Interpretation of Uplift Load Distribution Data

La Distribution de la Force de Soulèvement

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SYNOPSIS Deep cylindrical foundations subjected to axial uplift transfer the imposed loads along the foundation length. The nature of this transfer is of primary importance in understanding foundation behavior. The load transfer normally is computed from the measured distribution of internal axial loads in the foundation. The computed transfer is very sensitive to small errors in the measurement of the internal loads. Every effort must be made to acquire and interpret the load distribution correctly. This paper examines (1) the nature of load distribution, (2) the interaction of concrete and reinforcing steel that influences load distribution measurements, (3) residual loads and (4) tip tension and suction. The relative significance of the pertinent factors is illustrated and a consistent approach is suggested for determining the load transfer in cylindrical foundations subjected to axial uplift.

INTRODUCTION

Deep cylindrical foundations resist axial uplift by transferring the applied load, Q, to the surrounding ground along the foundation sides and across the foundation tip, as shown in Fig. 1. The side support is described by the load transfer function with depth, $\tau(z)$, in units of stress. Tip support, Q_t, can be developed by tension or suction. The shape of the load transfer function and the magnitude of tip support are crucial to good foundation design. This paper focuses on these two points, and addresses some of the problems which arise in interpreting load test data for deep cylindrical foundations subject to axial uplift loads. Particular emphasis will be given to drilled shaft and pile foundations.

DETERMINATION OF LOAD TRANSFER

The load transfer function, $\tau(z)$, is very difficult to measure directly, so it is normally inferred from the measured distribution of internal axial load. Considering the vertical force equilibrium of the infinitesimal foundation slice in Fig. 1, it can be shown that

$$\tau(z) = -\frac{1}{\pi D}\left(\frac{\partial P(z)}{\partial z} + w(z)\right) \qquad (1)$$

in which $P(z)$ = measured internal axial tensile load and $w(z)$ = weight per unit length of foundation, both as a function of depth, z. Fig. 2 shows a variety of load distributions and corresponding load transfer functions. Since $\tau(z)$ is computed from the derivative of $P(z)$, small errors associated with the measurement of $P(z)$ will be magnified in the computation of $\tau(z)$.

LOAD TRANSFER FUNCTIONS

The load transfer function varies considerably, as shown in Fig. 2, and depends on numerous factors, including the foundation type, method of construction, contractor skill, deformability of the surrounding ground and the foundation, strength parameters of the foundation interface with the surrounding ground, in-situ state of stress and sequence of loading. It is difficult at this time to quantify all of these factors;

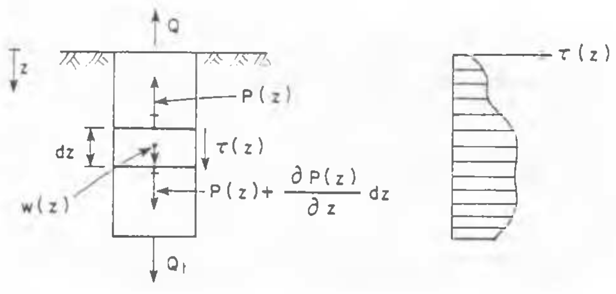

Fig. 1 Foundation Loads and Load Transfer

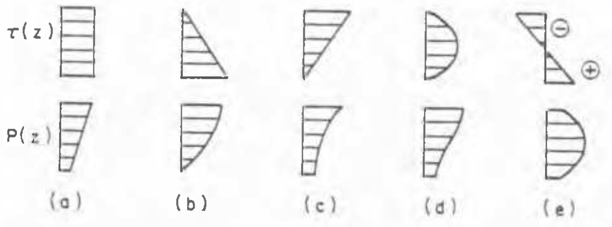

Fig. 2 Simple Load Transfer Functions and Corresponding Load Distributions (Vesić, 1970)

however some simple cases of load transfer can be examined to gain insight into the problem.

Consider the following cases: (I) relatively rigid foundation in a compressible medium of constant modulus, with compatible interface displacements (Coates and Yu, 1970), (II) relatively rigid foundation in a medium with stress-dependent modulus, allowing interface slip (Withiam and Kulhawy, 1978), and (III) compressible foundation of constant modulus in a rigid medium, with compatible interface displacements (Farmer, 1975). The results of these solutions are given in Fig. 3. By way of illustration, case I approximates a short horizontal grouted anchor in soil, case II a drilled shaft in soil, and case III a resin grouted rock bolt in very hard, competent rock. For rigid foundations, the load transfer reflects the variation of modulus in the medium. For compressible foundations, the greatest load transfer occurs near the point of load application, where the relative foundation-medium displacement is largest. Although field analogies occur for all of the cases shown in Figs. 2 and 3, space limitations preclude an evaluation of all of the cases. Therefore, case II was selected for further discussion.

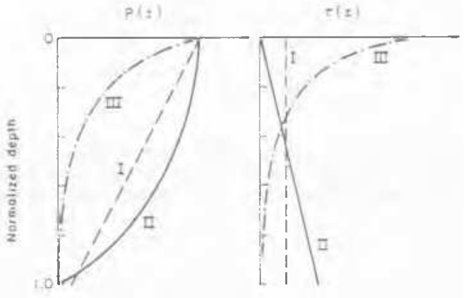

Fig. 3 Three Simple Cases of Load Transfer

Case II represents a drilled shaft subjected to uplift load. It was selected because it is not well-defined in the literature and design approaches vary widely. Fig. 4 summarizes the published internal axial load distribution data from 15 uplift tests in soils, normalized with respect to foundation depth and applied load. Details of these test results cannot be given because of space limitations; a complete discussion is given by Stewart and Kulhawy (1980). It should be noted, however, that the results include field and model tests, soils varying from loose sand to stiff clay, and drilled shaft, pipe pile and inflated anchor foundations.

The dotted line in Fig. 4 represents the case II solution. The data support the case II solution, even though there is significant scatter. The scatter is typically rationalized as being caused by soil variability, testing details and instrumentation reliability. However it is believed that there are three other significant factors which must be addressed to properly interpret uplift tests. These are: interaction of concrete and steel, residual loads, and tip tension and suction. These factors can influence markedly the measurement and interpretation of the internal axial loads.

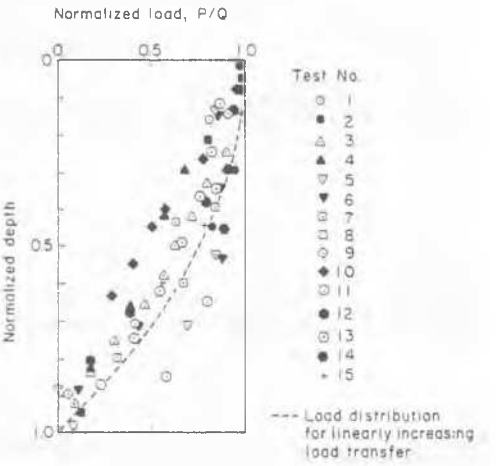

Fig. 4 Axial Load Distributions From the Literature (Stewart and Kulhawy, 1980)

CONCRETE-STEEL INTERACTION

The more common schemes for measuring the axial load distribution include strain gauging the reinforcing steel in drilled shafts and grouted anchors, or using concrete embedment gauges. The internal load is deduced from the measured strain. For compression members, it is assumed that the foundation is an ideal composite material, with the strain uniform across each section. Therefore the load is distributed between steel and concrete components consistent with their relative stiffness.

For tension members the situation is more complex because of concrete cracking. Consider the transverse cracking shown in Fig. 5. No tensile load is transmitted across the crack by the concrete; the entire load is resisted by the reinforcing steel. The resulting strains are shown schematically. Fig. 5 implies two main points: (I) The strain in the reinforcing steel at or near a discontinuity in the concrete is larger than that in an ideal composite member. Therefore, ideal composite behavior is not applicable since the measured strain in the steel will be too large near cracks and near the butt of the foundation. (II) By similar reasoning, the internal load

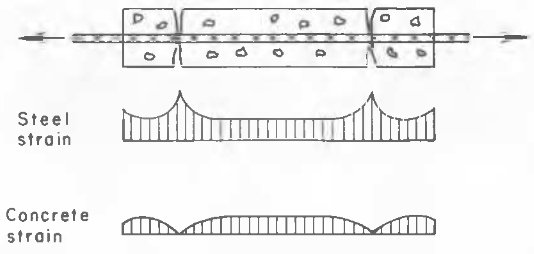

Fig. 5 Strain Distribution in Cracked Composite Section (Perdikaris, 1980)

computed from the measured strain in the concrete will be too small near cracks and near the butt of the foundation.

Shrinkage cracking can occur during curing, because the concrete shrinks while the reinforcing steel tends to resist the shrinkage. This process causes compression in the steel and tension in the concrete. If the tension is large enough, and it may be in the heavily reinforced sections typical of tension shafts, the concrete will crack. Unfortunately, it is impossible to predict the crack locations and their subsequent influence on the measured strains.

Cracking can also occur during tensile loading. Fig. 6 shows schematically the load displacement response for a reinforced concrete tension member. Initially, the member is stiff. As the axial load increases and additional concrete cracks develop, the member stiffness decreases gradually. The shape of Fig. 6 for a particular tension foundation will depend on the section properties and initial shrinkage cracking.

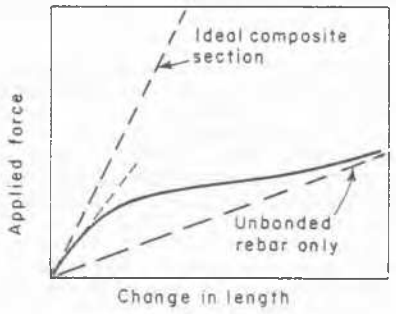

Fig. 6 Applied Tensile Force vs. Length Change of Composite Member (Perdikaris, 1980)

Evangelista and Sapio (1969) suggest assuming ideal composite behavior until the concrete is stressed to its tensile strength, after which the steel carries the entire load. This rule of thumb should be tempered by the results shown in Figs. 5 and 6, because crack locations normally are unknown and large tensile displacements must occur before the steel acts alone throughout the member.

This phenomenon is illustrated by the field data in Fig. 7. The axial strain distributions expected for ideal composite behavior and for reinforcing steel alone are shown for a linearly increasing load transfer (case II). The theoretical cracking strain of the concrete is 102 x 10^{-6}. The top 75% of the foundation is stressed beyond the cracking strain, but nowhere do the observations indicate that the steel carried the entire internal axial load. This test shows the necessity for using a more reliable scheme for measuring the internal loads in tension shafts. One such scheme is to install inserts in wet concrete to induce the inevitable tension cracks at strain gauge levels, insuring that the entire internal load is carried by the steel.

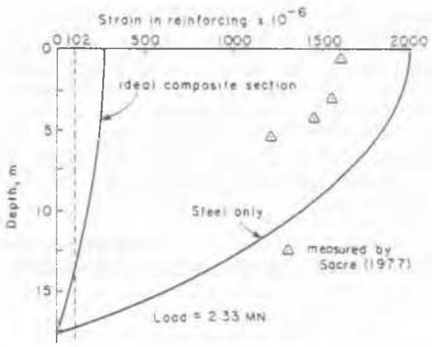

Fig. 7 Predicted and Measured Strains in Drilled Shaft Uplift Test

RESIDUAL LOADS

Another consideration is the zero load state. All measurements must be referenced to a zero condition. After installation of a driven pile, shrinkage during curing of a concrete shaft, and loading and unloading of a compressible pile, internal residual axial loads exist in the foundation, even in the absence of applied butt loads. In Fig. 2e, the foundation has expanded after installation, perhaps as a result of elastic expansion after unloading or driving. The soil exerts loads on the foundation resisting the expansion. These external loads are resisted by the internal loads shown in the lower part of Fig. 2e. This clearly is not a zero load condition and errors will result if the measured internal axial load distribution, P(z), in Fig. 2e is assumed to be the zero condition.

Fig. 8 (Tan and Hanna, 1974) shows the actual internal load distribution of a model foundation after installation. If the residual load was not recognized, the erroneous internal axial load distribution shown by the dotted line would have been determined. Signficantly different load transfer functions are determined from the two internal load distributions.

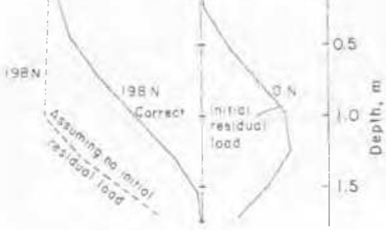

Fig. 8 Effect of Residual Load on Measured Load Distribution (adapted from Tan and Hanna, 1974)

TIP TENSION AND SUCTION

Compression foundations typically are assumed to develop a major portion of design capacity at the tip. The tip resistance for tension foundations is generally assumed to be zero because many soils have low tensile strengths and construction practices often result in a thin smear zone of low tensile strength at the tip. In ground with significant tensile strength and with careful construction practices, a tip tension may develop.

Some investigators (Adams and Radhakrishna, 1970 and Ismael and Klym, 1978) have observed or inferred suction forces beneath tension drilled shafts in relatively impermeable soils. A suction force is not a tension but represents a decreased pressure. Suctions are limited to zero absolute pressure or about 101 kN/m^2 gauge pressure. The suction force will dissipate with time. Radhakrishna (1973) measured suction beneath a tension shaft that required some 40 days to dissipate.

Tip suction forces may be significant. Adams and Radhakrishna (1970) report 10 to 20% of the ultimate load in tip suction in a short ($\ell/d=4$) underreamed pier in heavily overconsolidated clay. Back calculation shows the suction to be about 35 kN/m^2. Ismael and Klym (1978) report that 12% of the ultimate load for a 1.5m, $\ell/d=7.6$ straight-sided shaft in firm to stiff fissured silty clay was carried by suction. This is back calculated as 48 kN/m^2. Other similar examples exist in the literature.

Tip tension and suction are important in the interpretation of the axial load distribution because they represent a load intercept at the foundation tip. Disregarding this intercept will suggest a load distribution and load transfer different from the actual. Differentiating between tension and suction is difficult at the present time, unless pore pressure measurements are made at the tip. It must be noted that tip forces may be significant in some field situations. However, the suction can only be relied on for short-term loading, while the tension is permanent and can be relied on for long-term loads.

CONCLUSIONS

Load transfer is of major importance in foundation design, and is normally computed from measured axial loads in the foundation. For drilled shaft and pile foundations in soil, subjected to axial uplift loads, the studies presented in this paper lead to the following conclusions:

(i) the axial load distribution is essentially parabolic, which yields a linearly increasing load transfer,
(ii) concrete cracking during curing and loading can markedly affect the measured load distribution and the computed load transfer,
(iii) residual foundation loads must be corrected for in load test evaluations, and
(iv) tension or suction forces at the tip may be significant and will affect the measured load transfer.

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