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LOAD TESTS ON DRILLED SHAFTS FOR HIGHWAY BRIDGES

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ABSTRACT

Most of the highway bridges are supported on deep foundations. Safe and economical design and construction of deep foundations requires the use of rational procedures to determine the load capacity of the foundation. A static load test may be conducted to measure the response of a pile under applied load. Conventional static tests include axial compressive, axial tensile and lateral load testing. The purpose and advantages of load testing are explained in the light of large-scale construction of deep foundations for highways for the new millennia.

This paper presents a case history of load tests on high capacity drilled shafts. An adequate foundation design can be made with detailed subsurface exploration and soil testing, subsurface profile development through in situ tests, and static analysis. The results are compared with available solutions. Based on the results of the testing program, load transfer curves are provided for analysis. The focus of the paper is to give some useful information on load tests on drilled shafts along with a case history.

KEY WORDS

Drilled shaft, ultimate capacity, point resistance, side resistance, interpreted failure load, load test

INTRODUCTION

A large number of highway bridges are supported on drilled shafts. A drilled shaft is also known as drilled pier, drilled caisson, bored pile etc. The construction of drilled shafts is done by making a cylindrical excavation, placing a reinforcing cage if required, and then concreting the excavation. Shaft diameters of about 6m (20 ft) and depths exceeding 76 m (200 ft) are possible with available drilling equipment. Drilled shafts have added advantage over driven piles with respect to noise and vibration, and absence of a pile cap. In view of these advantages, drilled shafts have become the preferred type of foundation in many geological settings around the world.

Major advances in design of drilled shafts have been made possible during the past 30 years due to extensive field load testing, controlled laboratory testing and sophisticated numerical simulations. Kulhawy (1991), Greer and Gardner (1986), Reese and O'Neill (1988) summarized the useful information on the subject. Based on these studies, realistic analysis and design procedures have been developed. Performance of drilled shaft foundations also depends on the construction method used. The design engineer must be aware of the most recent information on construction methods, equipment, and their applicability in different subsurface conditions.

GENERAL BEHAVIOR

The general form of load-displacement curve for a drilled shaft in axial compression is shown in Fig. 1 (Kulhawy, 1991). The upper curve represents the total load applied to the top of the shaft. The other two curves (Fig. 1) separate the load into its side (or skin) and tip (or toe) resistance. When a compressive load is applied to the top of a shaft, downward displacement of the shaft occurs. This facilitates the mobilization of the soil shearing resistance. Thus the applied load is transferred to the supporting soil. As a result, the applied load becomes progressively smaller in the shaft with depth. To better understand the load-transfer behavior, Fig. 2 is very much helpful. At the point A (Fig. 1) of the loading, tip load is smaller than the load transferred to the soil. As the top load is further increased to point B, all of the available soil shearing resistance is mobilized along the side of the shaft. Generally, side resistance is fully mobilized at shaft displacements between 0.2 in (5mm) and 0.5 in (12.5mm). Any further load transfer must now develop at the shaft tip. When the load is increased further to its maximum value, the full tip resistance is mobilized (point C in Fig. 1). The load transfer is given by the solid curve in Fig. 2c. Typically, the end-bearing resistance is fully developed at a displacement of about one inch (25.4mm) or more (4% to 5% of shaft diameter). Figures 1 and 2 together illustrate several very important behavioral issues for drilled shafts in compression (Kulhawy, 1991).

1. The load-displacement response is generally nonlinear.
2. The full side resistance develops at relatively small displacements.
3. The full tip resistance develops at relatively large displacements.
4. The load transfer between the side and tip is a function of (i) Available shearing resistance along the side and below the tip, (ii) Geometry of the shaft (iii) Load level, and (iv) Relative stiffness of the shaft and soil

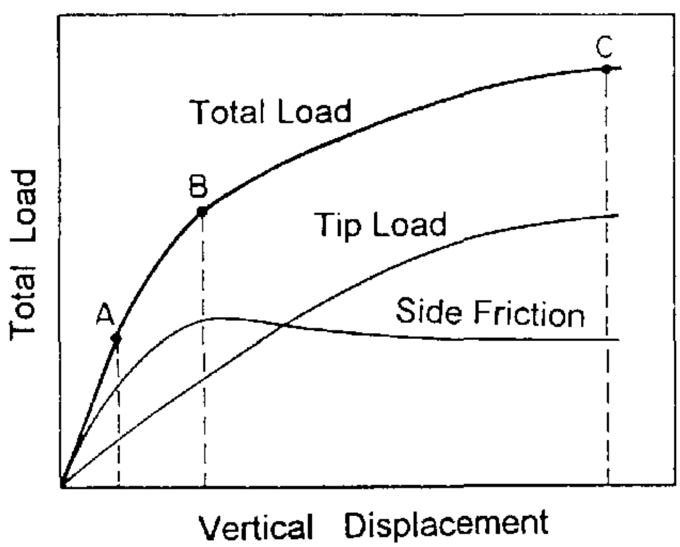

Fig. 1 Load displacement behavior for drilled shaft in compression

AXIAL COMPRESSION CAPACITY

The general equation for the ultimate capacity Q_u of drilled shafts in compression is:

$$Q_u = Q_p + Q_s \pm W \tag{1}$$

Where $Q_s = f_s A_s$ = skin resistance
$Q_p = q_p A_p$ = point resistance
f_s = unit skin friction on shaft
q_p = unit bearing resistance at shaft base
A_s = cross-sectional area of shaft
A_p = cross-sectional area of the shaft base
W = foundation weight, (-) for compression, (+) for uplift

As noted earlier, both Q_s and Q_p are displacement-dependent and develop their limiting values at significantly different displacements. The skin resistance represents the interface shearing resistance available along the shaft surface

and is given by

$$Q_s = \int_{surface} \tau(z)dz \tag{2}$$

z is the depth shown in Fig. 2. For a circular drilled shaft of diameter B, the above equation takes the following form

$$Q_s = \pi B \int_0^D \tau(z)dz \tag{3}$$

The point resistance is estimated as a bearing capacity problem and is given by

$$Q_p = q_p A_p = q_{ult} \pi B^2 / 4 \tag{4}$$

Where q_{ult} = ultimate bearing capacity. The general equation for the ultimate bearing capacity of a strip footing is given by the Terzaghi-Buisman equation (Vesic, 1975)

$$q_{ult} = cN_c + 0.5B\gamma N_\gamma + qN_q \tag{5}$$

in which c = cohesion, γ = unit weight of soil, q = vertical stress at shaft tip (γD), and N_c, N_γ, N_q = dimensionless bearing capacity factors.

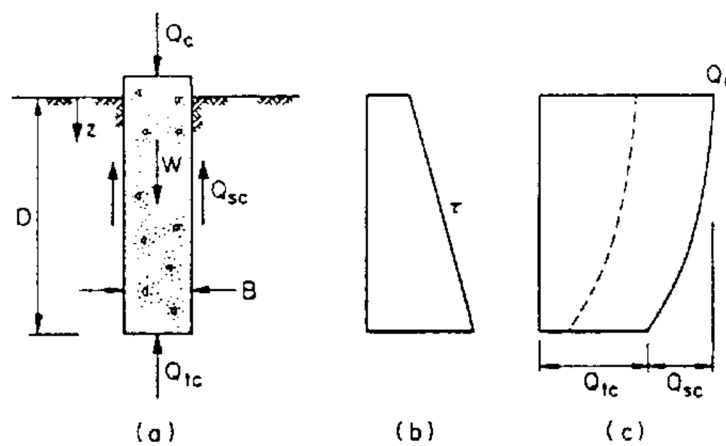

Fig. 2 Idealized force equilibrium diagram for drilled shaft in compression

AXIAL UPLIFT CAPACITY

When an uplift (tensile) load is applied to the top of a straight-sided drilled shaft, upward displacement occurs mobilizing soil shearing resistance. Very little tip resistance is developed. For all practical purposes, it can be neglected. Hence, the capacity results from side resistance and the weight of the shaft. There has been speculation that the skin resistance in uplift would be less than that in compression. Kulhawy et al(1983) examined possible Poisson's ratio effects for shafts in soil and discounted the negligible effects.

Stas and Kulhawy (1984) examined a large number of load test data and concluded that there is no appreciable difference between uplift and compression skin resistance.

SIDE RESISTANCE

There are three design methods those are considered the best among methods used to estimate ultimate side resistance of drilled shafts in sands and gravels: Meyerhof (1976), FHWA/Reese and O'Neill (1988), and Kulhawy (1991). The Meyerhof equation is entirely empirical and relies on correlation with in-situ tests. The FHWA method combines soil mechanics principles with empiricism. The Kulhawy method relies on basic soil mechanics principles with some adjustments for construction conditions. The following paragraphs summarize each method and give the critical design equations for drilled shafts in cohesionless materials only.

Meyerhof Method

Meyerhof (1976) proposed an empirical relation based on the results of the field tests. The ultimate unit skin friction of a drilled shaft in sand, in tons per square foot (tsf), is given by

$$f_s = \frac{N}{100} \le 0.5\text{tsf} \qquad (6)$$

where N is the average standard penetration resistance within the embedded length of the shaft. The ultimate side resistance is estimated by multiplying the unit resistance by the shaft surface area.

FHWA/Reese and O'Neill Method

The FHWA method was developed by Reese and O'Neill (1988) and is a semi-empirical method based on a database of 41 drilled shaft load tests. The ultimate unit side resistance in sand is given by

$$f_{sz} = \beta\sigma_z' \le 2.0tsf \qquad (7)$$

The ultimate capacity is obtained by integration of f_{sz} over the length of the shaft, L.

$$Q_s = \int_0^L \beta\sigma_z'\,dA \qquad (8)$$

where f_{sz} = ultimate unit side resistance in sand at depth z

σ_z' = vertical effective stress in soil at depth z

$\beta = 1.5 - 0.135\,z^{0.5}$, $0.25 \le \beta \le 1.2$ (9)

z = depth below ground surface in feet (0.33m)

dA = differential surface area of the shaft

The parameter β varies with the coefficient of lateral earth pressure K. Experimental studies have shown that the coefficient, both for soil and fresh concrete, exhibits some decrease with depth.

Kulhawy Method

The Kulhawy method (1991) proposes equations to determine ultimate drilled shaft capacity for both axial compression and uplift in drained and undrained conditions. The ultimate drained side resistance is simply a summation of the available soil shearing resistance over the side area of the shaft. It is given by

$$Q_s = \pi B\int_0^L \sigma_h \tan\delta\,dz \qquad (10)$$

where σ_h' = horizontal effective stress, and δ = drained friction angle for the soil-shaft interface. This equation can be expressed as

$$Q_s = \pi B\int_0^L \sigma_z' K \tan\delta\,dz \qquad (11)$$

where K = coefficient of lateral earth pressure (σ_h'/σ_z')

B = shaft diameter, σ_Z' = vertical effective stress,

L = shaft length

The interface friction angle δ can be expressed as a fraction of the soil friction angle ϕ. For good construction techniques, δ/ϕ equals 1 for rough surfaces in case of cast-in-place concrete. With poor slurry construction this ratio could be 0.8 or lower.

Kulhawy (1991) suggests that the coefficient of lateral earth pressure K is perhaps the most important and difficult parameter to determine. It is a function of the original in-situ horizontal stress coefficient K_o and stress changes caused by construction, loading, and time. Analysis of field load tests has shown K ranging from about 0.1 to over 5. A simplified relationship to determine K_o based on ϕ and OCR proposed by Kulhawy and Mayne (1982) is

$$K_o = (1 - \sin\phi)OCR^{\sin\phi} \qquad (12)$$

Generally, OCR is estimated based on geologic and construction history at each site and K_o is computed from the above equation.

INTERPRETATION OF LOAD TEST RESULTS

Hirany and Kulhawy (1989) reviewed the detailed literature on different methods for interpreting the load test results on drilled shafts. These methods fall into three broad categories: settlement, graphical construction, and mathematical model. The geotechnical conditions at site also affect the interpreted failure load. Based on their study, they provided a new simplified method of interpretation of failure load from a load test data. This method defines the load at a displacement equal to 4 percent of the foundation diameter as the interpreted failure load (Fig. 3). This method also provides guidelines for evaluating the tip and side resistance from load test data.

CASE HISTORY

Brazilian Society of Foundation Engineering (ABEF, 1989) conducted axial load tests on two drilled shafts as a pilot study for the 12th International Conference on Soil Mechanics and Foundation Engineering in 1989. The soil at the site is silty sand. The results of the SPT tests are shown in Fig. 4. The soil stratigraphy is also shown in Fig. 5. Fig. 6 and 7 show the load displacement curves. The load-transfer curves are shown in Fig. 8 and 9. Length of these drilled shafts was about 24.6 ft. Load tests were conducted in axial compression.

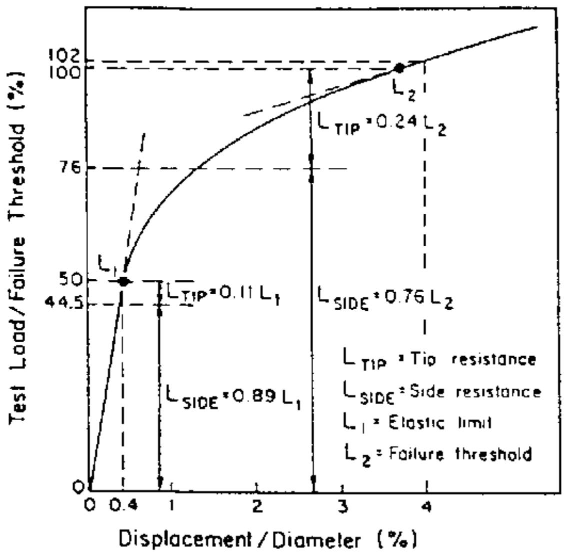

Fig.3 Average displacements at elastic limit and failure threshold

Load Test Interpretation Procedure

When a compression test is performed on drilled shafts, a load versus displacement curve is obtained having a shape as shown in Fig. 7. The ultimate capacity is estimated based on some interpretation methods such as double tangent, slope tangent, and 0.5 in (12.7mm) displacement. A description of ach method is presented below.

Double Tangent Method

The double tangent method is a graphical method in which the load corresponding to the intersection of the initial and final tangents to the load-displacement curve is interpreted as the failure load. The double tangent method is quick and easy to apply, however, it depends on individual judgment in determining the initial and failure slopes. In addition, if the final portion of the curve shows an increase in load with displacement, the interpreted failure load is decreased.

Slope Tangent

The slope tangent method suggested by Kulhawy et al (1983) is a modification of Davisson method for compression tests. A line is drawn parallel to the initial linear portion of the load-displacement curve beginning at a displacement equal to 0.15 inches. The load corresponding to the intersection of this line and the load-displacement curve is the ultimate capacity. The initial linear portion of the load-displacement curve is assumed to represent the elastic response of the foundation. Since the slope tangent method defines failure at a displacement of 0.15 inches (3.75mm) beyond elastic distortion of the shaft, the failure definition is tied to soil deformation and is independent of the length, area and elastic deformation of the shaft itself.

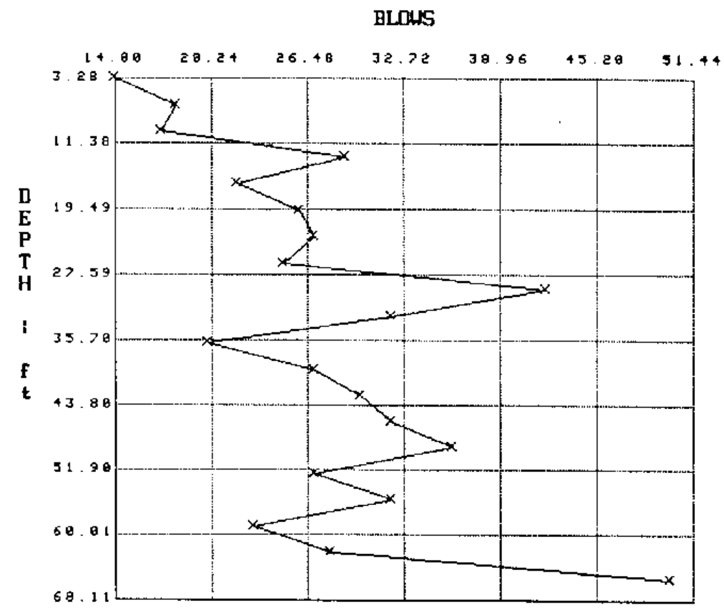

Fig. 4 SPT test results

Displacement of 0.5-inch

Based on review of a large number of load test results, Kulhawy and Hirany (1989) suggested that ultimate capacity be defined as the load at a displacement of 0.5 inch (12.7mm). They found that this deflection generally corresponded with what they called the threshold limit beyond which a small increase in load caused a significant increase in the displacement of the foundation. While the 0.5-inch criterion is simple and eliminates subjectivity of the user, it does not consider the elastic deformation of the shaft itself.

Rollins et al (1994) discussed the comparative importance of the various methods. They found that 0.5-inch displacement criterion yielded the highest ultimate capacity. Slope tangent and double tangent method provided 24% and 31% lower capacity than that given by 0.5-inch displacement criterion.

Comparison of Measured and Computed Capacities

Comparisons between the measured capacity using three methods described above, and the predicted capacity using Meyerhof equation are presented in Table 1.

Meyerhof method predicted 500 % more than the measured value for shaft # 1. For shaft # 2, it predicted 100% more than the measured value. Displacement of 0.5-inch criterion provided the maximum failure load in comparison with double tangent and slope tangent methods.

Table 1

Shaft #	Soil Type	Length (ft)	Diameter (in)	Mean SPT N	Meyerhof Q_u (ton)	0.5-inch Q_u (ton)	Slp. Tan. Q_u (ton)	Dbl. Tan. Q_u (ton)
1	SM	24.6	27.5	25	480	80	75	70
2	SM	24.6	12.6	25	113	58	48	45

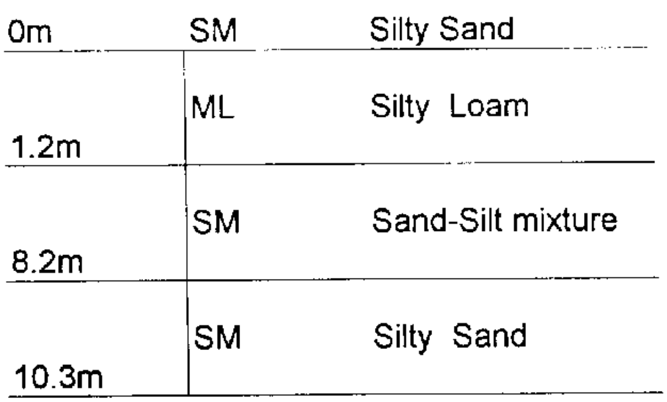

Fig. 5 Soil stratification

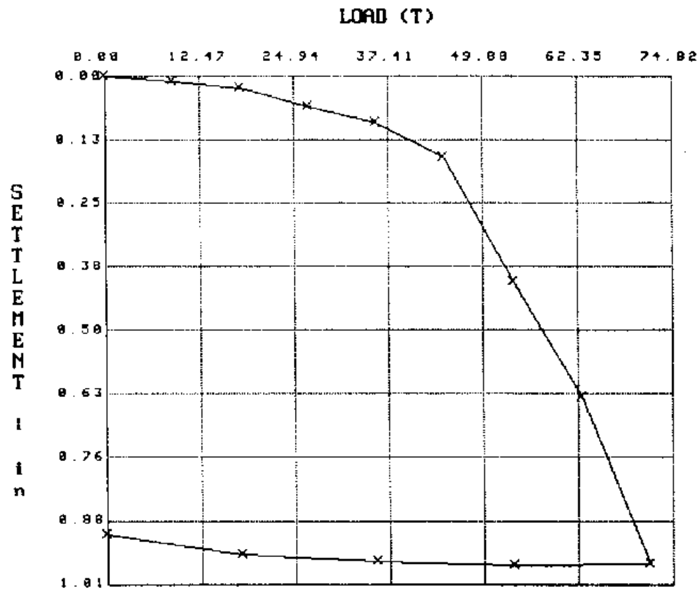

Fig. 7 Load settlement curve for load test on shaft # 2

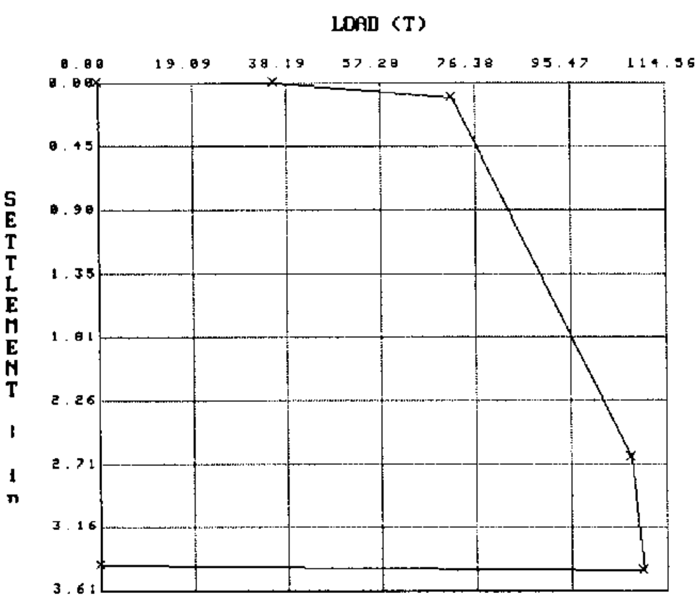

Fig. 6 Load settlement curve for load test on shaft # 1

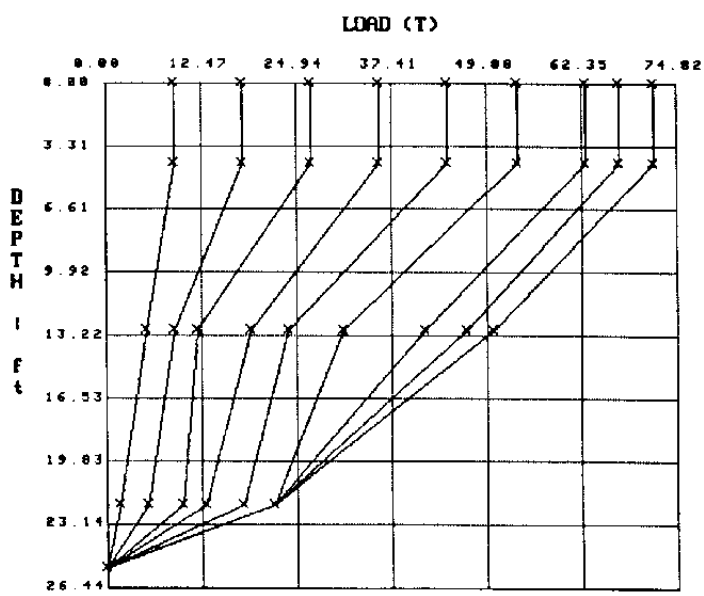

Fig. 8 Load transfer curves for shaft # 1

CONCLUSIONS

Based on the results of this study, it may be concluded that in this particular case Meyerhof's method predicted much higher than the measured capacity. For the shaft lengths tested, 0.5 inch criterion yielded measured capacities 10% to 30% higher than the slope tangent and double tangent methods. Load tests provided useful information regarding the total capacity of the drilled shafts.

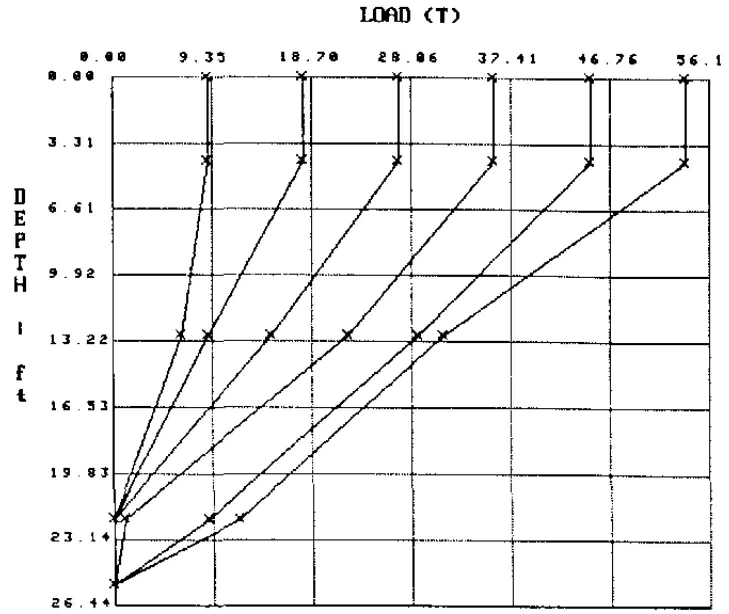

Fig. 9 Load transfer curves for shaft # 2

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