LOAD TRANSFER IN PILES DURING LOAD REVERSALS

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Reprinted from Proceedings of 10th Asian Regional Conference
On Soil Mechanics and Foundation Engineering
Beijing, China
August 29~September 2, 1995, pp.207-210

Load Transfer in Piles during Load Reversals

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SYNOPSIS Introduced herein is a procedure for computing the load-displacement relationships for piles with load reversals by using the concept of backbone curves. Once the backbone curves for a pile are established, the load-transfer curves for reversed loads can be established by nonlinear mapping using the procedures described herein. The method provides the potential of analyzing piles involving multiple load cycles, and effects of negative skin friction.

INTRODUCTION

The use of load-transfer curves for computing displacements of piles due to axial loads (Coyle and Reese, 1966) has gained popularity in recent years. It has the merit that the load transfer mechanism along the entire pile at different load levels can be fully appreciated.

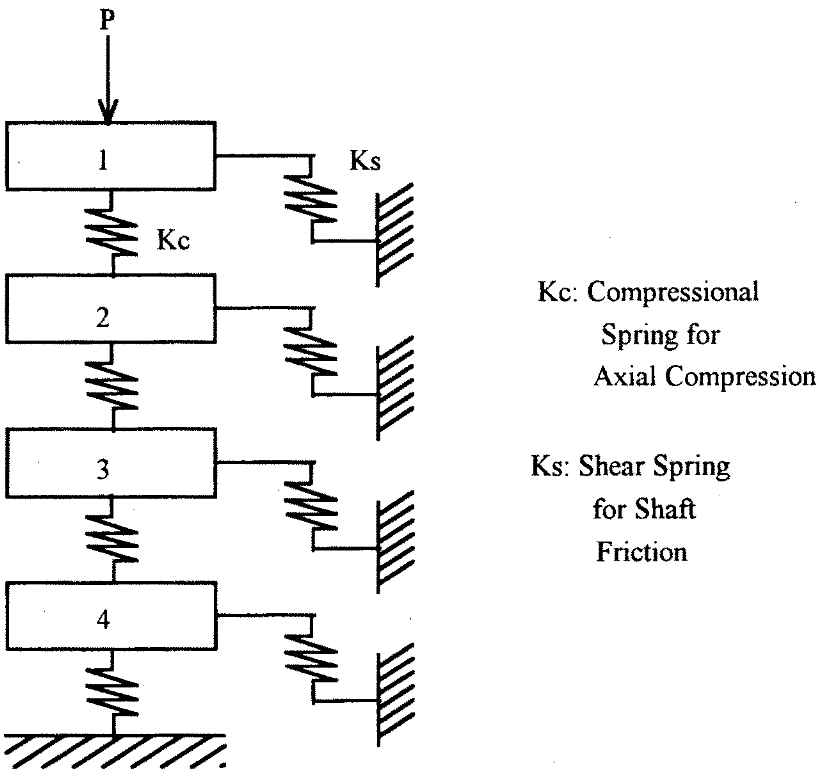


Fig. 1 Soil Spring Model for Pile Analyses

Figure 1 shows a model commonly used to analyze the behavior of piles subjected to axial loads. A pile is discretized into elements and the compression of each element is simulated by a compressional spring, usually with linear behavior, linking adjoining elements. Soils surrounding the pile are simulated by a series of shear springs. Both the frictional resistance, τ, developed along the shaft and the tip resistance, p, developed at the toe of the pile can be expressed as nonlinear functions of relative displacements between the pile and the far-field soils, d , as follows :

$$q = f(\delta) \qquad (1)$$

where q = soil resistance mobilized, representing either τ or p. Normally the above equation is written in a normalized form that:

$$\frac{q}{q_{max}} = f(\frac{\delta}{\delta_{max}}) \qquad (2)$$

in which d_{max} is the relative displacement at which the soil resistance reaches its ultimate value of q_{max}.

The displacements of the pile are obtained by solving simultaneous equations, of which each represents force-equilibrium at a particular node, i.e., the connection between two adjoining elements. The nonlinearity of soil springs is accounted for by using an iterative procedure till the results converge to a prescribed tolerance.

So far, to the best knowledge of the authors, the use of the above-mentioned procedure is limited to loading. Very few studies, if any, have been carried out for examining the load transfer mechanism during unloading and reloading which are important for structures subjected to repeated loading/unloading cycles such as wind forces, wave actions, traffic loads, etc. Introduced herein is a procedure for establishing the load transfer curves for unloading and reloading by using the concept of backbone curves.

SHAFT FRICTION

Loading tests have become a routine in projects involving load bearing piles and more and more test piles are instrumented for studying the load transfer mechanism. The axial loads at different levels in a pile can be determined through measurements of axial strains using strain gages. The difference in axial loads at two levels provides the total shaft friction mobilized and the unit shaft resistance for the corresponding section of pile shaft can be computed accordingly. The average relative displacement between the pile shaft and the surrounding soils for the same pile section can be calculated from the pile head displacement and the elastic shortening (or lengthening) deduced from the measurements of axial strains. Alternatively, the displacements at various levels can also be obtained by using extensometers. The load transfer curves, which represent the relationships between the mobilized soil resistance and the relative shaft displacement can readily be generated.

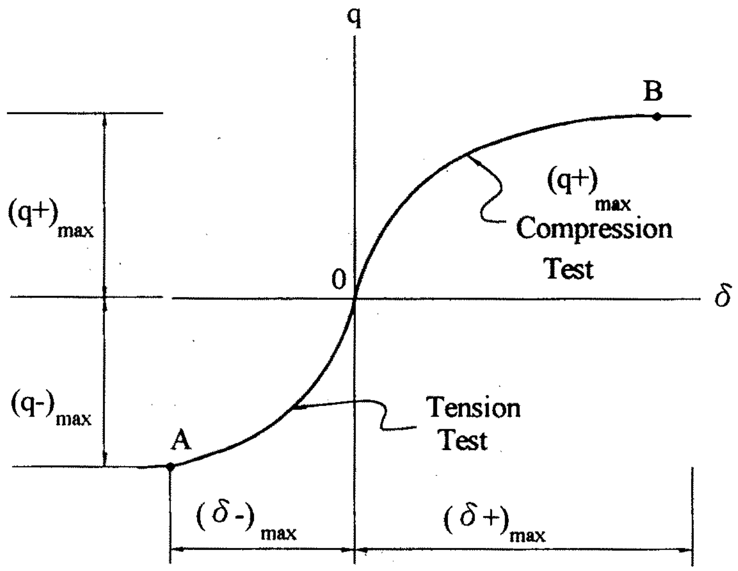


Fig. 2 Idealized Backbone Curve

Backbone Curves

Fig. 2 shows an idealized load transfer curve for shaft frictions on piles with its two ends, A and B, representing the limits beyond which the shaft friction will remain constant regardless of the displacement of the pile.

Generally speaking, shaft frictions in a tension test, i.e., negative frictions, are likely to be 80% to 100% of those in the compression test, i.e., positive frictions, on the same pile. The difference is not a major point to be addressed herein. For simplicity it is assumed that positive and negative frictions are practically equal.

Shaft frictions generally increase sharply in the initial stage and tend to flatten out as the loads increase. For loose sands, the shearing resistance will usually remain at its peak value even at very-large strains; while for clays, particularly sensitive clays, and dense sands, the shearing resistance may drop once the ultimate strength is mobilized.

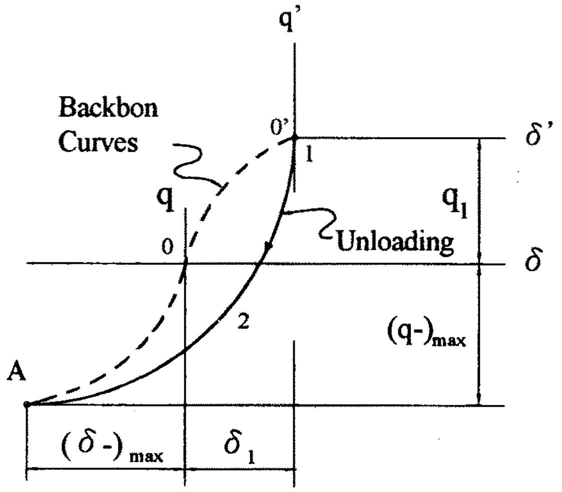
Mutant Curves

Take a multiple-cycle compression test as an example, once the backbone curve is established, the unloading curve for the first cycle can be constructed by:

(a) shifting the origin of the coordinate system to the position corresponding to the load and displacement before the load reversals, i.e., Position 1 in Fig. 3, and

(b) assuming Segment 1-A is mathematically similar to Segment 0-A.

In other words, there is a non-linear mapping of the load transfer curves from the q-δ coordinate system to the q'-δ' system as such:



Unloading
Fig. 3 Mutant Curve for Unloading

$$\frac{q+q_1}{(q-)_{\max}+q_1}=f\left(\frac{\delta+\delta_1}{(\delta-)_{\max}+\delta_1}\right) \tag{3}$$

where q_1 and δ_1 are, respectively, the resistance and displacement before unloading.

A similar procedure, as illustrated in Fig. 4, can be adopted for recompression such that:

$$\frac{q-q_2}{(q+)_{\max}-q_2}=f\left(\frac{\delta-\delta_2}{(\delta+)_{\max}-\delta_2}\right) \tag{4}$$

where q_2 and δ_2 are the load and the displacement at the beginning of the second cycle, respectively.

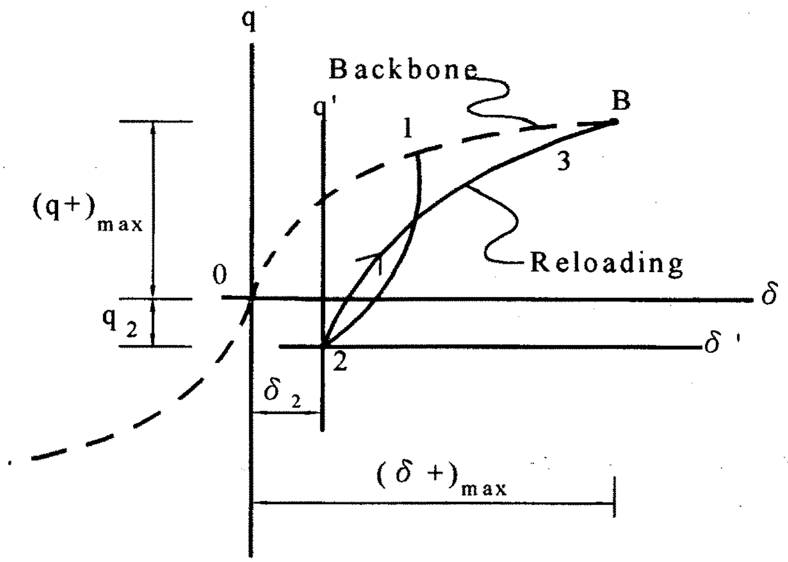


Fig. 4 Mutant Curve for Reloading

Since the same function, $f(\delta)$, is used in all the stages, modifications to existing computer programs which analyze load-settlement behavior of piles are minimal. All it requires is to redefine variables q and δ in the subroutine which computes q based on δ.

The determination of ultimate resistances $(q+)_{max}$ and $(q-)_{max}$ from deduced load transfer curve is relatively easy. On the other hand, the determination of $(\delta+)_{max}$ and $(\delta-)_{max}$, is sometimes rather arbitrary. Fortunately, experience indicates that the computed load-displacement curves are relatively insensitive to $(\delta+)_{max}$ and $(\delta-)_{max}$.

TIP RESISTANCE

For driven piles and for cast-in-situ bored piles solidly embedded in bearing strata, the above-mentioned procedure can also be adopted for constructing the load transfer curves for tip resistance. The backbone curve in such cases, as shown in Fig. 5, is assumed to be symmetrical to the origin. It is generally not possible for tension to develop at the toe and the unloading curve will thus be bounded by the x-axis.

For cast-in-situ bored piles constructed using slurry and the reverse circulation technique, it is likely that the presence of sediments will make it difficult for the concrete to establish a solid contact with the bearing strata at the toe. As a result, a certain amount of "sitting" settlement is unavoidable, as depicted in Fig. 6, before a "good contact" can be made between the pile tip and the bearing stratum. Even with dry holes, the loose particles at the bottom and the loosening of the bearing stratum will have similar, though smaller, effects.

For long piles embedded in rock or dense gravel, the resistance developed at the tip is usually a small fraction of the bearing capacity and the corresponding load transfer curve is practically linear. In such cases, the unloading and recompression curves can be constructed by assuming, as illustrated in Fig. 6, a slope of, say, 5 to 10 times steeper than that of the backbone curve During recompression, if the resistance exceeds its previous maximum, the backbone curve v be used.

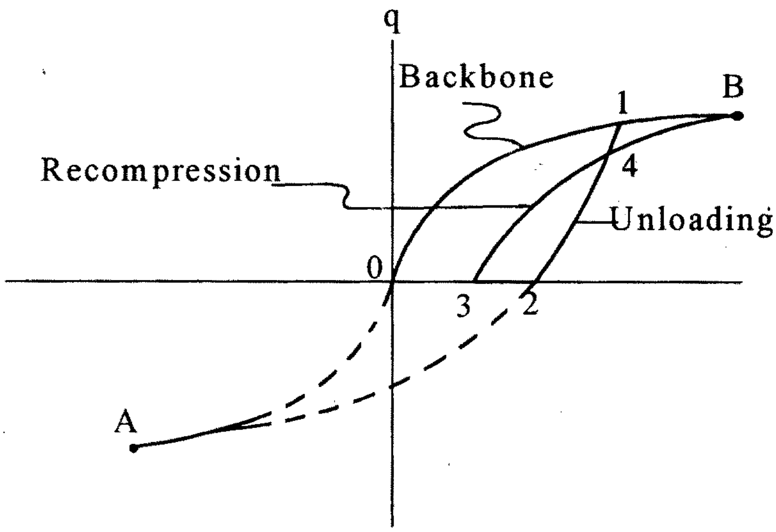


Fig. 5 Backbone and Mutant Curve

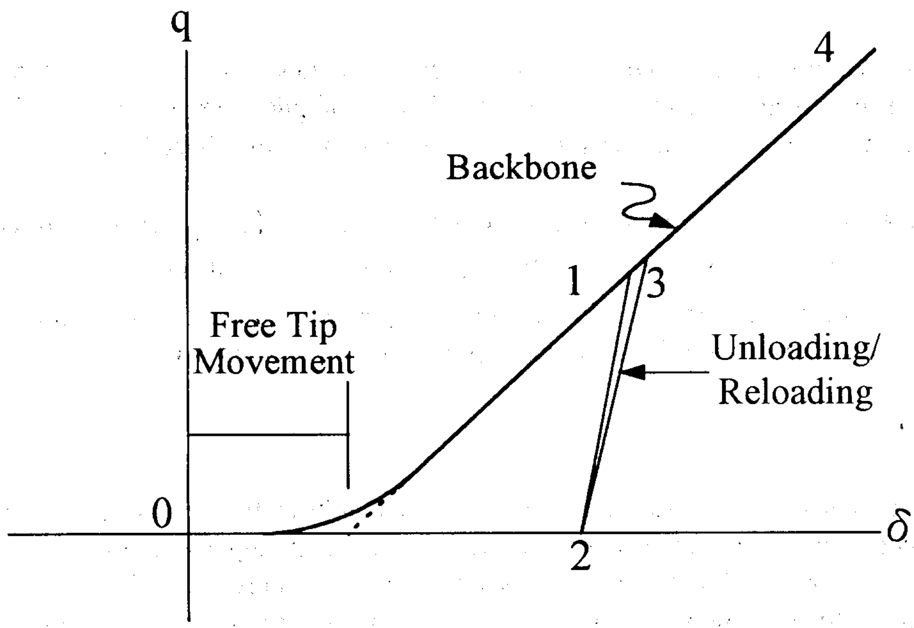


Fig. 6 End Bearing for Bored Piles

CASE STUDY

To illustrate the validity of this procedure, the results of a test pile, TP3 (Moh, et al, 1993) were analyzed. The 1m diameter pile is 10m in length and is embedded in fresh sandstone by 2.5m. At the ground surface is a layer of fill underlain by a thick layer of silty sand (SM). A simplified soil profile at the test site and the observed load distributions are shown in Fig. 7. The pile was first compressed to a maximum of 7.5 MN in four equal increments and was then

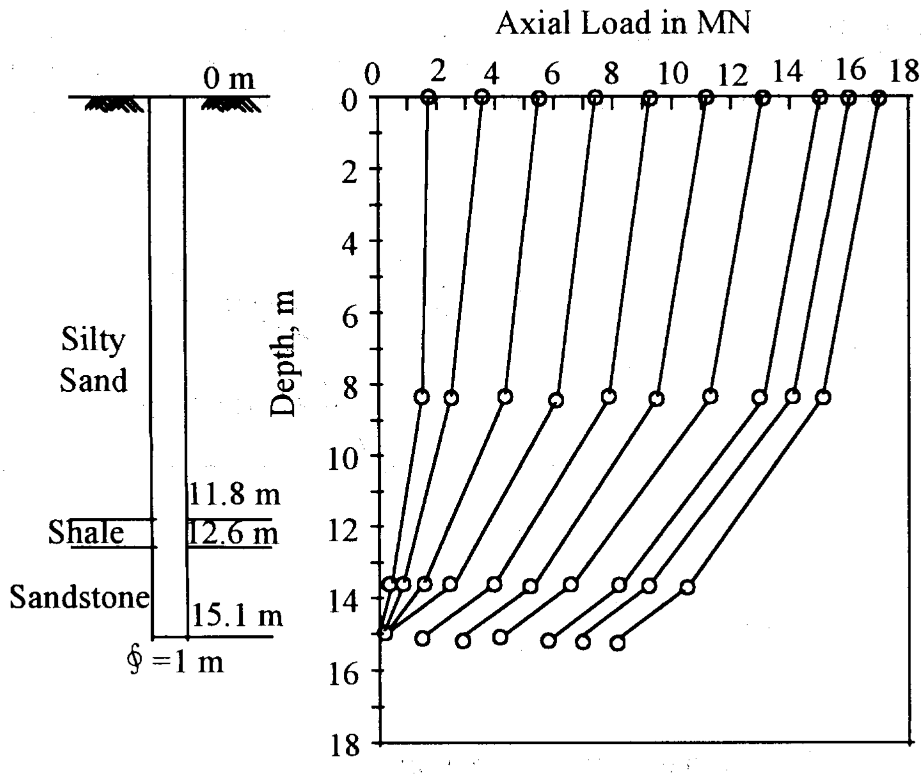


Fig. 7 Axial Loads in Test Pile TP3

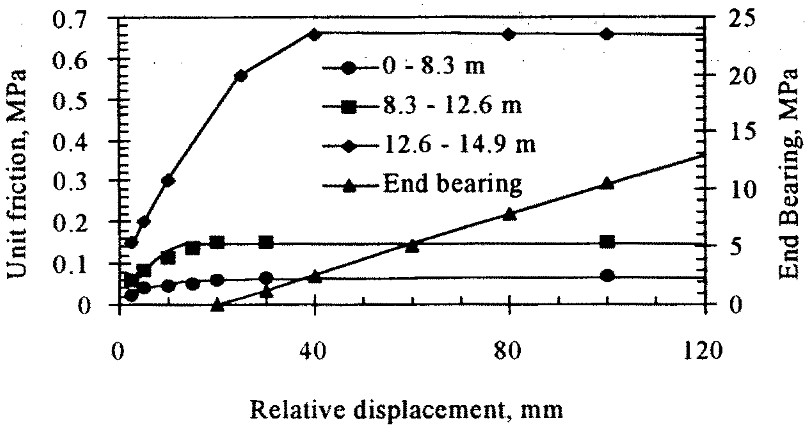


Fig. 8 Backbone Curves for TP3

totally unloaded. It was then recompressed to a maximum of 17 MN in 10 increments and totally unloaded in the second cycle.

Analyses were made using the backbone curves shown in Fig. 8. The computed displacements at the pile top are compared with those observed during the test are compared in Fig. 9. It can be noted that the two sets of data agree reasonably well.

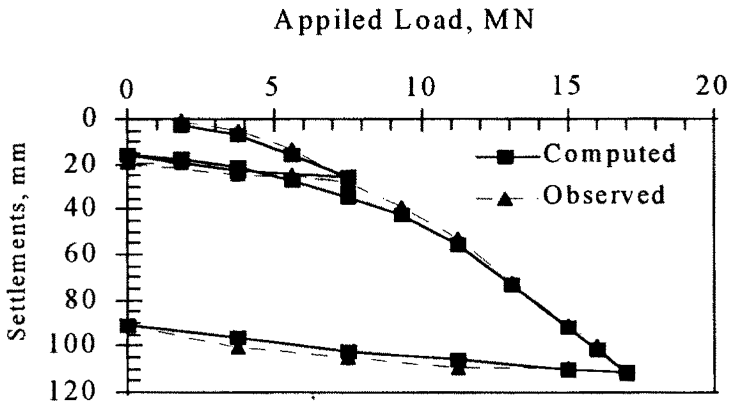


Fig. 9 Comparison of Observed and Computed Load-Settlement Curves

DISCUSSIONS

The proposed procedure has been used to evaluate the performance of piles with other types of load reversals. For examples, pressure grouting at the bottom of a pile will result in upward movements of the pile and hence the development of negative skin friction. As the pile is subsequently loaded, the downward movements of the pile will tend to reverse the skin friction from negative to positive. A phenomenon opposite to this is the reversal of positive skin friction to negative as a result of consolidation settlement of the ground due to lowering of groundwater. Reasonable success has been achieved in both cases.

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