Undrained elastic behavior of drilled shaft foundations in cohesive soils

Comportement non-drainé élastique de fondations sur pieux forés dans des sols cohérents

A.G.Cushing & F.H.Kulhawy – *Cornell University, Ithaca, New York, USA*

ABSTRACT: The undrained elastic (small-strain) behavior of drilled shafts in cohesive soils is addressed herein. A database of load tests is evaluated using the L_1-L_2 method, in which L_1 is the elastic limit, defined at a specific load (Q_{L1}) and corresponding displacement (ρ_{L1}). Values of undrained elastic soil modulus (E_u) are back-calculated from Q_{L1} and ρ_{L1} in the load tests and subsequently are normalized by the undrained shear strength (s_u), unit side resistance ($f = \alpha s_u$) and cone tip resistance (q_c). All three normalized E_u ratios are similar in that the coefficient of variation (COV) values on their means range from 60 to 70% in uplift to about 80 to 90% in compression. These COVs are, in general, somewhat larger than those for ρ_{L1}. The results demonstrate that elastic behavior can be quantified using either normalized ρ_{L1} or E_u values, but large COVs are inherent in subsequent displacement predictions.

RÉSUMÉ: On décrit le comportement non-drainé élastique (petites déformations) de fondations sur pieux forés dans des sols cohérents. Des données d'essais de chargement sont étudiées avec la méthode L_1-L_2, dont L_1 est la limite élastique, definie à une certaine charge (Q_{L1}) et déplacement (ρ_{L1}). Des valeurs du module de déformation élastique du sol (E_u) sont calculés inversivement de Q_{L1} et ρ_{L1} obtenus dans les essais de chargement; en suite elles sont normalisées avec la résistance à la rupture au cisaillement sous conditions non drainées (s_u), le frottement spécifique sur les côtes ($f = \alpha s_u$), et la résistance de la pointe du cône (q_c). Les trois rapports normaux E_u sont semblables puisque leurs coefficients de variation (COV) se trouvent dans une intervalle entre 60 et 70% sous des conditions de sous-pression, et entre 80 et 90% sous des contitions de compression. Ces valeurs de COV sont généralement un peu plus grandes que celles de ρ_{L1}. Les résultats démontrent que le comportement élastique peut être quantifié par des valeurs normales de ρ_{L1} ou de E_u; mais on peut toujours s'attendre à des grandes valeurs de COV das ses predictions.

1 INTRODUCTION

A database of axial load tests was used to examine the undrained elastic (small-strain) behavior of drilled shaft foundations in cohesive soils. The slenderness ratio [depth (D) / diameter (B)] for the shafts ranged from 1.6 to 64, with most less than 25, and the diameters ranged from 76 mm to 1.62 m, with most between 0.15 and 1.0 m. Mean undrained shear strength (s_u) values ranged from 12 to 265 kN/m^2, with most less than 150 kN/m^2. Database details are given by Cushing (2001).

This paper consists of two parts: (a) an assessment of the L_1-L_2 interpretation method for drilled shafts and (b) an evaluation of back-calculated undrained elastic soil modulus (E_u) values from this method and subsequent normalization by s_u, unit side resistance ($f = \alpha s_u$), and cone tip resistance (q_c).

2 ASSESSMENT OF L_1-L_2 METHOD

2.1 *Background*

Hirany & Kulhawy (1988, 1989a,b) proposed quantitative guidelines for load test data interpretation. They noted that load-displacement curves generally can be described by three distinct regions: initial linear, transition, and final linear. The end of the initial linear region is the elastic limit (L_1), while the beginning of the final linear region is the failure threshold (L_2), as shown in Figure 1. Both of these values are determined graphically. Based on available case history data for shafts in axial compression, L_1 occurred at a mean displacement equal to 0.4% B, while L_2 was at a mean displacement of 4% B. For shafts in uplift, L_2 occurred at a mean displacement of 13 mm (0.5 inch). It was implied that uplift and compression behavior in the elastic region would be similar, so it was inferred that L_1 in uplift would occur at about 0.4% B.

Using an expanded database, the L_1-L_2 interpretation method is re-evaluated herein. The uncertainties in this methodology are quantified by the coefficient of variation (COV), which is the standard deviation divided by the mean.

2.2 *Displacements at Elastic Limit (L_1)*

For the shafts in undrained axial uplift, the mean displacement (ρ_{L1}) = 0.37% B (n = 31, COV = 141%), as shown in Figure 2. However, for shafts with B > 0.15 m, the mean ρ_{L1} = 0.19% B (n = 25, COV = 43%), which is about half the Hirany & Kulhawy (1988) approximation. Visual inspection of these data indicates that these revised statistics are more representative of the overall undrained axial uplift database. These expanded and revised statistics also are in closer agreement with values for drilled shafts in drained axial uplift (Cushing, 2001). The mean absolute ρ_{L1} = 1.41 mm (n = 31, COV = 63%), as shown in Figure 3. For com-parison, the 0.4% B approximation gives a mean $\rho_{0.4\%B}$ = 2.62 mm for all 31 shafts in undrained uplift, which exceeds the mean observed value by 1.2 mm.

For the shafts in undrained axial compression, the mean ρ_{L1} = 0.55% B (n = 56, COV = 78%), as shown in Figure 4. This

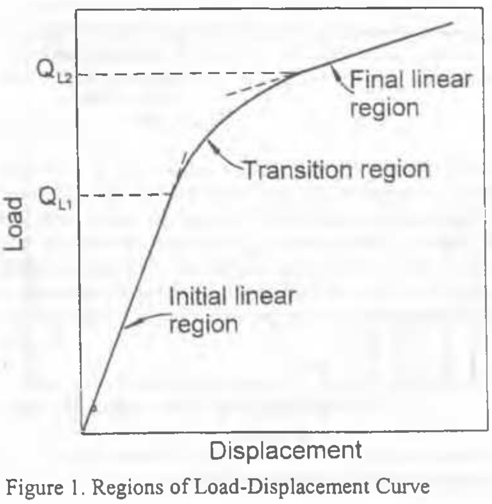

Figure 1. Regions of Load-Displacement Curve

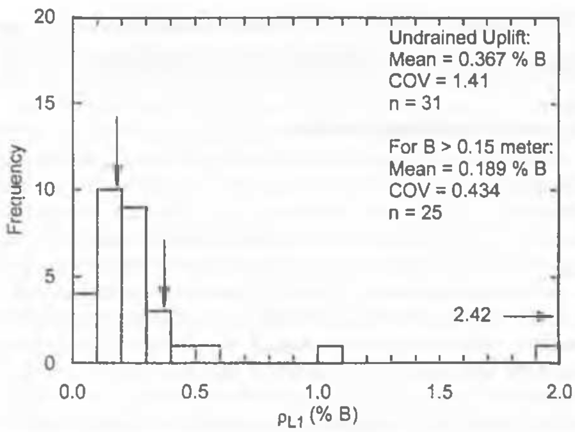

Figure 2. ρ_{L1} (% B) for Shafts in Undrained Uplift.

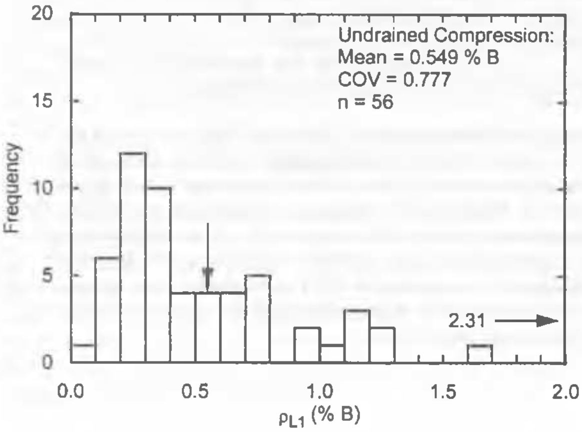

Figure 4. ρ_{L1} (% B) for Shafts in Undrained Compression.

value is a bit higher than the 0.4% B approximation, and it is slightly less than three times the mean value for undrained axial uplift (with B > 0.15 m). This comparison is consistent because all of the undrained compression shafts have B > 0.15 m. The mean absolute ρ_{L1} = 3.57 mm (n = 56, COV = 80%), as shown in Figure 5. Therefore, the mean absolute difference between the undrained uplift and compression displacements at L_1 is about 2 mm. The larger L_1 displacements for undrained compression result from the tip load transfer at the elastic limit. The 0.4% B approximation yields a mean $\rho_{0.4\%B}$ = 2.81 mm, which is about 1 mm less than the mean observed value. Clearly, large COVs are inherent in these elastic limit displacement predictions. However, these displacements, on average, are quite small.

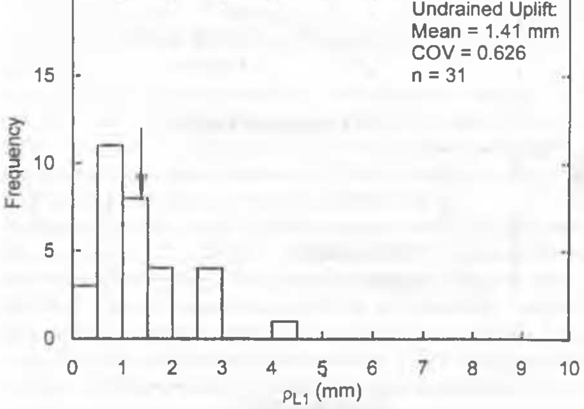

Figure 3. ρ_{L1} (mm) for Shafts in Undrained Uplift.

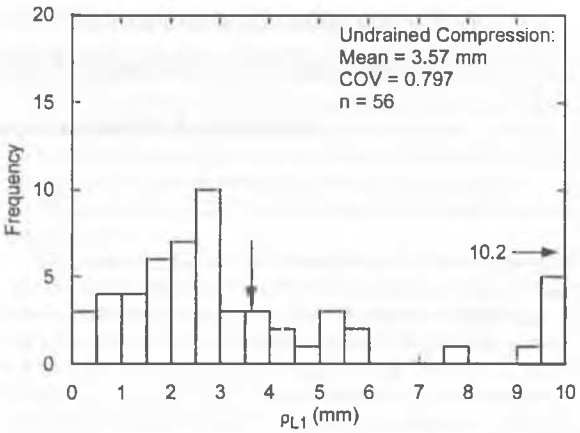

Figure 5. ρ_{L1} (mm) for Shafts in Undrained Compression.

Table 1. Summary of Load and Displacement Data.

Parameter	Uplift			Compression		
(Units)	Mean	COV	N	Mean	COV	n
ρ_{L1} (% B)	0.19[a]	0.43[a]	25[a]	0.55	0.78	56
ρ_{L1} (mm)	1.41	0.63	31	3.57	0.80	56
$\rho_{0.4\%B}$ (mm)	2.62	0.64	31	2.81	0.47	56
$Q_{0.5inch}/Q_{L2}$	0.99	0.05	31	-	-	-
$Q_{4\%B}/Q_{L2}$	-	-	-	1.00	0.14	55[b]
Q_{L1}/Q_{L2}	0.56	0.17	31	0.53	0.19	55[b]

a - Revised statistics for B > 0.15 meter
b - One load test was terminated prematurely, so Q_{L2} was not determined

2.3 *Loads at Elastic Limit (L_1) and Failure Threshold (L_2)*

The Hirany & Kulhawy (1988) approximations for the interpretation of the load at the failure threshold (Q_{L2}) were validated for drilled shafts in undrained axial loading. As shown in Table 1, the mean $Q_{0.5\ inch}$ / Q_{L2} for uplift = 0.99, while the mean $Q_{4\%B}$ / Q_{L2} = 1.00. The COVs on these values = 5% for uplift and 14% for compression.

The analyses also showed that the mean load ratios (Q_{L1}/Q_{L2}) were equal to 0.56 in uplift (COV = 17%) and 0.53 in compression (COV = 19%). These results indicate that, on average, for design factors of safety greater than 1.8 or 1.9, the shaft-soil behavior will be essentially elastic, and the displacements will be very small. It should be noted that the uncertainties associated with the mean L_1 displacements are significantly greater than those for the corresponding loads. A summary of the load and displacement data is given in Table 1.

3 UNDRAINED SOIL MODULUS

3.1 *Back-calculation Procedure*

Undrained soil modulus values (E_u) were back-calculated from the load tests in axial compression using the Poulos & Davis (1980) method, as given by:

$$E_u = Q_{L1}\, I_p / B\, \rho_{L1} \qquad (1)$$

in which $I_p = I_o R_K$, I_o = settlement influence factor for a single, straight-sided, incompressible shaft embedded in a homogeneous, isotropic, linear-elastic soil with ν_s = 0.5, and R_K = correction factor for shaft compressibility.

Values of E_u were back-calculated from the load tests in axial uplift using a modified version of Equation 1 given by Withiam & Kulhawy (1981):

$$E_u = (Q_{L1} - W)\, I_p / B\, \rho_{L1} \qquad (2)$$

in which W = foundation weight. With these equations, only one value of E_u can be obtained from a single load test at a particular stress level, which assumes the soil to be homogeneous and isotropic for back-calculating E_u. In addition, the shafts in axial compression were assumed to be floating instead of end-bearing.

By definition, Q_{L1} is the load at elastic limit, or the largest load at which nominal elastic load-displacement response occurs. Therefore, the "elastic" undrained soil modulus is defined using Q_{L1} and ρ_{L1}. The resulting E_u values represent the average secant modulus of the strained soil along the shaft and near the tip at the observed L_1 load level.

3.2 *Soil Moduli Normalized by s_u and αs_u*

The values of E_u were normalized by the mean undrained shear strength (s_u) along the shaft and the unit side resistance ($f = \alpha s_u$), in which α = dimensionless adhesion factor. The values of s_u were determined either from direct simple shear (DSS) tests or they were converted to equivalent DSS values from another test type using the relationships given by Kulhawy & Mayne (1990). For consistency, the α value should be calibrated to the strength test conducted so that αs_u is independent of the test type, as given below:

$$f = \alpha s_u = \alpha_{DSS}\, s_u(DSS) \tag{3}$$

In this study, the semi-log relationships for α_{DSS} given by Chen & Kulhawy (1994) were used, as given below:

Undrained Uplift:

$$\alpha_{DSS} = 0.63 - 1.12 \log [s_u(DSS) / p_a] \tag{4}$$

Undrained Compression:

$$\alpha_{DSS} = 0.72 - 0.79 \log [s_u(DSS) / p_a] \tag{5}$$

in which p_a = atmospheric pressure in the desired stress units. An upper limit of α_{DSS} = 1.0 was adopted, in accordance with typical geotechnical practice.

The resulting $E_u/s_u(DSS)$ and $E_u/\alpha s_u$ are plotted versus D/B in Figures 6 and 7, respectively. Mean and COV values of $E_u/s_u(DSS)$ and $E_u/\alpha s_u$ for these load tests, considering uplift and compression separately, are given in Table 2. These statistics, and examination of Figures 6 and 7, indicate similar results for normalizing by either $s_u(DSS)$ or αs_u. Typical upper and lower bounds to $E_u/s_u(DSS)$ and $E_u/\alpha s_u$, excluding obvious outliers, are provided in the figures. The lower bound of 200 proposed by Callanan & Kulhawy (1985) is valid for $E_u/\alpha s_u$, but a value of 100 appears to be more appropriate for $E_u/s_u(DSS)$. The upper bounds range from a high of about 5000 for shafts with small D/B to 2000 or less for shafts with high D/B values.

3.3 *Soil Moduli Normalized by q_c*

The elastic modulus of cohesive soils also has been correlated with in-situ test results. Recognizing this, the back-calculated values of E_u from the load tests were normalized by the cone tip resistance (q_c). Of the 87 shafts in which values of E_u were back-calculated, in-situ penetration testing results [either cone penetration test (CPT) or standard penetration test (SPT)] were available for 34 cases, with 14 uplift and 20 compression. The SPT N-value profiles were converted to equivalent CPT q_c profiles using

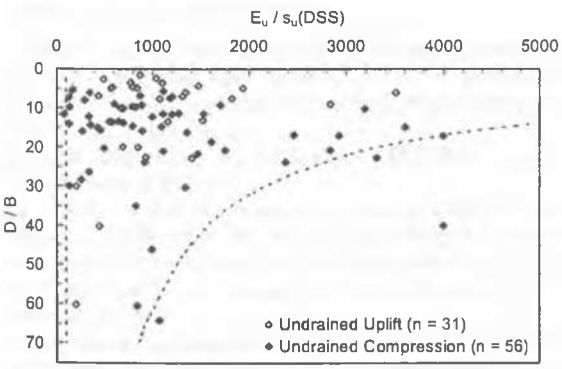

Figure 6. E_u / s_u (DSS) vs. D / B for Shafts in Undrained Loading.

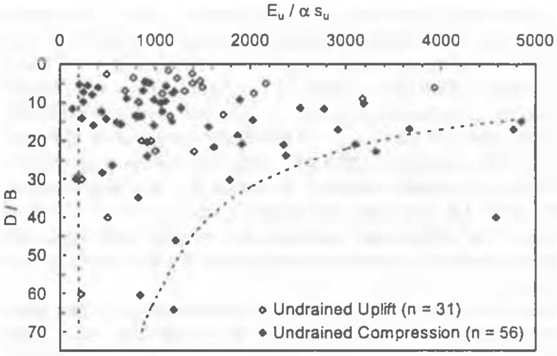

Figure 7. E_u / α s_u vs. D / B for Shafts in Undrained Loading.

Table 2. Summary of Normalized Elastic Soil Modulus Data.

Normalized	Uplift			Compression		
Modulus	Mean	COV	n	Mean	COV	n
$E_u/s_u(DSS)$	1100	0.64	31	1150	0.89	56
$E_u/\alpha s_u$	1250	0.62	31	1430	0.84	56
E_u/q_c	12.7	0.67	14	25.3	0.86	20

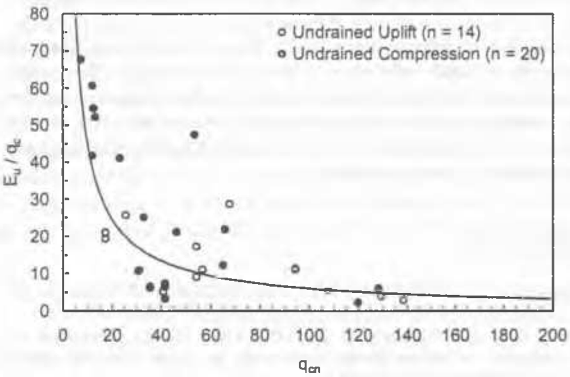

Figure 8. E_u / q_c vs. q_{cn} for Shafts in Undrained Loading.

the N-q_c relationship proposed by Kulhawy & Mayne (1990), as given below:

$$(q_c / p_a) / N = 5.44\,(D_{50})^{0.26} \tag{6}$$

in which D_{50} = mean grain size (mm). The resulting q_c values were averaged over the shaft depth (D) and were used to normalize E_u, the results of which are given in Table 2.

An analysis of these data indicates that all three normalized E_u ratios [$E_u/s_u(DSS)$, $E_u/\alpha s_u$, and E_u/q_c] have COVs on their means ranging from about 60 to 70% in uplift to about 80 to 90% in compression. The increased uncertainty for the compression test data is most likely a consequence of complications introduced in modeling the behavior at the shaft tip.

In addition, the E_u/q_c data are plotted in Figure 8 versus a normalized, dimensionless cone tip resistance defined as follows:

$$q_{cn} = (q_c / p_a) / (\bar{\sigma}_{vm} / p_a)^{0.5} \tag{7}$$

in which $\bar{\sigma}_{vm}$ = mean vertical effective stress over the shaft depth (D). The usefulness of the mean trendline in the figure was evaluated for predicting ρ_{L1}. The overall results, considering data over the entire range of q_{cn} encountered, in uplift and compression separately, yielded overall COVs on the mean predicted to measured elastic limit displacements that were comparable to, if not greater than, the other values for the normalized E_u data in Table 2.

4 SUMMARY AND CONCLUSIONS

Using an expanded database, the L_1-L_2 interpretation method was re-examined for the axial behavior of drilled shafts in cohesive soils. The focus was on L_1, the elastic limit. The results showed that the interpretation procedure for the loads (Q_{L1} and Q_{L2}) was satisfactory, and that the mean ratio $Q_{L1}/Q_{L2} = 0.53$ in compression and 0.56 in uplift. The original Hirany & Kulhawy (1988) study suggested $Q_{L1}/Q_{L2} \approx 0.5$. For displacements, the original study indicated $\rho_{L1} \approx 0.4\%$ B for compression and probably similar for uplift, although it was not evaluated specifically. For the expanded database, the mean ρ_{L1} in compression = 0.55% B = 3.6 mm, and the mean ρ_{L1} in uplift = 0.19% B = 1.4 mm. The differences between the original and expanded studies are relatively small, on the order of 0.1 to 0.2% B or 1 to 1.5 mm.

The elastic limit load (Q_{L1}) and displacement (ρ_{L1}) then were used to evaluate the secant undrained soil modulus (E_u). Data analyses showed that three normalized E_u ratios [E_u/s_u(DSS), $E_u/\alpha s_u$, and E_u/q_c] have COVs on their means ranging from about 60 to 70% in uplift to about 80 to 90% in compression. These values are, in general, somewhat larger than the COVs for the mean values of ρ_{L1} presented in Table 1, expressed either as an absolute displacement (mm) or as a percentage of B. These data indicate that use of correlations representing E_u as a single multiple of either s_u(DSS), αs_u, or q_c for predicting the elastic limit displacement are no better than direct estimates of ρ_{L1} as a single absolute value or percentage of B. Therefore, while the elastic limit displacement can be estimated using mean normalized E_u values with available elastic solutions, it may be more appropriate to focus on the failure threshold load (Q_{L2}). Employing design factors of safety greater than 1.8 or 1.9 on Q_{L2} are likely to maintain the shaft-soil behavior in the elastic range. The subsequent elastic limit displacement then can be estimated using the ρ_{L1} values in Table 1. Clearly, large COVs are inherent in such elastic limit displacement predictions. Fortunately, the displacements typically are quite small.

REFERENCES

Callanan, J. F., and Kulhawy, F. H. 1985. Evaluation of Procedures for Predicting Uplift Movements. *Report EL-4107*. Palo Alto: EPRI.

Chen, Y-J., and Kulhawy, F. H. 1994. Case History Evaluation of Behavior of Drilled Shafts Under Axial & Lateral Loading. *Report TR-104601*. Palo Alto: EPRI.

Cushing, A. G. 2001. Small-Strain Elastic Deformation of Drilled Shafts in Axial Uplift & Compression Loading. *MS Thesis*. Ithaca: Cornell University.

Hirany, A., and Kulhawy, F. H. 1988. Conduct & Interpretation of Load Tests on Drilled Shaft Foundations. *Report EL-5915*. Palo Alto: EPRI.

Hirany, A., and Kulhawy, F. H. 1989a. Interpretation of Load Tests on Drilled Shafts (1): Axial Compression. In F. H. Kulhawy (ed), *Fndn Eng:Current Principles & Practices (GSP 22)*: 1132-49. New York: ASCE.

Hirany, A., and Kulhawy, F. H. 1989b. Interpretation of Load Tests on Drilled Shafts (2): Axial Uplift. In FH Kulhawy (ed), *Fndn Eng:Current Principles & Practices (GSP 22)*: 1150-59. New York: ASCE.

Kulhawy, F. H., and Mayne, P.W. 1990. Manual on Estimating Soil Properties for Foundation Design. *Report EL-6800*. Palo Alto: EPRI.

Poulos, H. G., and Davis, E. H. 1980. *Pile Foundation Analysis & Design*. New York: Wiley.

Withiam, J. L., and Kulhawy, F. H. 1981. Analysis Procedure for Drilled Shaft Uplift Capacity. In MW O'Neill (ed), *Drilled Piers & Caissons*: 82-97. New York: ASCE.