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Load-Displacement Response of Piles under Uplift Loading

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Introduction

Pile foundations are often subjected to axial, lateral loads and moment. Under the action of lateral load and moment, some of the piles in a group experience uplift. Load-displacement response of pile under uplift, therefore, becomes a necessary input for the estimation of response of foundations resting on group of piles. The literature reveals considerable progress in the development of procedures for estimation of load-settlement behaviour of piles under compressive loading. However, there seems to be only a limited effort in this respect on piles under uplift loading. Here, a procedure for estimation of load-displacement behaviour of piles subjected to uplift loading has been suggested taking into account the most commonly encountered field situation.

Available Analytical Procedure

Methods for the estimation of the load-displacement of piles under uplift loading, available in the literature, can be grouped into following two categories :

1. Elastic continuum approach
2. Load transfer approach.

Methods Based on the Elastic Continuum Approach

Madhav and Poorooshasb (1988) presented a method which follows closely the method developed by Poulos and Davis (1968) for compressive load on pile. The soil is assumed to be a linear, elastic continuum and the elastic deformation of the pile under the load is neglected. The pile, considered to be of uniform diameter, is subdivided into a number of elements. The soil displacements are obtained from Mindlin's solution (1936), which are then equated with the pile displacements for satisfying compatibility of displacements. From the resulting equation, the pile head displacement is obtained.

Reddy et al. (1997) presented a numerical model to predict the load-displacement behaviour of a pile under uplift load in cohesionless soils. The

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method is based on the elastic continuum approach for piles under compressive loading as suggested by Randolph and Wroth (1978). Both the pile and soil material are assumed to behave elastically.

Methods Based on the Load Transfer Approach

Sulaiman and Coyle (1976) have proposed a method of estimating the load-displacement behaviour of a pile under uplift loading in sand, using the load transfer approach suggested by Coyle and Reese (1966) for piles under compressive loading. The pile is discretized into a number of segments. A small upward tip movement is assumed, corresponding to which the shaft resistance in all the pile segments is evaluated using load transfer curves from load tests on model steel pipe piles embedded in sand of medium density (Figure 1). The pile discretization is done in such a manner that the depth of the mid point of each element corresponds to a confining pressure associated with a particular load transfer curve of Figure 1. The elastic deformation of the segment is neglected in the estimation of shaft resistance. The summation of all the segment forces gives the total upward load at the pile head for the assumed tip movement. The computation is repeated for a number of tip movements and a curve representing uplift load vs. rigid pile movement is plotted (curve a, Figure 2). Then, knowing the pile cross-section and material properties, the elastic deformation of the pile is obtained (curve b , Figure 2). The sum of the elastic deformation and the tip movement gives the total displacement at the pile head (curve (a+b)).

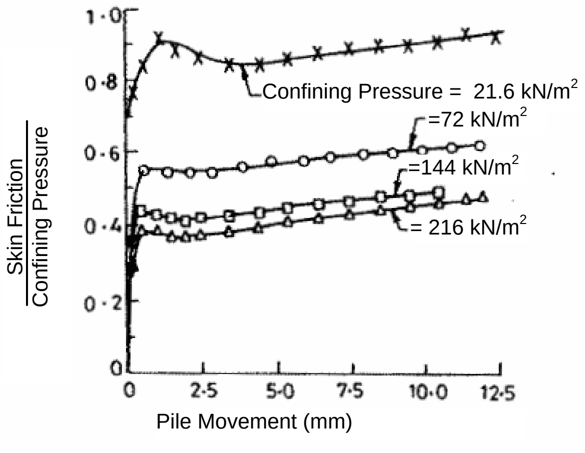

Fig. 1 Laboratory Determined Load Transfer Curves used by Sulaiman And Coyle (1976)

Reddy et al. (1998) have attempted to improve the Sulaiman and Coyle (1976) model by taking into account the elastic extension of the pile shaft in evaluating the shaft resistance. However, dependency on the use of the laboratory-determined load transfer curves (Figure 1) still remained. The numerical algorithm used for obtaining the load-displacement response is the same as in the elastic continuum model (Reddy et al., 1997). Results obtained from this model were reported to be better than those obtained from the Sulaiman and Coyle (1976) model.

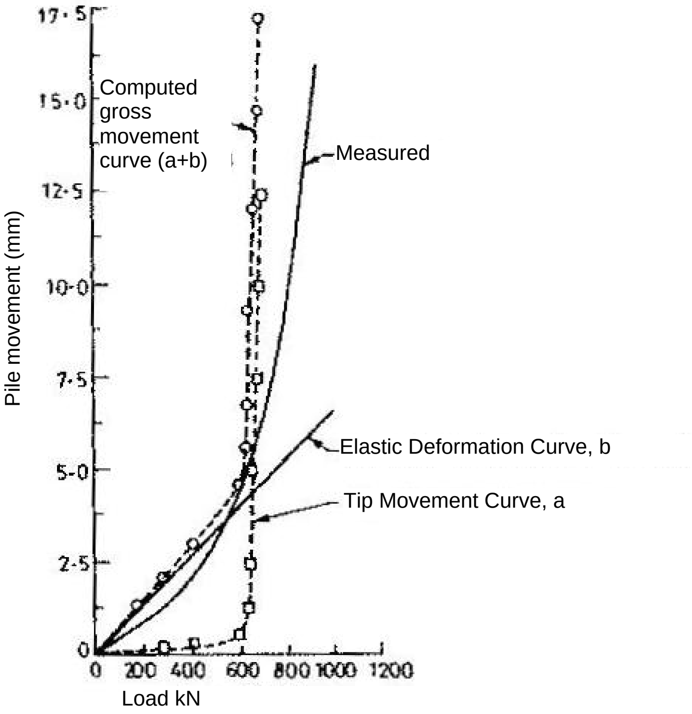

Fig. 2 Computed and Actual Load-Movement Curves for Pile under Uplift (Sulaimanm and Coyle, 1976)

A Critical Appraisal of the Methods

The methods described above have their own limitations due to the assumptions made in the analysis. For instance, applicability of the procedure developed by Sulaiman and Coyle (1976) is limited by the use of load transfer curves obtained from load tests on model piles. The assumption that the load transfer curves obtained from a model pile set-up would be valid for a prototype pile does not appear to be very sound. For example, the load transfer curves obtained from the model pile tests (Figure 1) have shown that the peak shaft resistance is mobilised at displacements less than 1 mm whereas, the literature suggests that the peak resistance occurs at displacements ranging from 5mm to 12.5mm in the case of prototype piles (Table 1).

The elastic deformation of the pile shaft may constitute a considerable portion of the total pile movement as is evident from the results reported by Sulaiman and Coyle (1976) (Figure 2). Therefore, neglecting the elastic deformation in the estimation of the shaft resistance as assumed in some of the methods (Sulaiman and Coyle,1976 ; Madhav and Poorooshasb, 1988) does not appear to be justifiable. The methods proposed by Reddy et al (1997,1998) involve assumption of the load and displacement at the pile head arbitrarily at the beginning of the computation procedure which results in a number of trials before the solution is obtained.

Table 1: Displacement Required to Mobilize Maximum Skin Resistance Under Uplift Loading

Shaft displacement at max. skin resistance, mm (1)	Pile-soil condition (2)	Reference (3)
5.0 – 6.25 (0.98 to 1.23% of pile dia.)	Steel pipe piles, 0.51 m dia., 14.6 m long in uniform beach sand; Driven piles and driven and Jetted piles	McClelland (1974)
6.25 – 12.5 (0.57 to 1.14% of pile dia.)	Bored cast-in-place piles in sand; 1.1m dia., 6.4m long piles	Ismael and Klym (1979)
5 - 10 mm (a summary based on large-scale model tests and full-scale field load tests)	Bored piles in sand	Kulhawy (1985)

Further, the methods have the following limitations:

1. Only piles in homogenous soil medium is considered.
2. Soil is considered cohesionless (except in the method by Madhav and Poorooshasb,1980).
3. Piles considered are of circular shape and uniform size.

In view of the above, an analytical procedure to estimate the load-displacement behaviour of piles under uplift loading is presented accounting for the following :

I. variation in pile-soil properties with depth and
II. skin resistance as a function of pile displacement including that due to elastic elongation of the pile.

Proposed Analytical Procedure

The procedure is based on the following assumptions :

1. The uplift load is resisted by the shaft resistance only, tip load being absent.
2. The variation of shaft resistance as a function of pile displacement under uplift loading is qualitatively the same as that applicable under compressive loading.
3. Due to uplift loading, the pile undergoes an elastic extension and a rigid body movement (equal to the tip displacement), which together give the gross upward displacement of the pile head.

The analysis consists of the following two components :

a) Estimation of load transfer curves to describe the mobilization of shaft resistance as a function of pile movement.

b) A numerical procedure for calculating the forces and displacements in the pile under the applied uplift load.

Load Transfer Curve

A load transfer curve describes mobilization of soil resistance in the pile shaft as a function of pile movement, z. For evaluating the shaft resistance of the pile in uplift, Equation 1 recommended by Vijayvergiya (1977) (Figure 3) for piles under compressive loading is assumed valid under uplift loading also and the same is adopted. However, f_{max} under uplift loading may be appropriately estimated and used in Equation 1.

$$f = f_{max}\left(2\sqrt{\frac{z}{z_s}} - \frac{z}{z_s}\right) \qquad (1)$$

where,

f = unit shaft resistance mobilized at pile movement z.

z_s = shaft displacement at which maximum unit shaft resistance f_{max} is mobilized in uplift (Typical values suggested in the literature shown in Table 1, column 1 may be adopted) and $z \le z_s$.

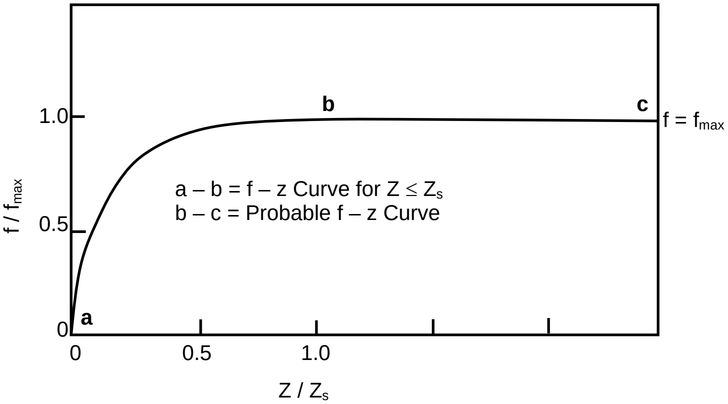

Fig. 3 Normalized f-z Curves (Vijayvergiya, 1977)

It is assumed that the shaft resistance remains constant beyond the displacement, Z_s though some reduction in side resistance can be expected for displacement beyond the one corresponding to the peak value.

Estimation of f_{max}

Cohesionless Soils

$$f_{max} = K_u \overline{\sigma}_v \tan\delta \qquad (2)$$

where

K_u = lateral earth pressure coefficient in uplift

$\overline{\sigma}_v$ = effective vertical overburden pressure at the depth considered

δ = angle of wall friction for the pile-soil system considered

f_{max} = the maximum unit resistance mobilised

The values of K_u and δ depend on many factors such as, the material and the surface roughness of the pile, the method of construction, the type of soil, elapsed time after construction etc. (Das, 1983; Chattopadhyay and Pise, 1985; Lehane et al. 1993; Hussein et al., 1994; Chow et. al 1997; Oneill, 2001; Ramasamy et al., 2004). Because of the complexities of estimating these parameters, considerable engineering judgment, backed by knowledge base reported in the literature and experience, must be applied to judiciously choose appropriate values to these parameters.

Studies reported in the literature (Tomlinson, 1987; Poulos and Davis, 1980; Nicola and Randolph, 1993; Lehane et al., 1993; Hussein et al., 1994; Chow et al., 1997; O'Neill, 2001) have shown that the shaft resistance of piles under uplift load could be significantly lower than that under compressive loading. Elhakim and Mayne (2002) and Ramasamy et al. (2004) have presented a summary of the values reported in the literature on the ratio of skin friction under tensile to compression loading, Q_T / Q_C . These literature on piles under uplift loading and many more on piles under compressive loading provide a large data base for a designer to choose judiciously the various parameters governing skin resistance under uplift loading.

Cohesive soils :

$$f_{max} = \alpha \; C_u \tag{3}$$

where

α = adhesion factor in uplift

C_u = undrained shear strength of the soil.

The value of α depends on many factors including changes brought about in the soil surrounding the pile by the method of construction. Elhakim and Mayne (2002) suggest that in low permeability soils pile resistance in uplift may be considered to possess the same resistance in compression, as also suggested by the results of Sowa (1970). Accordingly, the value of α may be chosen based on the literature available for piles under compression loading.

Thus, with the various parameters appearing in Equation (1) defined as above, f-z relationship for a given pile-soil situation can be established.

Numerical Procedure

The pile is discretized into a number of convenient segments. An initial upward tip displacement is assumed, and then working towards the pile head, the shaft resistance mobilized and elastic deformation experienced by each segment are worked out to finally obtain the uplift load and gross upward displacement at the pile head. The procedure is detailed in the following steps.

Solution Steps

1. Discretize the pile into a convenient number of segments, numbered from top as 1,2,3….n (Figure 4). Assign appropriate geometrical and pile material properties to each such segment.
2. First consider the lowermost segment, i.e. 'n'.
3. Assume an upward tip movement Y_{tip} (n)
4. Corresponding to Y_{tip} (n), tip load is zero i.e. Q_{tip} (n) = 0
5. Estimate mid point movement, Y_{mid} (n) of the bottom segment. For the first trial, Y_{mid} (n) may be assumed equal to Y_{tip} (n).
6. Using this value of Y_{mid} (n), refer to a load transfer curve or Equation 1 (which has been predetermined for the soil layer surrounding the segment considered, Figure 3) to obtain the unit shaft resistance f_n corresponding to z = Y_{mid} (n).
7. The shaft resistance S_n mobilized by the segment is calculated as

$$S_n = f_n \,.\, L_n \,.\, C_n \tag{4}$$

Where

L_n = length of the segment
C_n = perimeter of the segment

8. The tensile load at the top of the segment is obtained as

$$Q_{top}(n) = S_n + Q_{tip}(n) \tag{5}$$
$$= S_n \; [\because Q_{tip}(n) = 0 \text{ for this segment}]$$

9. Assuming a linear variation of load distribution within the segment, the load at mid point level is obtained as

$$Q_{mid}(n) = \frac{Q_{top}(n) + Q_{tip}(n)}{2} = \frac{Q_{top}(n)}{2} \tag{6}$$

$[\because Q_{tip}(n) = 0$ for this segment$]$

10. The elastic extension at the mid point of the segment ΔY_{mid} is given by PL/AE, in which P = the average tensile load applied to the pile segment, L = the length of the pile segment, A = cross-sectional area and E = Young's modulus of the pile material. Accordingly,

$$\Delta Y_{mid}(n) = \frac{\dfrac{Q_{mid}(n) + Q_{tip}(n)}{2} \text{ x } \dfrac{L_n}{2}}{A_n E_n} = \frac{Q_{mid}(n).L_n}{4A_n E_n} \tag{7}$$

$[\because Q_{tip}(n) = 0]$

where

A_n = cross-section area of the segment n

E_n = Young's modulus of the segment n

11. Compute the new mid point movement of the bottom segment as

$$Y_{mid}(n) = Y_{tip}(n) + \Delta Y_{mid}(n) \qquad (8)$$

12. Compare the new mid point movement with that assumed in step (5). If the two values agree within the prescribed accuracy limit, move to the next step (i.e. step 13); else repeat steps (6) to (12), starting with the Y_{mid} (n) value calculated in step (11), till convergence is achieved.

13. The total upward movement of the top of segment n is obtained as

$$Y_{top}(n) = Y_{mid}(n) + \frac{\frac{Q_{top}(n) + Q_{mid}(n)}{2} \text{ x } \frac{L_n}{2}}{A_n E_n} \qquad (9)$$

14. Proceed to the next upper segment (i.e. (n-1)th segment) whose tip load and tip displacement are given by

$$Q_{tip}(n-1) = Q_{top}(n)$$
$$Y_{tip}(n-1) = Y_{top}(n) \qquad (10)$$

15. Proceed in this manner segment wise to finally obtain the tensile load Q_{top} (1) and displacement Y_{top} (1) at the top of the first segment, i.e., at the pile head.

16. The above steps are repeated for a set of tip movement values and the corresponding load and displacement at the pile head are obtained. The same are plotted to give the load-displacement curve for the pile under consideration.

Results and Discussions

The analytical procedure is translated into a program LOADRISE using 'C' language. The program is used to estimate the load-displacement behaviour of piles under uplift loading for a few numerical problems. The results of this exercise are presented and discussed.

Response of a Steel Pipe Pile in Uplift

The working of the proposed numerical procedure is demonstrated by estimating the response of a steel pipe pile installed for a waterfront structure as shown in Figure 5. The soil deposit is layered, having variation in soil strength. The pile has 5 m of free standing length in water. For the clay layers, the value of α is taken same as that recommended for compressive loading ; however in the sand layer, the value of K_u is selected as 2/3 of K_s applicable under compressive loading. Critical shaft displacement z_s is taken as 8 mm in all the soil layers.

The estimated uplift load vs displacement relationship at the pile head is shown in Figure 5 (curve 'a'). The corresponding tip displacements are shown by curve 'b' (Figure 5). For a given load, the difference in displacements at the pile head and the pile tip gives the elastic extension of the pile under the load. It may be noted from Figure 5 that the elastic extension is quite significant and therefore, omission of this displacement in the calculation of mobilized shaft resistance as suggested by Sulaiman and Coyle (1976) and Madhav and Poorooshasb (1988) may result in substantial deviation from the actual.

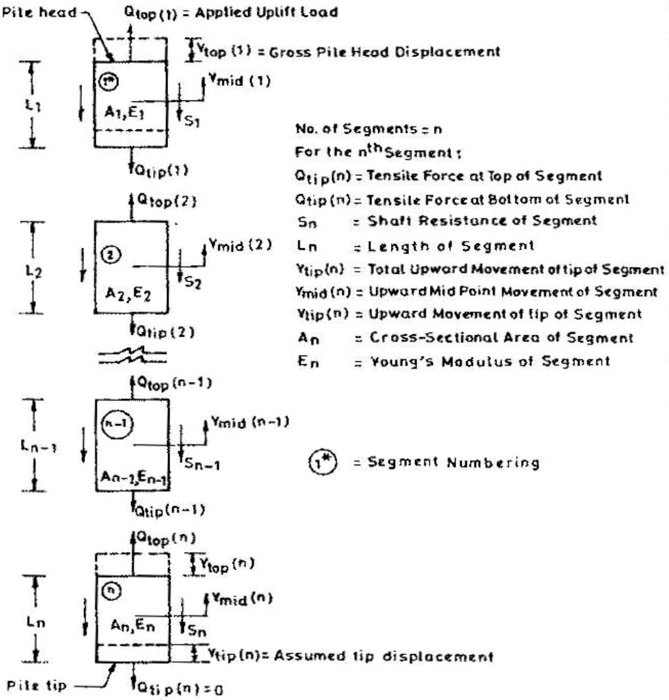

Fig. 4 Discretization of Pile and Forces and Displacements Acting on the Segments under Uplift Loading

Comparison of Predicted and Observed Load–Displacement Curves

The program LOADRISE is utilized to compute the load-displacement response for a full-scale test pile reported by McClelland (1974). A steel pipe pile was driven into a medium dense beach sand deposit at Padre Island (USA) and then tested in uplift. The pile-soil situation and the observed load-displacement curve are shown in Figure 6 wherein the geotechnical parameters estimated for use in the computations are also mentioned. Water table has not been reported, but assumed to be at the ground level.

The uplift load-displacement has been estimated for the above pile-soil situation assigning two sets of values for k_u, δ and Z_S. The predicted and the observed load-displacement plots are shown in Figure 6. The comparison shows that the observed and the predicted (for $k_u = 0.5$; $\delta = 20^o$ and $Z_S = 8$ mm) load-displacement values agree well. However, for values of $k_u = 0.6$, $\delta = 25^o$ and $Z_S = 10$ mm, the observed and the predicted load-displacement values, particularly for loads more than 400 kN (about 50% of ultimate load), do not agree well. This shows that while the suggested procedure is capable of estimating closely the actual load-displacement behaviour, selection of appropriate values for K_u, δ and Z_s is crucial for a reliable prediction.

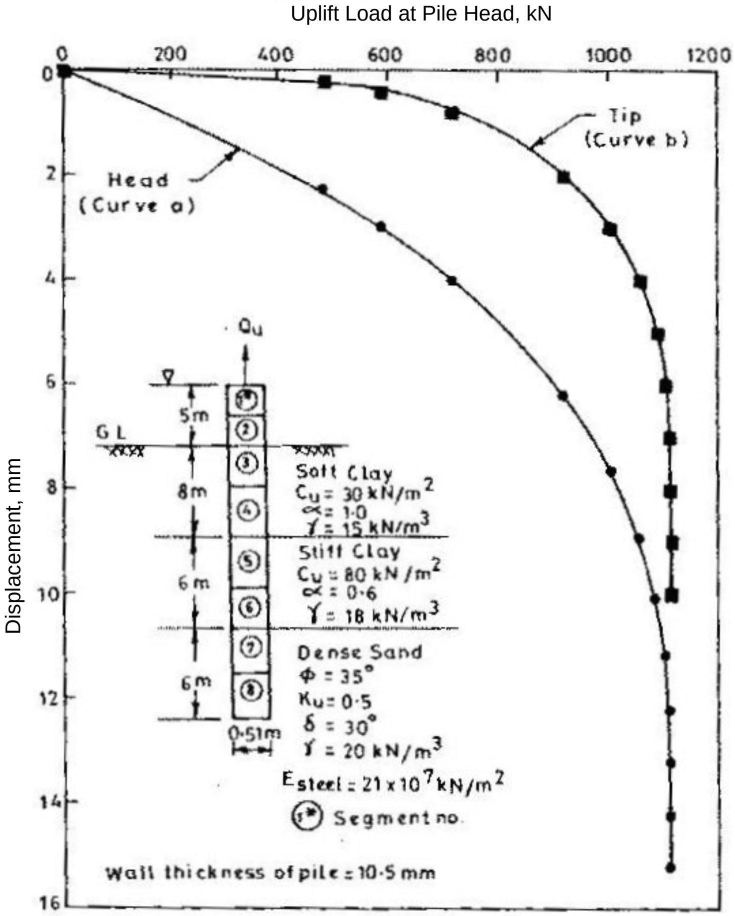

Fig. 5 Load-Displacement Curve for Steel Pipe Pile in Uplift

Conclusion

An analytical procedure for the evaluation of load-displacement behaviour of pile foundations under uplift load has been outlined. The suggested procedure can take into account variation in pile cross section as in step tapered piles and variation in soil properties as in layered soil along the length of the pile. The procedure has been used for predicting the load-displacement response of a load-tested pile, and a comparison of the predicted and the observed load-displacement values suggest that the procedure is capable of providing a reliable estimate of load-displacement behaviour, provided the associated input parameters are chosen appropriately.

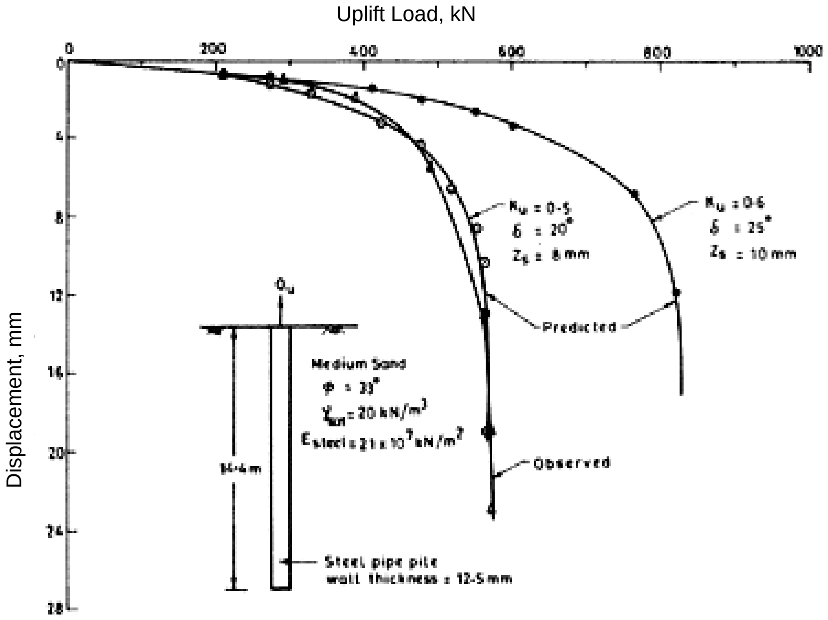

Fig. 6 Computed and Observed Load-Displacement under Uplift Loading

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