Influence of residual forces on pile driveability

G.G. GOBLE
Ph. D., Professor, University of Colorado, Boulder, Colorado
P. HERY
M.S. (CE), Private, French Army

INTRODUCTION

The existance of shear forces at the pile-soil interface of a pile subjected to no load has been known for some time (ref. 1,2,-3). Originally the existence of this phenomenon, known as residual forces, was proven by the analysis of test results on instrumented load test piles. Holloway et al. (ref. 4) investigated residual forces induced during pile driving and he developed a computer program that performed a wave equation analysis including residual pile-soil forces. He was primarily concerned with improving the understanding of the influence of residual forces on static pile behavior. One interesting result of the study was the implication that the critical depth phenomenon in sands was just the manifestation of the presence of residual forces. Holloway examined field results and correlated those data with capacities obtained from the analysis. He did not emphasize the effect on pile driveability of the residual forces although he noted that the residual force analysis predicted considerably higher capacities at high blow counts for offshore piles (ref. 5).

When the WEAP program appeared in 1976 (ref. 6) its use was actively promoted by the United States Department of Transportation, Federal Highway Administration, the sponsor of the program development. Shortly after the resulting increased program usage wave equation analysis came under heavy criticism from some pile suppliers. They maintained that the program consistently underpredicted the strength of certain pile types. In 1978 load test data, collected by the Union Metal Company, was analyzed by the Piling Research Laboratory at the University of Colorado. In a report submitted to the Federal Highway Administration (ref. 7) it was concluded that, based on the data supplied by Union Metal, their claims seemed to be supported. Finally, in 1982 the Union Metal Company provided a research grant to The University of Colorado to modify WEAP to include a residual force analysis and to evaluate the influence of residual forces on pile driveability.

The algorithm used by Holloway essentially continued the dynamic analysis much further in time until the kinetic energy contained in the pile had become small. This lack of static equilibrium was further converted to approach static equilibrium.

After completion of the dynamic analysis of one hammer blow the final soil spring deformations were used as the initial conditions for a subsequent hammer blow. This operation was repeated until some sort of convergence criteria was satisfied. The basic nature of this "multiple blow: analysis causes a large increase in computer time since the convergence may be quite slow. Generally at least three or four cycles were required and occasionally many more.

MODIFIED WEAP ALGORITHM

The WEAP program uses the basic Smith model (ref. 8) to represent the pile, soil and driving system. Since this approach has been used for an extended period of time and has been discussed extensively it will not be described in detail here. The pile and driving system is modeled as a series of discrete masses and springs having realistic properties. The soil is represented by a set of elasto-plastic springs with linear dashpots. Other more elaborate soil models have been used but they have not been generally accepted due to the difficulty in obtaining the necessary constants.

The modified WEAP (CUWEAP) follows the same general concept as that suggested by Holloway. That is, successive impacts are analyzed, each one using the permanent displacements from the previous analysis. The dynamic analysis was allowed to run until all element soil forces were less than the ultimate static soil resistance. At this point both spring forces and velocities might be quite large. From another viewpoint substantial energy both potential and kinetic may be present in the pile. In the next analysis step a static analysis is performed on the displaced poistions at the end of the dynamic analysis and static equilibrium is imposed. Due to the connectivity of the pile-soil model the static analysis requires very little running time. Again, from an energy viewpoint, the kinetic energy has been simply discarded and the minimum potential energy position is obtained.

Consider the analysis algorithm in more detail. At the point where static analysis is considered there are four forces acting on a pile element, the force due to the spring deformation above the element, the force due to the spring deformation below the element, the soil spring force and the element weight as illustrated in Figure 1. If equilibrium conditions are imposed

$$gm(I) + F(I) + F(I+1) = R_s(I) \qquad [1]$$

where gm(I) is the weight of the Ith element, F is the pile spring at the indicated location and $R_s(I)$ is the force acting from the Ith soil spring.

If, at the end of the dynamic analysis, the displacement of the pile elements from their initial at rest position, prior to the beginning of the dynamic analysis, is U_0 (I) and the static soil resistance is $R_S(I)$, then at the end of the static analysis the soil resistance is

$$R_s(I) = R_0(I) - k_s(I)\ u\ [u_o(I)-u(I)] \qquad [2]$$

where k_S is the soil spring stiffness, u is the displacement of the element for static equilibrium, and R_0 is the soil spring force at the beginning of the static analysis. Since the soil springs are elasto-plastic a set of conditions must be verified on $R_0(I)$:

For the skin friction springs

$$R_s(I) \leq R_u(I),\ I = 1,N \qquad [3]$$

and for the point resistance

$$0 \leq R_s(N+1) \leq R_u\ (N+1). \qquad [4]$$

Now the equilibrium equations can be written

$$k(I)u(I-1) - [k(I)+k(I+1)+k_s(I)]u(I) + k(I+1)u(I+1)$$
$$= R_0(I) + gm(I) - k_s(I)U_0(I) \qquad [5]$$

For the top and bottom elements of the pile the left side of the equation is reduced by the absence of one force.

These equations are conveniently written in matrix form producing a symmetrically banded stiffness matrix only three elements wide. It can be stored in a two column matrix to reduce storage requirements. Thus the set of equations take on the general form

$$[K(I,J)]\ [U(I)] = R\ [I] \qquad [6]$$

Efficient routines are available for the solution of this set of equations.

After the solution of the equations element displacements, u, are obtained. From these displacements soil forces must be determined and checked against the inequality conditions of [3] and [4]. If they are violated the equilibrium equations are appropriately modified and solved again. This process is repeated until no additional soil springs conditions are violated.

Experience with the analysis showed that four conditions could occur as illustrated in Figure 2. It was found that all element displacements are reduced in the static phase of the analysis. Thus, the possibilities are

(1) The soil spring had not become plastic and it unloaded to a lower displacement level (Fig. 2a).

(2) The soil spring was at the load level R_u and it unloaded along the assumed unloading line (Fig. 2b).

(3) The soil spring unloaded to the point where it became plastic in the negative direction and then it unloaded further at that force level (Fig. 2c).

(4) The soil spring was at the $-R_u$ force level and it continued to experience further reductions in displacement at this load level (Fig. 2d). This condition was common between two cycles of static analysis.

The total algorithm then performs the following functions:

(1) Impact dynamic analysis is performed using the appropriate soil spring forces. For the first hammer blow in a bearing graph development the initial soil springs are assumed to have zero displacements. At subsequent points on the bearing graph when the total ultimate force is incremented the soil spring forces at the end of the previous load level are assumed.

(2) When all element displacements have stopped increasing or are elastic the dynamic analysis is stopped.

(3) The static analysis is performed on the displacement pattern at the end of the dynamic analysis.

(4) The soil forces are checked against the limiting soil forces and are corrected as required and the analysis repeated.

This cycle is repeated using the soil spring displacements from step (4) and the entire process is continued until convergence occurs. At convergence the final incremental displacements of all elements should be the same. In this analysis the criterion

$$\frac{\left|u_{tip} - u_{top}\right|}{u_{tip}} \le 0.01 \qquad [7]$$

was used. The subscripts refer to the elements of the pile.

For some cases convergence could be quite slow. This was the case for high blow counts with axially flexible piles and most of the resistance distributed as shaft friction. To reduce the required computer time for diesel hammers the stroke and the residual forces were converged together. Further time saving resulted from using the solution of the previous load level as a starting point. With the solution of the previous resistance level as an initial condition usually no more than three analyses were required.

SAMPLE RESULTS

Some simple examples will be presented to illustrate the influence of the residual force analysis. In Figure 3 the force-displacement relationship is shown for the tip element. The displacement at the end of successive dynamic analyses and the associated static analysis position is shown for ten cycles of dynamic and static analyses. In this case the resistance is dominantly skin resistance and it is uniformly distributed. The soil springs were all unloaded at the beginning of the analysis. Note that the tip element only reaches the plastic condition at the seventh cycle. The convergence criteria is reached on the eighth cycle. At this stage the soil springs at the top part of the pile are all plastic in the negative direction.

The results of two test cases are given to illustrate the influence of residual stresses in driveability analyses with both air/steam and diesel hammers. It should be noted that these test cases were selected to examine the analysis process not to represent particular realistic examples. The hearing Graphs are given in Figure 4 and 5.

CONCLUSIONS

The modifications made to WEAP have produced an efficient analysis system including the effect of residual forces. So far as can be determined this new analysis seems to be good representation of real conditions encountered during impact driving. The following conclusions can be drawn from the results of studies performed with the program:

(1) For steel piles the use of an analysis of this type is absolutely necessary for blow counts greater than about 40 blows per foot if the pile has substantial skin resistance. For blow counts above 200 blows per foot the difference in capacity prediction may be as much as 40% between residual and non-residual analyses. This difference increase with higher blow counts.

(2) It has been noted that dynamic analyses tend to underpredict capacities for high blow counts. This problem is partially satisfied by the residual force analysis.

(3) Substantially higher driving stresses are induced than would be determined by the usual analysis, particularly for steel piles. Therefore, high strength steels can be effectively used for these cases.

ACKNOWLEDGEMENT

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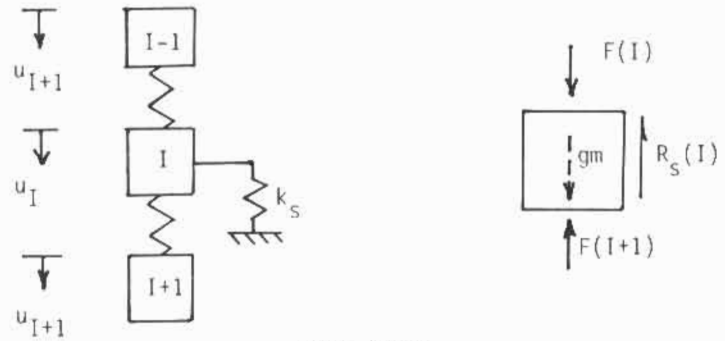
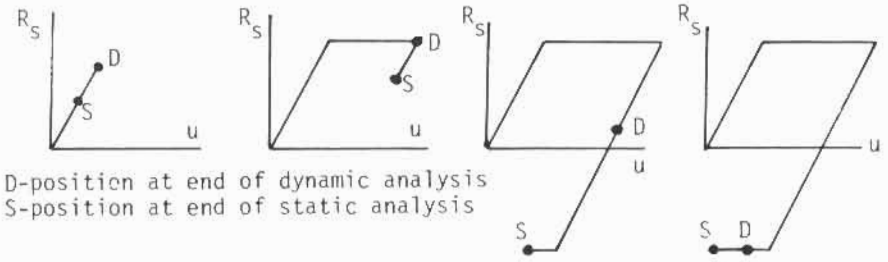


PILE MODEL

Figure 1

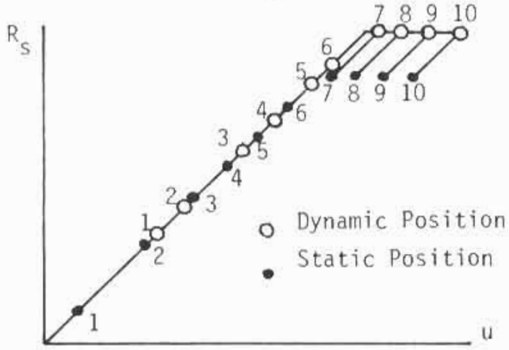


D-position at end of dynamic analysis
S-position at end of static analysis

(a) (b) (c) (d)

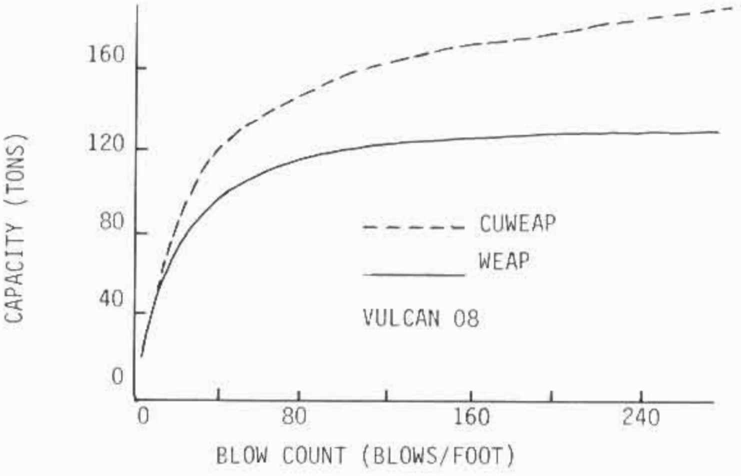
NONLINEAR LIMITATIONS

Figure 2



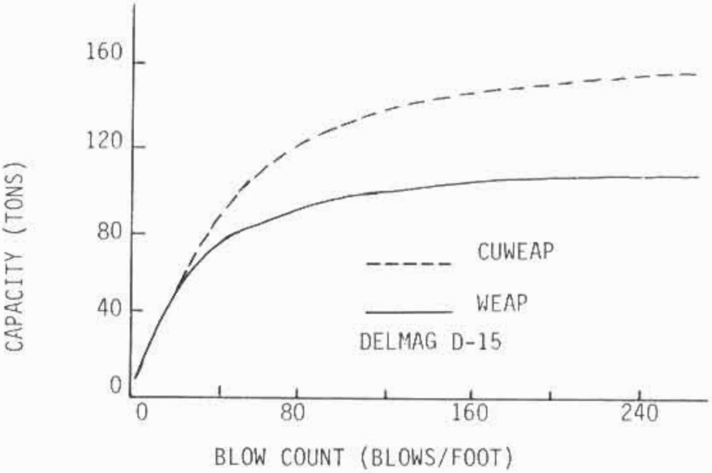
EXAMPLE OF TIP ELEMENT DISPLACEMENT FOR SUCCESSIVE DYNAMIC-STATIC ANALYSIS CYCLES

Figure 3



TEST EXAMPLE No. 1 (AIR/STREAM HAMMER)

Figure 4



TEST EXAMPLE No. 2 (DIESEL)

Figure 5

EXAMPLE DATA

Pile-Steel, area 7.7 in^2 (496 mm^2), length 100 ft(30.5m)
Soil-100% skin friction, uniform distribution, quake 0.1 in(2.5mm)