toe area over which it will be distributed.

Pile Toe Area – The pile toe area to be used with the unit end bearing to calculate total end bearing may now be varied by soil layer or pile penetration into various soil layers, as opposed to varying it over the entire pile penetration. In addition, a partially plugged condition can be modelled, where the toe area used for calculation of the end bearing would be some portion of the fully plugged toe area.

Pile Model Input – A subroutine which allows for a simpler input process for the pile model and includes a model for the stabbing guides has been added. This allows for input based upon the add-on sections and stabbing guide dimensions. However, it should be noted that the subroutine only models the stabbing guide as an increase in the pile area along the bottom of each add-on section where the stabbing guide is actually welded to this section.

Static Bending Stress Calculation – By providing the pile inclination, hammer weight and center of gravity above the pile top, the analysis calculates the static bending stress along the pile length for that portion of the pile extending above the top of jacket location. These stresses can be superimposed on the dynamic stresses to indicate the location and extent of the combined dynamic and static stresses. This is often of critical importance when performing analyses for hydraulic hammers which have variable hammer energy settings. The hammer energy setting must often be reduced at the start of driving of add on sections in order to prevent over stressing.

Fatigue Analysis Data – The results from driveability analysis are sometimes used to perform fatigue analysis. Output tables can be produced that include the maximum compressive and tensile stress for each segment multiplied by the number of occurrences from the average blow count. These tables may be used for fatigue analysis by other means.

Several additional improvements have been provided which may also be useful for performing driveability analysis. Improvements to the pile capacity calculation subroutines, the depth modifier table, area calculator, automatic gain/loss factor assignment and numeric output have all been provided. These improvements may be useful to users performing driveability analyses for offshore installation projects.

3 ANALYSIS METHODS

Producing a driveability analysis requires consideration of the hammer model, proposed driving system, the pile model and the soil model. The analyst should also have clear restrictions on blow count and allowable stresses before proceeding with the analysis. Hammer model and driving system descriptions are summarized by Rausche and Klesney (2007). Some details regarding pile and soil modelling are summarized below.

3.1 Pile Model

One of the first steps in performing driveability analysis is to input the proposed pile model into the wave equation program. This is normally a straightforward procedure as the pile makeup drawings detail the pile wall thickness and lengths of the proposed pile sections. Often not included is the modelling of the stabbing guides. However, stabbing guides must be included as they will result in a localized increase in dynamic compression stress due to the increase in steel area. This increase in compression driving stresses combined with the static bending stress occurs in the area just above the top of the stabbing guide and becomes the critical location with respect to stress control at the restart of driving of the add-on sections.

Since the top of the stabbing guides are typically only welded to bottom of the add-on section, it may be appropriate to only include an increase in pile area over this portion of the pile. However, the stabbing guide does extend into previously driven pile section below although this material is not welded together. Based upon the authors' experience it should be sufficient that some increase in pile area be provided from the top of the stabbing guide to the bottom of the add-on section, as this will result in the critical stress location being just above the stabbing guide with respect to stress control. If one ignores this issue overstressing of the pile section may occur at the restart of driving of a given add-on section and has resulted in pile buckling at this location.

Calculation of the static bending stress caused by the pile inclination, pile weight and hammer weight has become more important due to the common use of variable energy hydraulic hammers. Before the use of hydraulic hammers, steam hammers were usually employed for driving offshore piles. These hammers have fixed strokes and energies so a variety of hammer sizes were typically used to drive a single pile, with lighter and lower energy hammers being used for the first add-on sections and heavier and higher energy hammers for the final add-on sections. This resulted in fairly consistent dynamic stresses depending upon the size of the hammer used. With the use of hydraulic hammers, the same size hammer is typically used for driving all pile sections, with reduced hammer energies being deployed for early sections and higher energy for later sections. Therefore, the driveability analysis must determine what hammer energy will be suitable such that the combined static bending stress and dynamic stress do not result in pile buckling. As per API code the combined stress should remain below the pile yield strength.

3.2 Soil Model

Once the pile model has been entered the soil model must be established. The soil model is largely consistent with that used in Smith (1960) and will consist primarily of quake (a static stiffness parameter), damping, unit skin friction and unit end bearing. Quake and damping values must be determined for both skin and toe parameters. The program recommended value for skin quake is 2.54 mm, while the recommended value for toe quake is 2.54 mm for an opened pile section. This toe quake of course assumes that the pipe pile is open ended and will not develop a plug during driving. Based upon the authors' experience from numerous dynamic test results and signal matching analyses with CAPWAP® (Webster et al., 2008; Rausche et al., 2009), the use of such a low toe quake for these types of piles does not seem justified.

Typically toe quakes proportional to the pile's outer diameter (D) on the order of D/120 are indicated by CAPWAP analysis unless the soil layer is very dense and significant end bearing is encountered. In some cases much higher toe quakes are indicated for clay soil conditions. As such we recommend that the toe quake for driveability analysis be selected as D/120 for sand, D/60 for clay and if very dense sands or rock are expected to result in large amounts of end bearing then the toe quake should be D/240. These values for such large diameter piles will be much greater than the 2.54 mm typically used for open ended pipe piles. As such, the predicted blow counts when using these toe quake values will be increased from those provided when using the 2.54 mm value. However, for most offshore piles the vast majority of soil resistance will be developed from skin friction rather than end bearing; use of these higher toe quakes should only slightly increase the predicted blow counts which would provide for a somewhat conservative driveability analysis.

The program recommended skin damping parameters are 0.16 s/m for sand layers and 0.65 s/m for clay layers. The program recommended toe damping is 0.5 s/m. These values have been generally indicated from CAPWAP analyses performed on dynamic testing results for offshore piles. As such we strongly recommend the use of these program recommended values. Of course at a given site these parameters could be slightly different based upon the actual soil conditions. However, it is recommended that these damping parameters not be adjusted, without data from dynamic monitoring and CAPWAP analysis to support such variations.

The unit skin friction and unit end bearing parameters must be input to allow the program to calculate the soil resistance to driving. The unit resistance parameters should be entered based upon the static pile capacity calculations. We do not recommend that these parameters be adjusted as a baseline is needed for determination of the SRD. Since nearly all offshore piles are currently designed according to API standards the static pile capacity calculation serves as this baseline for future driveability analysis as well as for analyses done for various project sites. Typically the SRD is somewhat lower than the static pile capacity calculation as most offshore piles will demonstrate soil setup conditions where by the soil resistance to driving is lower than the ultimate pile capacity. However, for sites where significant amounts of granular soils are present, or where rock layers will be encountered the SRD can exceed the static pile capacity calculations which have limiting values particularly for end bearing conditions.

With the above information entered into the wave equation program, the driveability analysis may be performed for various SRD profiles. Typically, this is provided by assigning soil loss/gain factors for the overall soil profile and individual soil setup factors for the various soil layers. Soil loss/gain factors are applied to all soil layers in proportion to their assign soil setup factor. Therefore, for a soil loss/gain factor of 0.5 and a soil setup factor of 2.0 the SRD is reduced to 50% of the static pile capacity for that layer. However, if additional layers are assigned soil setup factors of say 1.5 then the SRD in these layers would be reduced proportionally to the maximum soil layer setup factor of 2.0. For this example the layers with soil setup factors of 1.5 and the soil loss/gain factor of 0.5 their SRD would be reduced by 33% of the static pile capacity. The soil setup factors only apply for skin friction resistance and do not apply to end bearing. End bearing resistance can be varied by the loss/gain factor directly without variation by the soil setup factors. Therefore, a soil loss/gain factor of 0.5 for the toe results in a 50% reduction in the calculated end bearing regardless of the soil setup factor.

Finally, it is useful to consider variable soil setup based upon the planned pile makeup and anticipated delays in driving. The variable soil setup analysis must include specified waiting times at the pile penetrations where splicing or other delays are expected to occur. A reasonable estimate of the typical waiting period for splicing of offshore piles would be between 6 and 24 hours. In addition, to perform the variable setup analysis the setup time and limit distance for each soil layer must be provided. The program recommend limit distance, the distance which the pile must be driven in order to obtain the fully reduced skin friction resistance, is 2 meters. Soil setup times will vary depending upon the soil types. For the typical driveability analysis a soil setup time for clay layers of one week would be considered reasonable while a setup time of 24 hours or less for sand layers would be recommended.

Given the above discussion, it is clear that to perform the driveability analysis a good understanding of the subsurface conditions must be provided. It may often be reasonable to simply perform the driveability analysis based upon an SRD being equal to some minor reduction of the static pile capacity and the static pile capacity. In this case soil setup factors for individual layers and the variable soil setup analysis would not be considered. Restart or restrike evaluation would be provided from the analysis using the static pile capacity estimate as the SRD. This type of analysis would be recommended for sites where the predominate soil conditions are sands and where the expected reduction in SRD would be relatively small, about 25% or less. It should also be considered that the SRD could be greater than the static pile capacity estimates particularly for sites where the primary soil deposits are sands. This is possible as the static pile capacity calculations are often quite conservative and may under predict the pile capacity, or the sands layers could become denser during driving. A reasonable increase in the static pile capacity estimate would be 25%. Therefore the drivability analyses could be performed using soil loss/gain factors of 0.75, 1.0 and 1.25 for the skin friction and end bearing resistance. We would recommend that the pile toe area be considered as plugged as this will result in the highest SRD for the analysis. This type of analysis would be considered conservative for predicting pile driveability for the vast majority of offshore projects.

For more complex soil profiles (layered clay and sand deposits) it is likely more reasonable to model these using the appropriate soil setup factors and the variable soil setup analysis options provided in the GRLWEAP program. For sites with significant clay layers it is likely that these materials will have soil setup factors of 2.0 or greater. If little is known about the project site and remolded strengths are not provided then it would be recommended that these layers be assign a soil setup factor of about 2.0. The gain/loss factor to be analyzed would then be 0.5 allowing the clay layers to experience a 50% reduction in resistance from the static pile capacity. If previous pile driving experience is available, or if remolded strengths are provided, then the soil setup factor and corresponding gain/loss factor should be based upon this information. Our experience indicates that soil setup factors as high as 4 have been found to be appropriate for some clay soils. For sand layers we would recommend that a soil setup factor of 1.0 be used for these layers so that no reduction in the skin friction for the sand layers would be provided. Of course the sand layers may also provide an opportunity for soil setup and use of soil setup factors for these layers should be based upon previous experience or detailed soil properties.

These recommendations apply to the skin friction resistance only and end bearing resistance should be estimated based upon the fully plugged pile toe cross section. Although it is likely that at many sites the pile will not behave as a fully plugged section (pile cores through the soil) this model should only be used if it previous experience in the area indicates that this will occur. By using the fully plugged area the end bearing resistance can be modified if needed by the loss/gain factor. In this way a fully plugged to coring condition can be modelled or anything in between. All too often engineers only consider the two extremes or plugged or unplugged while the possibility of a partially plugged condition is normally not considered. Based upon the authors' experience, it is quite common that the end bearing resistance during driving is somewhere between these two conditions, which may represent a partially plugged condition or higher/lower than predicted end bearing during driving based upon the static pile capacity calculations. As such we generally recommend that the end bearing be modelled as fully plugged and a soil loss/gain factor of 1.0 be used for sites where predominantly clay soils are present. This allows for a relatively conservative analysis of the end bearing conditions, particularly in the sand layers between clay deposits where the end bearing resistance is normally considered to be much greater. As a variation the end bearing soil loss/gain factor could be provided between 0.5 and 1.0 for an indication of the expected range of end bearing resistance.

The above approach has been used for multiple offshore projects in variable soil conditions around the world and has shown to be quite successful in conservatively predicting the expected blow counts with depth as well as the hammer performance and pile stresses. A few examples are provided here for review. It should be noted that some variations were provided based upon our experience at specific sites. Also dynamic pile monitoring was also performed at these sites which have added to the understanding of the driveability results.

4 CASE I – SAND SITE

Figure 1 provides the predicted and observed blow counts from an offshore project in the Arabian Gulf where 1067 mm diameter pipe piles were driven with a Menck MHU 500 hammer into predominantly sand deposits. For this site a fairly simple approach was selected as the soil conditions were primarily sand deposits. The analysis provided for soil loss/gain factors of 0.75 and 1.0 for both the skin and toe resistance. The site usually has minor soil setup based upon the dynamic testing results and CAPWAP analysis. The typical skin friction setup factor is 1.4. Refusal or hard driving in this area has also been encountered when the sand layers are denser than anticipated by the static pile capacity estimate. Refusal driving typically occurs when end bearing values are greater than those predicted by the static pile capacity estimate.

As shown, the predicted blow counts match well with the actual blow count encountered until a pile penetration of about 27 meters. At this depth the actual blow counts are greater than those predicted by the driviability analysis. This is partially explained by the use of slightly lower hammer energy for actually driving the piles than that which was used in the preconstruction driveability analysis. Below about 32 meters, the predicted blow counts far exceed the observed blow counts. This is a result of significantly lower end bearing being encountered during pile driving as well as slightly lower skin friction as indicated by CAPWAP anlyses. The lower skin friction likely could have been predicted as previous dynamic analyses had indicated a soil setup factor of 1.4 (so loss/gain factor of 0.7 instead of 0.75) however, the end bearing resistance is nearly half that anticipated from the static pile capacity estimate. This is a good example of a pile that is likely partially plugged during driving as the end bearing indicated from the CAPWAP analysis is too great for just the coring condition and is much lower than that predicted from the static analysis. Therefore, either the end bearing will experience soil setup or the open ended pipe pile is partially plugged during driving. Either of these conditions might be appropriate and both can be modeled in the driveability analysis using the soil loss/gain factors.

5 Case II – Clay Site

Figure 2 provides the predicted and observed blow counts from an offshore project in the Bay of Bengal where 1829 mm diameter pipe piles were driven with a Menck MHU 800 hammer into predominantly silty clay or clayey silt deposits. For this site the more complex variable soil setup analysis was selected, as soil setup between splicing of add on sections needed to be evaluated. The analysis provided for soil loss/gain factors of 0.5 and 0.7 for the skin friction resistance and 1.0 for the toe resistance. These values are relatively higher than what one might normally assign for the clay soil conditions present at this site. However, the site is a fairly new location where little previous driving results have been obtained. One might argue that the use of the 1.0 soil loss/gain factor on the toe is overly conservative particularly since the full toe area (plugged condition) was used for the analysis.

As shown in Figure 2, the predicted blow counts are generally much higher than the actual blow counts observed, although a fairly good match is provided at the final splicing depth of about 75 meters. It is clear that the driveability analysis provided a conservative prediction of the blow counts and use of lower soil loss/gain factor (and of course higher setup factors) likely would have provided a clear match between the predicted and observed blow counts. The only question then would be if the end bearing resistance was reasonable for the driveability analysis. A review of the dynamic monitoring results indicates that the end bearing resistance at final driving was approximately 6.8 MN which relates to a unit end bearing resistance of about 2500 kPa. However, the geotechnical report indicates that the unit end bearing for static pile capacity estimate is only 1800 kPa. The results from the CAPWAP analysis seems to indicate that a higher unit end bearing resistance could be used for static pile capacity estimates and also confirms the use of the 1.0 soil loss/gain factor and fully plugged condition for the end bearing resistance. As such the only means left to reduced the predicted blow count would be to use a lower soil loss/gain (higher soil setup factor) for the clay layers. A reasonable match of the observed blow counts can be provided if the soil loss/gain factor is reduced to 0.25 and the soil setup factor for the clay layers is of course increased to 4.0.

6 CASE III – CLAY SITE WITH WELL ESTABLISHED SOIL BEHAVIOR

Figure 3 provides the predicted and observed blow count from an offshore project in the Middle East where 1676 mm diameter piles were driven with a Menck MHU 500 hammer. Several platform installations were performed in the vicinity of this site and the soil conditions were well known. The predominate soil profile consisted of silty clay with multiple relatively thin layers of cemented sands. As indicated at previous nearby installations, it was expected that the SRD would be considerably lower than the static pile capacity estimates. Therefore, the driveability analysis was performed using soil loss/gain factors of 0.3 and 0.4 for the skin friction resistance, and a partially plugged condition, soil loss/gain factor 0.5 was modelled for the toe resistance. These values are somewhat lower than what one might normally assign for a typical clay site but were developed based upon previous pile driving experience as well as sensitivity values developed for the clay.

As shown in Figure 3, the predicted blow counts generally match well with observed blow counts during pile installation. Over the first 60 meters the predicted blow counts are greater than the observed which may be a result of using higher than expected hammer energies for the Menck MHU 500 hammer over these depths. At the splice depth of 61 meters the predicted values are much greater than the observed which indicates that the WEAP results over predicted the amount of soil setup which occurred during the splicing operations. It should be noted that the average splicing time required 32 hours to complete at this location while the WEAP analysis assumed about 12 hours for the splicing operations. Based upon this comparison it appears that the WEAP analysis provided a conservative estimate of the restart driving conditions at this location. Finally, the observed blow counts over the final 60 meters of driving are bracketed by the predicted blow counts when using the soil loss/gain factors of 0.3 and 0.4 for the skin friction. The single exception to this is at approximately 85 meters where the observed blow counts increase. This is most likely due to a thin sand layer located between 75 and 90 meters which resulted in higher blow counts due to increased end bearing. A similar condition appears to have occurred at pile penetrations of approximately 112 and 115 meters where somewhat higher end bearing resistance appears to be encountered.

Based upon these results it is apparent that modelling the SRD for this clay site with relatively low soil loss/gain factors is appropriate. Thus the expected soil resistance during driving is considerably lower than that static pile capacity prediction. Such conditions are quite common in soil profiles dominated by clay or other fine grained deposits. In fact based upon the authors' experience soil loss/gain factors as low as 0.2 maybe appropriate for sites where little or no sand layers are indicated and the sensitivity values of the clay deposits approach 4 to 5.

7 CASE IV – VARIED SOIL PROFILE

Figure 4 provides the predicted and observed blow counts from an offshore project where 1219 mm diameter pipe piles were driven with a Menck MHU 800 hammer into a highly varied soil profile. The most predominate soil type was a silty clay although multiple layers and lenses of sand, silt, calcilutite, calcisiltite, gypsum and limestone were also present in the soil boring. The analysis provided for soil loss/gain factors of 0.5 and 0.7 for the skin friction resistance and 1.0 for the toe resistance. Multiple nearby jackets have been installed in similar soil conditions and it was generally considered that hard driving could be encountered in the dense sand or rock formations. This would be particularly true if the predicted end bearing resistances were considerably lower than what would actually be encountered by the piles during driving. This condition could generally be expected based upon that fact that the end bearing resistance from the static pile capacity calculations were often provided as limit values for the soil/rock types. As such the use of these soil loss/gain factors was considered appropriate as the predicted blow counts could easily under predict driving conditions depending upon the actual end bearing conditions encountered. However, given the previous pile driving experience in the area and the fact that dynamic pile monitoring would be provided this was considered acceptable for this project.

As shown in Figure 4 the predicted and observed blow counts agree fairly well with the following notable exceptions. The restart of driving at the 62 meter pile penetration blow count was much higher than predicted although not so high as to be an issue for restart driving. The predicted blow counts are generally higher than actual between about 68 and 78 meters. This is likely due to the presence of the calcilutite and calcisiltite layers between these depths. Clearly these "rock" formations are considerably weaker than expected by the static pile capacity calculations. The observed blow counts between 78 and 86 meters are quite erratic which is likely a result of the highly variable end bearing resistance in these layers. Finally, the end of driving blow counts are higher than predicted at the final penetration of 86 meters. This is clearly due to the actual end bearing at final driving being higher than predicted from the static pile capacity calculations. Based upon the CAPWAP analysis the actual average end bearing was approximately 14.5 MN while the static pile capacity end bearing at this penetration was limited to about 11 MN for the driveability analysis. Even considering these short comings, in the analysis it is clear that a reasonable prediction of the expected blow counts was provided prior to pile installations.

8 CONCLUSIONS

Based upon these results it appears that use of the static pile capacity estimate for calculation of the driveability SRD will result in a reasonable estimate of the SRD. For primarily sand sites we recommend that the SRD be modelled using soil loss/gain factors of 0.75, 1.0 and 1.25 for both the skin and toe resistance. A soil setup factor would need to be assigned for the 0.75 loss/gain factor but would not have an effect on the 1.0 or 1.25 factors. Therefore, soil setup conditions between splices might need to be estimated from the analysis performed for the 1.0 or 1.25 soil loss/gain factors. For clay sites or sites with varied soil layers we recommend that the skin friction SRD be calculated as 50% of the static pile capacity calculation for the clay layers and 100% for the sand layers. Of course these values are presented for conditions where significant previous pile driving experience is not available. If previous experience is available or if the soil testing results appear to indicate a variation from this estimate then this should certainly be taken into account. Specifically, if remolded compression tests (sensitivity) indicate a higher or lower loss of strength, then this information should be used to estimate the percentage of the static pile capacity to be used for the skin friction SRD calculations. Of course the appropriate soil setup factor(s) for the clay layers would need to be provided. For the end bearing resistance, we recommend that the fully plugged condition be modelled for the driveability analysis. The end bearing resistance can then be adjusted using the toe soil loss/gain factor to model either the fully plugged or a partially plugged condition. If previous experience indicates that a coring condition will be encountered, then this condition can also be modelled by using the steel area only for the end bearing calculation. While some sites may require that the pile toe be modelled as coring, the authors' experience would suggest that using the fully plugged end bearing condition makes more sense and provides a reasonable, although slightly more conservative match. This is particularly true for sites where dense sand layers are present between softer clay layers and hard or refusal driving could be encountered in these dense sand layers.

In addition to the above, the program recommended quake and damping factors, as provided above, should be used for the various soil layers. Toe quakes should be selected for the fully plugged condition with the standard recommended toe quake of D/120 being used for granular soils and D/60 used for cohesive soils. If very dense layers (sands or rock) are to be encountered then D/240 may be used for these layers.

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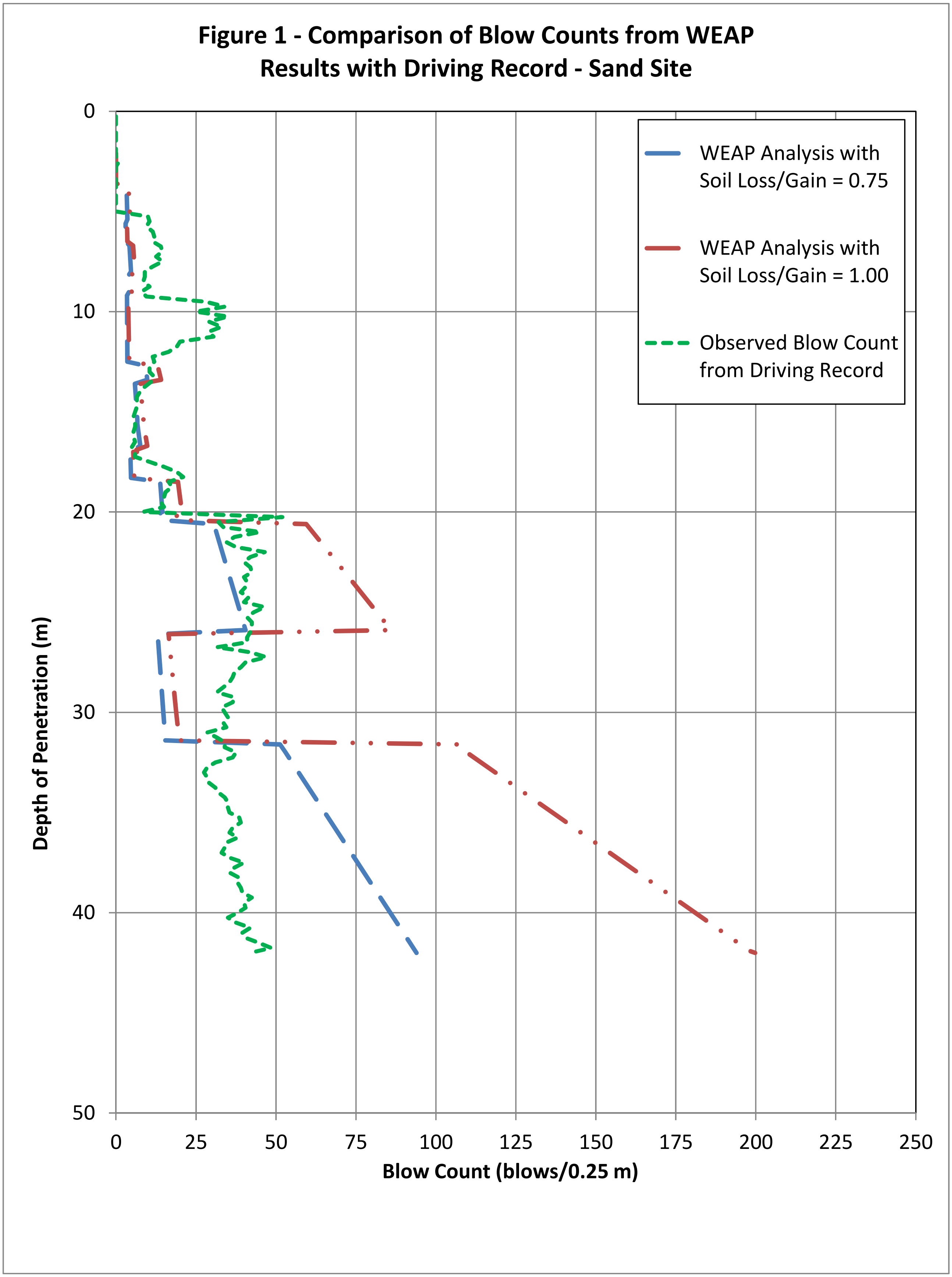
Figure 1 - Comparison of Blow Counts from WEAP Results with Driving Record - Sand Site
WEAP Analysis with Soil Loss/Gain = 0.75
WEAP Analysis with Soil Loss/Gain = 1.00
Observed Blow Count from Driving Record
Depth of Penetration (m)
Blow Count (blows/0.25 m)
0
10
20
30
40
50
0
25
50
75
100
125
150
175
200
225
250

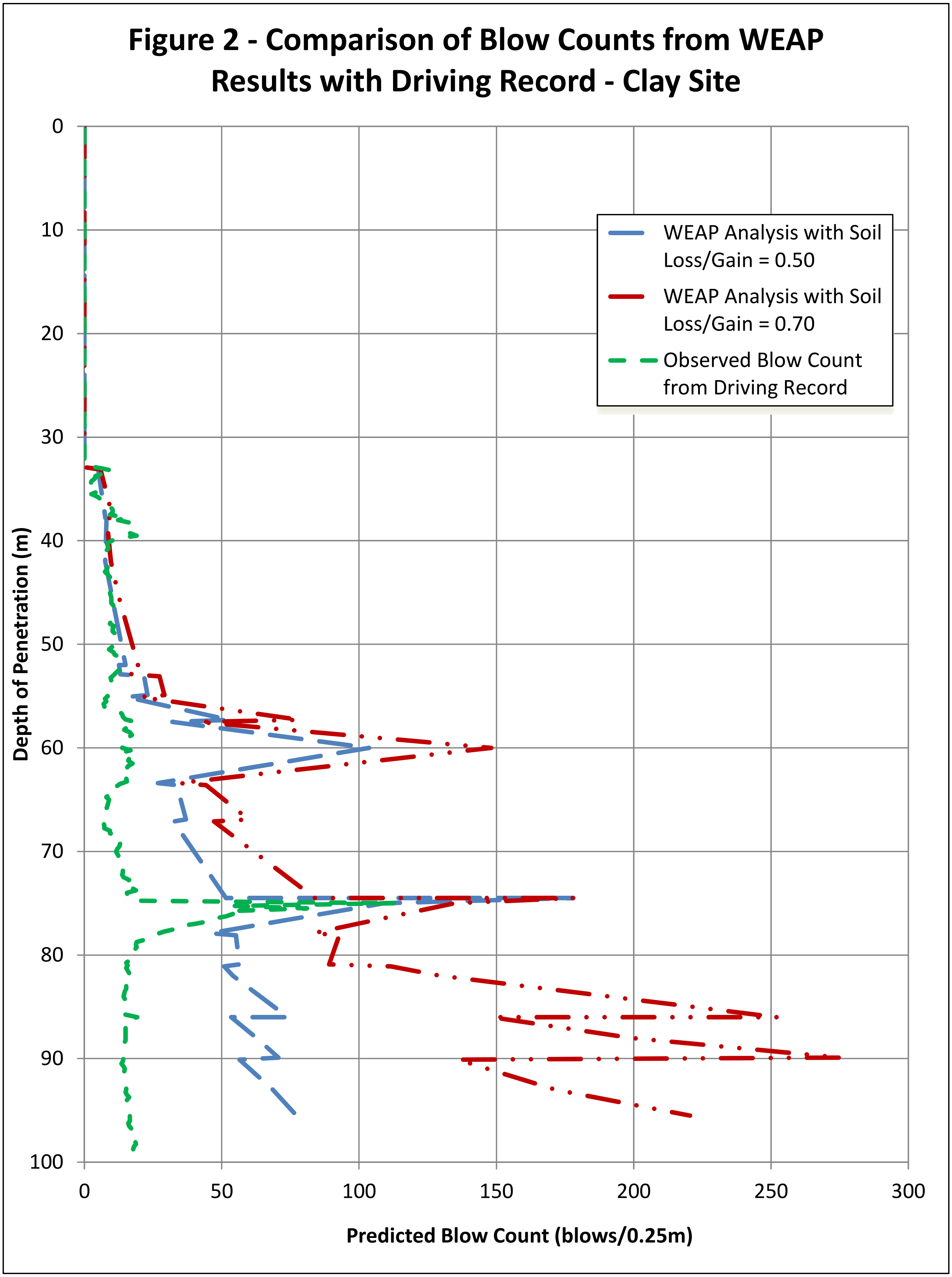
Figure 2 - Comparison of Blow Counts from WEAP Results with Driving Record - Clay Site
WEAP Analysis with Soil Loss/Gain = 0.50
WEAP Analysis with Soil Loss/Gain = 0.70
Observed Blow Count from Driving Record
Depth of Penetration (m)
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
Predicted Blow Count (blows/0.25m)

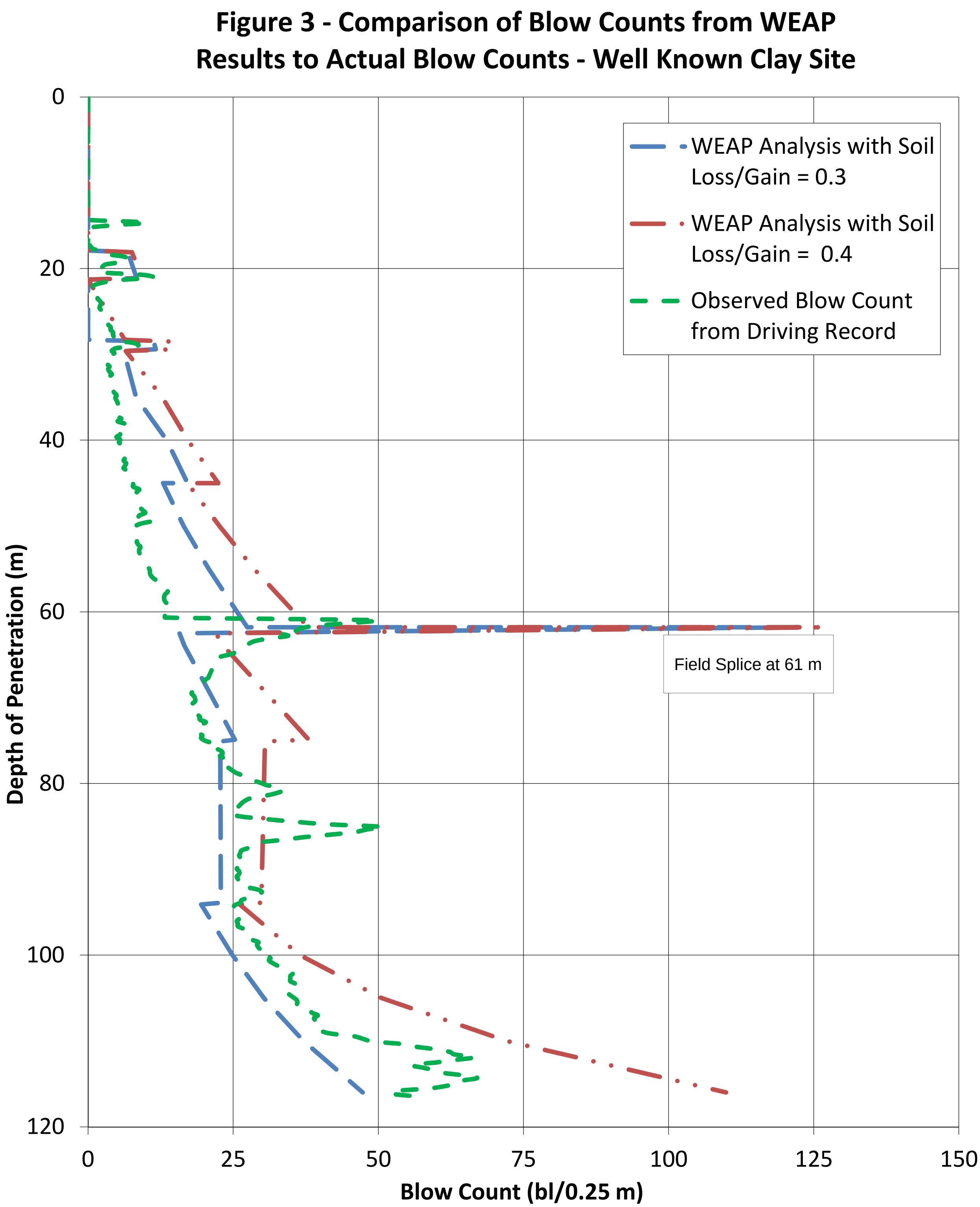
Figure 3 - Comparison of Blow Counts from WEAP
Results to Actual Blow Counts - Well Known Clay Site
WEAP Analysis with Soil Loss/Gain = 0.3
WEAP Analysis with Soil Loss/Gain = 0.4
Observed Blow Count from Driving Record
Field Splice at 61 m
Depth of Penetration (m)
Blow Count (bl/0.25 m)
0
20
40
60
80
100
120
0
25
50
75
100
125
150

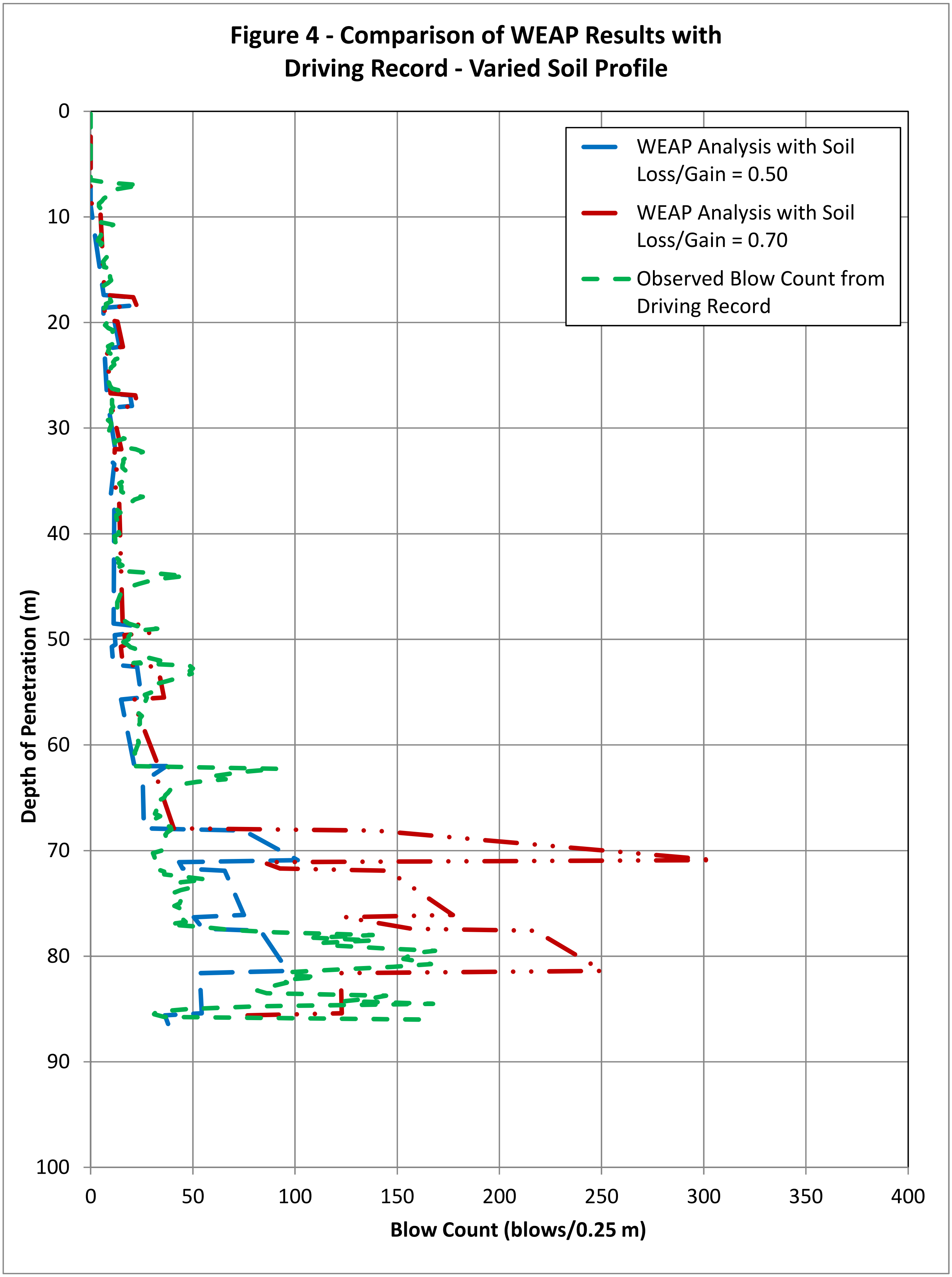

Figure 4 - Comparison of WEAP Results with
Driving Record - Varied Soil Profile
WEAP Analysis with Soil Loss/Gain = 0.50
WEAP Analysis with Soil Loss/Gain = 0.70
Observed Blow Count from Driving Record
Depth of Penetration (m)
Blow Count (blows/0.25 m)
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400