A simplified procedure for predicting residual stresses for piles

Une méthode simplifiée pour la prévision des contraintes résiduelles dans les pieux

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SYNOPSIS: The process of impact pile driving may result in the generation of significant residual loads. The existence of these loads should have a significant effect on load transfer between the pile and the soil, which will govern the general behavior of the pile foundation. Several methods have been proposed for the evaluation of residual stresses. However, these methods are either too simplistic, or they involve incorrect assumptions. In this study, existing procedures for predicting residual stresses were evaluated. All important parameters that affect the magnitude and distribution of such stresses were examined. Based on available wave equation techniques, a simplified prediction procedure for piles driven into cohesionless soils was developed. The procedure is given in terms of easy-to-use charts and equations, allowing rapid estimates to be made. Comparisons with actual measurements, indicate that this procedure is reliable and useful.

INTRODUCTION

Residual stresses in driven piles have significant effects on all aspects of the pile foundation behavior. The generation of residual loads is a function of the load-unload-reload mechanisms of pile installation. This phenomenon was explained in detail by Holloway, et al. (1975), Vesic (1977) and Briaud and Tucker (1984).

Figure 1 shows typical residual load and stress distributions for selected pile parameters. Analyses performed by the authors, and also by Holloway, et al. (1975) and by Hery (1983), as well as measurements reported by Hunter and Davisson (1969) and Rieke and Crowser (1987), indicate that the shape of these curves is typical of driven piles in sand, irrespective of the variables involved in the problem. In order to determine these distributions, the shape factors b_r, b_c and b_m, defined on Figure 1, should be known, provided that Q_{PR} is known. The prediction of Q_{PR} in terms of the pile point capacity (Q_p), as well as the other shape factors, is the major contribution of this paper.

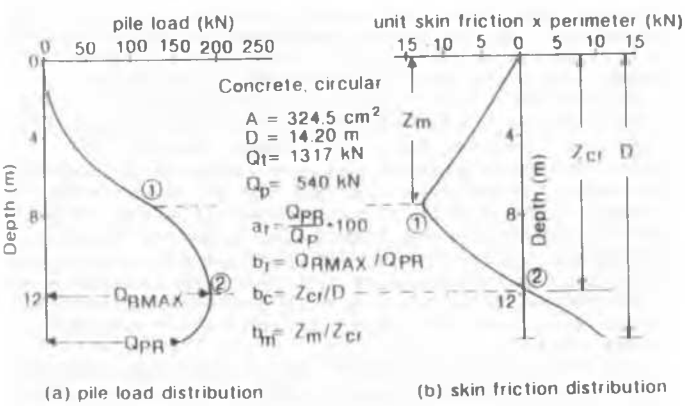

Figure 1. Typical Residual Pile Load and Skin Friction Distributions

Although the existence of residual stresses does not affect the total pile capacity, it could significantly alter the load transfer mechanism which affects the working loads at particular deformation levels (Vesic, 1977); the single pile and the pile group settlements (Leonards, 1972); and pile stresses, driveability, etc. (Hery, 1983 and Darrag, 1987). On the other hand, load test results may be incorrectly interpreted or extrapolated if the actual load transfer is not known.

CURRENT METHODS FOR RESIDUAL STRESS EVALUATION

Several methods have been proposed for the evaluation of residual stresses: direct measurements (Rieke and Crowser, 1987); indirect evaluation using compression/tension load testing sequences (Hunter and Davisson, 1969); wave equation analyses (Holloway, et al., 1975; Hery, 1983); boundary element analyses (Poulos, 1987); and correlations with the Standard Penetration Test (Briaud and Tucker, 1984).

Direct measurements involve zeroing the pile instrumentation prior to driving, which is not routinely done in practice. On the other hand, the Hunter-Davisson procedure assumes that tension loading results in no residual stresses, and that the distribution of shaft friction in loading is the same as for the case of unloading. The wave equation analyses have proven to provide excellent predictions of residual stresses (e.g. Hery, 1983; using the computer code CUWEAP). The use of boundary element techniques (Poulos, 1987) also provided reasonable results, with some limitations (Leonards and Darrag, 1988). However, both wave equation and boundary element analyses require the availability of certain computer codes. Such an approach may not be very practical, especially when rapid predictions are needed. Correlations with the Standard Penetration Test (Briaud and Tucker, 1984) provide such quick estimates, but they use too many simplifying assumptions, do not consider certain key parameters, and involve significant scatter (Darrag, 1987). For the above reasons, the authors felt the need to develop a simple, and yet accurate procedure to predict residual driving stresses.

FACTORS AFFECTING MAGNITUDE AND DISTRIBUTION OF RESIDUAL STRESSES

Review of current procedures for residual stress prediction indicates that the wave equation method is the only technique capable of incorporating all important factors. The computer code CUWEAP developed by Hery (1983), based on the original WEAP program (Goble and Rausche, 1976), is probably the most versatile wave equation program available (Darrag, 1987). For this reason, the authors utilized CUWEAP to examine the effects of various parameters on residual stresses. Parametric studies were conducted for piles driven into cohesionless soils only. The magnitude of residual stresses was represented by the residual stress percent, a_r, defined as:

$$a_r = \frac{\text{point residual load}(Q_{PR})}{\text{pile point capacity}(Q_p)} \times 100 \qquad (1)$$

1. Effect of the Driving System and Elements

The authors found that the driving system and elements (hammer, cushions, caps, etc.) have very slight effects on the magnitude and distribution of residual stresses. Since residual stresses are caused by the load/rebound cycles occurring during driving, they should be mainly affected by the relative pile-soil stiffness.

2. Effect of Total Pile Capacity and its Distribution

Parametric studies indicated that as the total pile capacity increases, with other parameters held constant, the residual point load increases. This is because the pile elastic rebound, and hence the negative friction that is balanced by the upward residual forces, increases.

The distribution of soil resistance (i.e., tip and shaft capacities) also has a very important effect on residual stresses. In order to quantify this effect, the skin friction percent "m" is defined as:

$$m = \frac{\text{shaft capacity }(Q_s)}{\text{total capacity }(Q_t)} \times 100 \qquad (2)$$

The value of Q_s is the "true" shaft friction, without including residual stresses. For the same pile capacity and dimensions, a_r increases as m increases. It should be noted that if the pile were entirely end bearing (m = 0), no residual stresses would be generated.

3. Effect of Pile Dimensions and Material

Residual stresses are greatly affected by the pile stiffness, represented by its length, cross section and material. For a given soil condition, residual stresses increase as the pile stiffness decreases. Therefore, residual stresses were found to increase as the pile length (D) increases, the cross sectional area (A) decreases and the pile modulus (E_p) decreases.

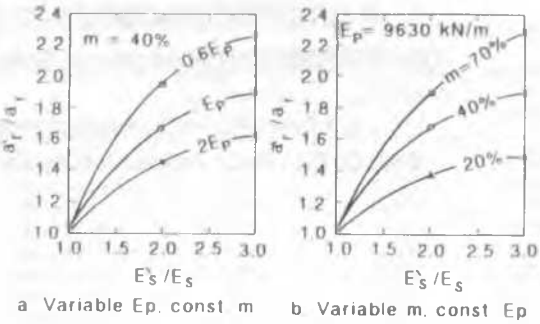

Figure 2. Effect of Interface Stiffness on Residual Stress Percent

4. Effect of Interface Stiffness

Analyses conducted by the authors indicate that residual stresses increase as the pile-soil interface stiffness (E_s) increases. This increase was found to be a function of the skin friction percent (m) and the pile modulus (E_p). Figure 2 shows these effects (the ratio a_r/a_r^p corresponds to E_s'/E_s, E_s' being the higher modulus). An increase in (E_s) for driven piles is usually expected due to densification and prestressing caused by driving the pile. The distribution of residual forces is also affected by increase in E_s. As E_s increases, the point defined at Z_{cr} (Figure 1), becomes closer to the pile tip.

On the other hand, Leonards and Darrag (1988) showed that residual stresses are also affected by a higher soil modulus at the pile tip than along the shaft (due to further densification and prestressing at the pile tip), and by a higher modulus in unloading than in loading.

SUGGESTED PROCEDURE FOR RESIDUAL STRESS PREDICTION

Darrag (1987) reported that the wave equation analysis is the only analytical procedure that allows the accommodation of all important factors contributing to residual stresses. Therefore, the writers utilized the CUWEAP wave equation program (Hery, 1983) to develop a simplified procedure for predicting residual stress magnitude and distributions. The authors performed more than 250 CUWEAP computer runs to develop a set of charts for predicting the residual stress percent (a_r). Two sets of charts were developed for concrete and steel piles, respectively. For each set, the parameters used were the pile capacity (Q_t), the pile length (D) and its diameter (d). For these charts, the skin friction percent (m) was arbitrarily fixed at 40%, the effect of which can be corrected later. The effect of interface stiffness could be introduced using Figure 2. A more accurate representation of the distribution of soil moduli was followed, as described by Leonards and Darrag (1988). All of the above analyses were conducted for piles driven into cohesionless soils.

Figures 3 and 4 present the prediction charts for a_r, in the case of m = 40% for concrete and steel piles, respectively. For m values other than 40%, a_r should be multiplied by a factor β_m such that:

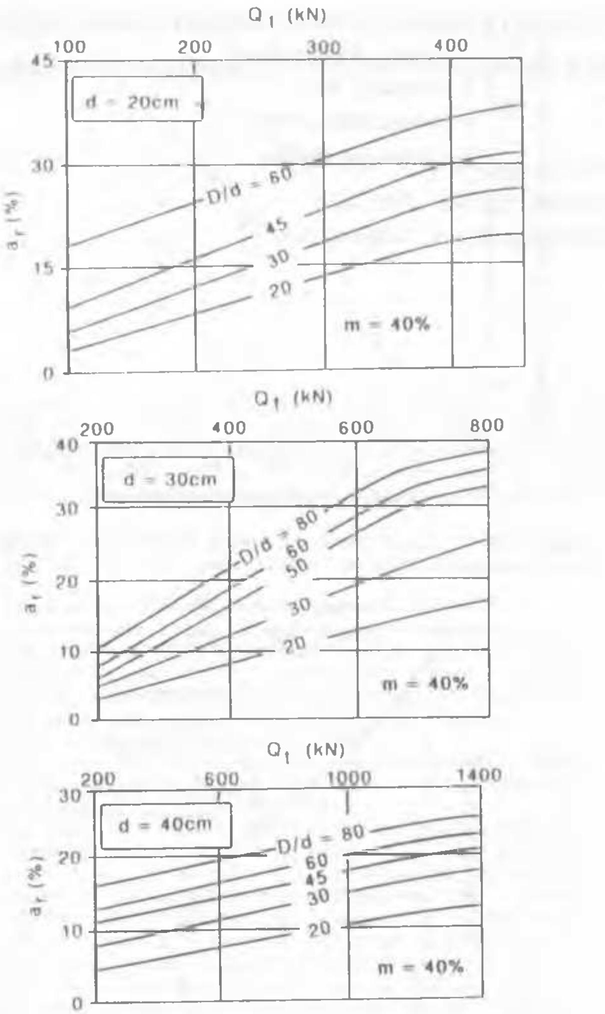

Figure 3. Prediction Charts for a_r for Concrete Piles - m = 40%

$$(a_r)_{m\%} = (a_r)_{40\%} * \beta_m \qquad (3)$$

β_m is defined such that:

$$\text{for } a_m < 55\% \quad \beta_m = 0.025\, m \qquad (4)$$

$$\text{for } m > 55\% \quad \beta_m = 1.375 + 0.01(m-55) \qquad (5)$$

The charts given in Figures 3 and 4 were prepared based on an assumed normally consolidated initial condition. For an initially overconsolidated sand, the interface stiffness modulus is higher than for the NC case. To take this effect into account, the charts previously given in Figure 2 should be used to adjust the a_r values.

In the case when the total pile capacities and their components are known (or reliably estimated), Figures 3, 4 (and 2 if necessary) can be easily used to predict a_r. However, when the results of a load test need to be adjusted for the effect of residual stresses, the skin friction percent (m) that is obtained from the load test represents the "measured" value of

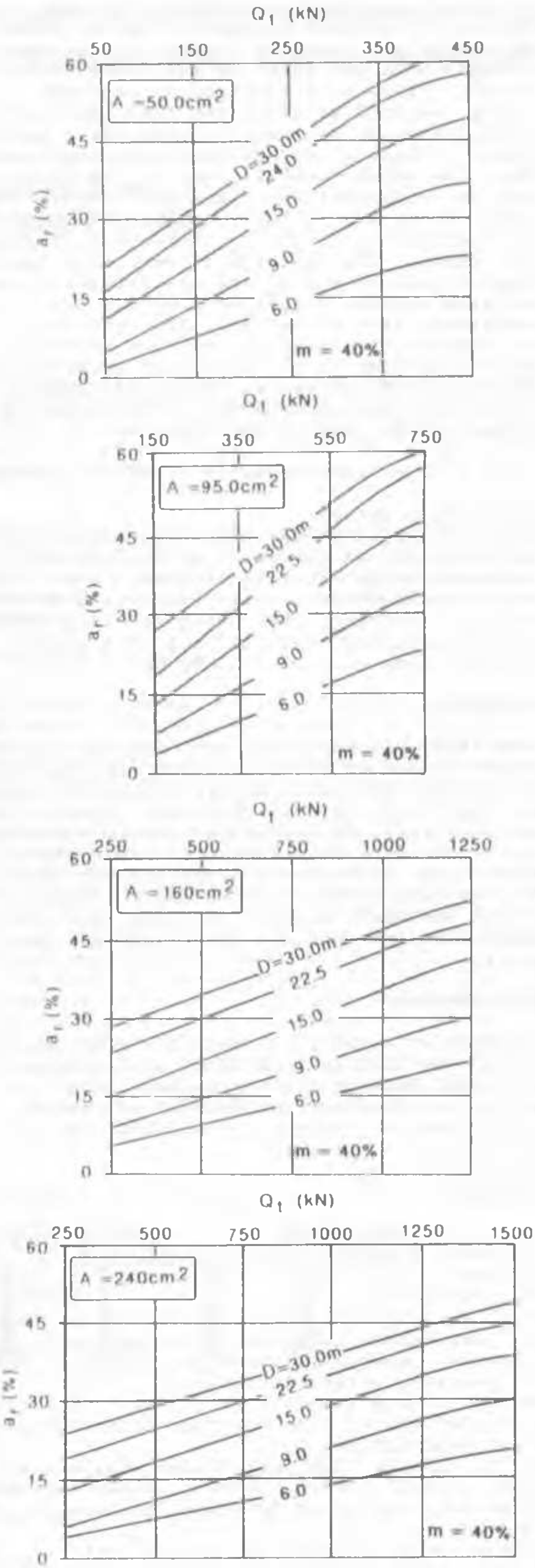

Figure 4. Prediction Charts for a_r for Steel Piles - m = 40%

shaft friction, which was affected by the existence of residual stresses. On the other hand, values of m used as initial conditions in the CUWEAP code are based on the "true" skin friction. Since m is affected by residual stresses, as well as affecting them, an iterative procedure is necessary to achieve a good estimate of both m and a_r.

After the point residual load Q_{pr} is determined, the distribution of residual loads along the pile shaft may be fully determined if the shape factors b_r, b_c and b_m, defined in Figure 1, are known. The analysis of available data indicated that b_r and b_m are approximately constant with average values of 1.05 and 0.6, respectively (for NC soils). The ratio b_c, which defines the critical depth at which the residual friction is reversed from negative to positive, was found to vary with pile length (D) and skin friction percent (m). The following equation can be used to calculate b_c:

$$(b_c) = [1 - 0.004(m-40)] * [0.904-0.0015D] \quad (6)$$

where D is in meters.

Figure 5 compares the authors' predictions for a_r with actual measurements, as well as with determinations by other techniques. The authors' predictions compare well with measurements. In addition, prediction of the residual force distribution compares well with actual measurements as shown in Figure 6.

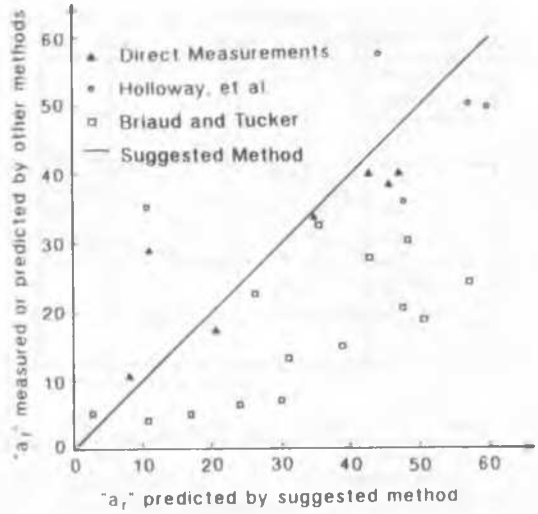

Figure 5. Comparison between Different Methods for Residual Stress Prediction

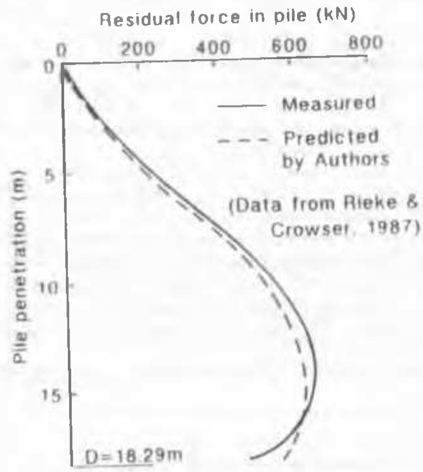

Figure 6. Comparison between Predicted and Measured Residual Force Distribution

CONCLUSIONS

A simplified procedure was developed to predict residual stress magnitude and distribution for piles driven into cohesionless soils. This procedure was based on available wave equation analyses that take all important factors affecting residual stresses into account. Predictions compared well with actual measurements. More effort is required to provide quality measurements of residual stresses to allow additional comparisons with this and other proposed procedures.

ACKNOWLEDGEMENT

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