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Combining static pile design and dynamic installation analysis in GRLWEAP

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ABSTRACT: Wave equation simulations of pile installations by impact driving have become an important part of the pile design process in many countries. In its traditional form, the wave equation approach replaces a dynamic formula, i.e. it leads to a bearing graph which is a relationship between pile bearing capacity and blow count. In addition, the simulation calculates realistic dynamic pile stresses. GRLWEAP, probably the most widely used wave equation program, also enables the user to calculate blow count stresses vs depth in a so-called driveability analysis. This procedure requires soil resistance vs depth input which thus far had to be precalculated in a separate analysis either manually or using another computer program. The program has now been expanded to include this pre-analysis. This paper presents the method itself, its correlation with static tests and another similar method. It also briefly discusses limitations and special considerations that make this method somewhat different from other static pile analysis formulas..

1 INTRODUCTION

As originally proposed by Smith (1960) the wave equation method generates a so-called bearing graph which is a relationship between pile bearing capacity and blow count. In addition, maximum tension and compression pile stresses are usually plotted. These results are well suited for the selection of hammers, hammer performance parameters and cushions for a given pile type and soil condition.

The GRLWEAP program (Goble et al. 1999) not only calculates bearing graphs but also offers a convenient method for predicting the blow count as a function of pile penetration. However, for meaningful results, this so-called driveability analysis requires a much more detailed soil parameter input than the original approach. The required static and dynamic soil resistance input parameters should reflect the various layers that the pile penetrates. For realistically calculated blow counts vs depth, it is necessary that these soil parameters are determined with as much accuracy as possible based on quality geotechnical information. From such improved analysis, it is possible to obtain the best estimate of both the total number of blows required to install the pile, and the total installation time. In addition, the GRLWEAP program allows for consideration of different pile lengths during installation and hammer and pile cushion parameters, which may be adjusted as driving resistance varies to most closely model the pile installation process.

For user-friendliness the GRLWEAP program has now been expanded to accept soil strength and soil-type data input. Based on this information, an automated static formula approach has been devised which estimates the static soil resistance parameters and calculates a load-movement curve at the design depth. The program automatically selects the dynamic soil resistance parameters including resistance loss factors, which relate static resistance to driving to static long term capacity values. The complete GRLWEAP driveability approach is described in this paper and its benefits and shortcomings are discussed.

It has to be emphasized, however, that there is no universal approach which is fully reliable, and that the pile driveability analysis requires the local knowledge of an experienced geotechnical engineer to be most accurate. It is also evident that the quality of the prediction is a function of the quality of the soil information which is available. The method presented here should not replace the design calculation that the geotechnical normally performs for pile type selection.. Instead, GRLWEAP's analysis is an additional effort in the preparation of the driveability analysis.

2 GENERAL CONSIDERATIONS

Driven pile analysis is generally performed in two steps (Hannigan et al. 1996): an initial static analysis which is followed by a dynamic or wave equation analysis. Static analysis can be based on one of the many proposed approaches, which calculate shaft resistance and end bearing for a particular pile penetration depth. Depending on the quality of the available soil strength data, the variability of the soil properties over the site, and the realism of the calculation procedure, the reliability of the results obtained from such analyses varies significantly. Statically calculated capacities are indirect estimates based on site soil parameters estimated from the foundation investigation, not based on the additional information provided by the installation process. Because of this inherent shortcoming, engineers often prefer the use of a dynamic formula and/or wave equation analysis which provide a more direct method of capacity evaluation for each individual pile. In these approaches, blow counts from pile installation observations, plus a calculated relationship between blow count and bearing capacity (the bearing graph) is used to make a pile capacity prediction. The driveability approach can also be used prior to pile installation to predict rather than confirm the installation process. In this case, field observations of the installation process are not available to improve the reliability of the analysis procedure.

In traditional methods of static pile analysis, the requirement that the analysis provide a safe design is paramount. Efficiency of design is something for which all engineers should strive, however, it is of less importance than providing a safe structure. Conservatism in the design is provided in several ways:

1. In conservative interpretations by the engineer of the site soil strength parameters;
2. In upper limits on strength values imposed by the design method;
3. In a conservative appraisal of the data on which the design method is premised;
4. In the application of safety factors or strength reduction factors.

The last of these factors affects only the maximum structural load which can be allowed on the foundation element during its service life. However, the first three of these factors ensure that most design methods applied in practice will underestimate ultimate pile capacity.

Driveability analyses are conducted as part of the design process for a number of reasons:

1. To evaluate the ability of a given pile driving hammer to drive the pile to the nominated capacity and/or penetration;
2. To estimate the final blow count;
3. To evaluate the stresses which will be induced in the pile during the installation process.

In such an analysis, a conservative choice of soil strength parameters has an ambiguous meaning. For instance, when assessing tension stresses or the required penetration, an underestimate of soil resistances would usually produce a conservative analysis, whereas in assessing, compression stresses, an overestimate of soil resistances would generally be conservative. Assessment of the bearing capacity which can be achieved by a given hammer may not be significantly affected by the assumed distribution of resistance. Because of this ambiguity, and because the consequences of an incorrect assessment of soil resistance distribution does not have the same implications as traditional static design with regard to the safety of the structure, it is most appropriate to undertake driveability analysis using the most realistic assessment of soil strength parameters.

In the GRLWEAP static calculation method, it was therefore attempted to avoid a static resistance bias as much as possible. Again, the assessment of the pile's bearing capacity should always be done with prudent limits or reductions as dictated by experience.

Having calculated the static soil resistance based on in-situ soil strength parameters, an estimate has to be made of the static soil resistance that is actually present during pile driving. For example, pore water pressure changes in the ground during pile installation tend to change the effective stress regime and therefore the resistance acting on the pile. Unfortunately, no matter how accurately the soil exploration and static analysis was conducted, estimating the Soil Resistance to Driving (SRD) based on its static capacity may generate significant errors and although experience values are available, the selection of so-called gain-loss or capacity reduction factors is one that should always be carefully reviewed. These uncertainties are greater for sensitive soils such as marine clays and it is common practice to estimate both a lower and an upper bound SRD and calculate lower and upper bound blow counts by the wave equation.

When performing a dynamic analysis using GRLWEAP, it is not only necessary to calculate the static resistance and its distribution, additional dynamic soil resistance parameters, damping and quake, both at shaft and toe have to be estimated. Actually, GRLWEAP recommendations (Goble et al. 1999) are rather simple for standard analyses where little is known about the soil. Based on these commonly accepted rules, unless dynamic test results indicate otherwise, only the shaft damping factor is a function of soil type. Toe damping is probably independent of soil type because the dynamic resistance component at the pile toe is more a function of inertia forces caused by the soil being displaced around the pile toe than with forces of viscous flow. Similarly, shaft quakes are assumed independent of soil type with no evidence that this assumption affects the accuracy of wave equation predictions. For the toe quake, experience indicates that pile size has to be considered and, in the case of rock, the hardness of that material. With soil type and pile size known, it is therefore a simple task to assign the necessary additional parameters automatically.

3 THE GRLWEAP STATIC ANALYSIS

To estimate the ultimate static capacity of a pile, two quantities must be calculated: the shaft resistance and the toe resistance. Many methods of static capacity estimation exist for cohesionless and cohesive soils. These range from empirical methods based on SPT and CPT values (e.g. Meyerhof, 1976 and Nottingham and Schmertmann, 1975) to semi-empirical effective stress and total stress methods (e.g. Fellenius, 1991 and Tomlinson, 1980). All of these methods require that soil type and some soil strength parameter (SPT-N value, CPT cone pressure, friction angle, unconfined compressive strength, etc.) is known. Unfortunately, the methods often give no clearly defined solutions for certain ranges of soil strength parameters, because their experience base is limited.

While it is certainly desirable, and theoretically more accurate, to know as much about the geotechnical properties of a site as possible, funds allocated for soil exploration studies typically are kept to a minimum, usually in a false sense of economy. Particularly for small projects, only a few soil borings with depth, soil type and SPT N-value are available to the deep foundation designer. In such instances, a sophisticated analysis method will not add much to the quality of the prediction. In fact, there is often a wide gap between what should be known about the soil to satisfy a method's input requirements and the available data. For example, specific weight, friction angle and pile adhesion often must be known, however, the soil exploration yielded only soil type and SPT N-value. The designer therefore has to choose an empirical approach to convert soil type and SPT N-value to the required parameter, before the calculation method can be employed. This two-step approach has been automated in GRLWEAP.

GRLWEAP estimates shaft resistance based on an effective stress approach. The unit shaft resistance at a point along the pile is therefore calculated from

$$f_s = k\,\sigma_{v,mid} \tan\delta \qquad (1)$$

In Equation 1, k is the lateral earth pressure coefficient, $\sigma_{v,mid}$ is the mid-layer vertical effective stress and d is the friction angle at the soil-pile interface. The effective stress requires that the

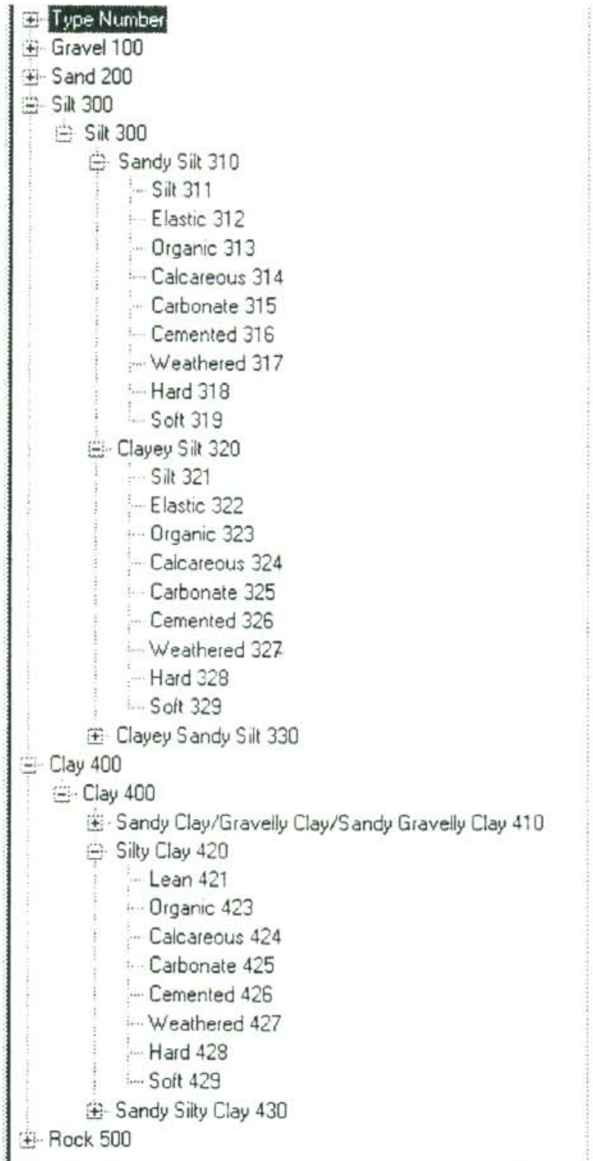

Figure 1. Partial list of soil types in GRLWEAP

buoyant weight of the soil is calculated and that requires knowledge of water table and specific weight. The depth of the water table is therefore an additional input into GRLWEAP. The specific weight (as well as the friction angle) is based on SPT –value and soil type. Thus, an extensive soil type table was developed which also serves to estimate dynamic soil resistance parameters such as quake and damping. A portion of that "click-on" table is shown in Figure 1. The table contains much more detail than necessary for a simple SPT based soil and pile analysis. However, it contains information necessary to expand the analysis methods in the future.

The unit toe resistance in kPa is estimated according to Meyerhof, 1976 using the simple empirical expression:

$$f_{toe} = \min(200N;\ 12{,}000) \qquad (2)$$

where N is the SPT N value in the strata at the bottom of the pile. Of course, it is possible to improve this very simple method in future updates and as experience is gathered with this approach.

Soil data should be entered where layers change, where the water table is encountered, or where major changes in N-values occur; also, data must be entered when the soil type changes, and at minimum intervals of 3.5 m.

As discussed, the N-value and soil type is used to estimate unit weight, friction angle (effective friction angle for clays) and horizontal stress based on correlation studies by Kulhawy et al. (1989 and 1991), Schmertmann (1975 and 1978), and Robertson and Campanella (1983). The lateral earth pressure coefficient is estimated from the horizontal stress for sands and from the effective friction angle for clays and from the diameter of the pile. This value must fall between the Rankine active and passive earth pressure coefficients.

Both calculated unit shaft resistance and end bearing values are then input into the GRLWEAP driveability analysis. Since soil type is known, the damping factor for the shaft can be automatically assigned. Toe resistance calculations from unit toe resistance also require the knowledge of an effective toe area (for open profiles such as pipes and H-piles these may be the plugged areas), which can be immediately converted to toe quake. As discussed, shaft quake and toe damping are independent of pile size and soil type.

For a particular pile depth, the static analysis method can be coupled with the static load-set curve calculation method proposed by Fleming (1992). This additional result requires estimation of the settlement characteristics of the soil. Again, soil type and SPT –values are converted to provide the necessary input. Obviously, calculation of settlements is an even more challenging task than bearing capacity prediction, particularly when only SPT information is available. These results must therefore be used with appropriate caution. A correlation study on this result had not been completed by the time this paper was finished.

4 CORRELATION WITH STATIC LOAD TESTS

Using data from the database presented by Likins et al. (1996), a correlation study was conducted on 53 cases for which static pile load test was available in a variety of soil and pile types. The proposed GRLWEAP static capacity method was used. It is noted that the predictions are automated, and thus operator independent. The ratio of predicted static failure load to actual capacity as evaluated by the Davisson offset method averaged 0.92, with a coefficient of variation of 0.31 (see Table 1). By comparison, the same data was also subjected to analysis by the SPT97 approach which is popular in the South-Eastern United States (Townsend et al. 1997), which yielded a mean of 0.81 and a coefficient of variation of 0.39. Figure 2 shows the capacity ratios of GRLWEAP and SPT97, demonstrating that the two methods show similar tendencies of underprediction or overprediction. This may be an indication of the failure of the basic soil data, primarily the SPT –value, to provide correct and sufficient soil strength information. Clearly, for the particular set of correlation cases investigated, GRLWEAP's static method is slightly less conservative than SPT97 and also less scattered (Coefficient of Variation 0.31 vs 0.39).

Table 1. Static capacity predictions divided by load test capacity (percent).

-	GRLWEAP	SPT-97
Minimum	35	28
Mean	92	81
Maximum	175	166
Standard Deviation	29	32
Coefficient of Variation	31	39

5 SUMMARY AND CONCLUSIONS

A static analysis method has been presented that has been incorporated in the dynamic wave equation analysis program GRLWEAP. The method is based on SPT –values plus an assessment of soil type. An effort has been made to make this method:

1. fully automated and therefore independent of user judgement. Covering the complete range of possible N-values and soil types.

2. Unbiased, i.e. neither conservative nor non-conservative for capacity, stress and blow count predictions.

3. Generate automatically the dynamic soil resistance parameters necessary for both bearing graph and GRLWEAP whole-installation driveability analysis.

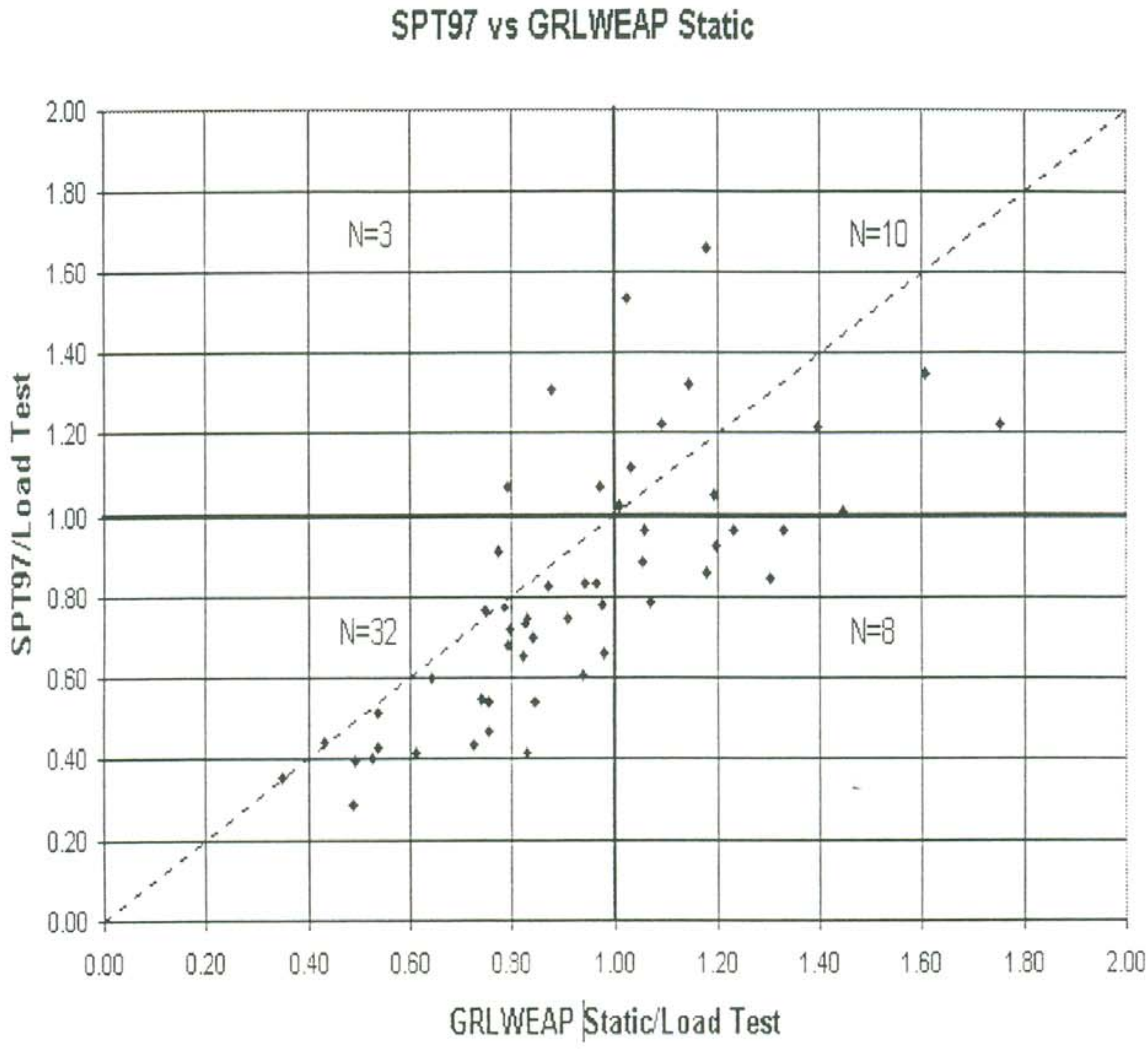

Figure 2. Comparison of GRLWEAP with SPT97 correlation.

4. Capable of calculating a prediction of pile-top load-movement for a specific pile embedment.

Results from this analysis method compare favorably with similar methods. However, the user of this approach is advised of the shortcomings inherent in any static formula approach.

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