HYDRAULICS RESEARCH DIVISION

Technical Note

DATE:  December 1978        REPORT NO:  78-17

TITLE:  "Calculation of Bearing Capacity and Settlement for Proposed Installation of Vertical Automatic Profiler in Central Lake Erie Basin"

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REASON FOR REPORT:

This technical note has been written in response to a request by Mr. F. Roy, Mechanical Engineering Unit, SSD, NWRL The computational procedure is documented in detail in order to provide a reference for future use.

CORRESPONDENCE FILE NO:

1371

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# 1.0 INTRODUCTION

The configuration of an NWRI vertical automatic profiler is shown in Figure 1. The proposed installation site is not yet fixed, but it will be located approximately $81^\circ 15'$ W, $42^\circ 15'$ N in the central Lake Erie basin.

As shown in Figure 2, in this area the lake bottom is underlain by a deposit of very soft to soft post-glacial silty clay up to about 20 m thick near the centre of the lake (Lewis, 1966).

Designers of the profiler system would like to know in advance the amount of penetration that can be expected for both the anchor and the profiling winch (Figure 1).

# 2.0 SOIL CONDITIONS

No geotechnical data are available for the immediate area of interest. Geotechnical properties of the same deposit were, however, measured in eight deep cores during a 1972 offshore drilling programme in connection with the investigation of the foundation performance of jack-up drilling platforms (Lewis et al., 1972).

Geotechnical data employed for the calculations below come from laboratory testing carried out on soil samples from Boreholes 13163 and 13193 (Figure 2) which were located about 40 km SW and 30 km SW, respectively, of the proposed location for the profiler system.

For the calculation in Section 4.0 following, measured values of the cohesion (c) and the submerged unit weight ($\gamma'$) from Borehole 13163 are used. In other boreholes, not as many tests were carried out on samples from the silty clay topstratum. When data from Borehole 13193 or from other boreholes are used, the bearing capacity is overestimated due to the paucity of data and, consequently, smaller penetration estimates are obtained.

Results of one-dimensional consolidation tests on samples from Borehole 13193 are used in Section 5.0 following. These were the only consolidation tests performed during the 1972 programme.

## 3.0    BEARING CAPACITY THEORY

In the first analysis of the problem, the amount of penetration is estimated by means of the Terzaghi bearing capacity equaiton (Terzaghi and Peck, 1967), in which the two installations in question are regarded as shallow footings[1].

The bearing capacity equation assumes a footing failure to occur due to a downward displacement of the wedge of soil beneath the footing and the lateral displacement of the surrounding soil (Figure 3). The analysis further assumes predetermined rupture surfaces, as shown in Figure 3, and the bearing capacity represents the smallest load at the limit equilibrium that may lead to the failure of the soil-footing system. In the Terzaghi bearing capacity equation, the shear resistance above the base of the footing is disregarded and it is replaced with a surcharge

$$q = \gamma' D \qquad (1)$$

where q is the surcharge (kPa), $\gamma'$ is the submerged unit weight of soil (kN/m$^3$), and D (m) is the depth of the footing.

The ultimate bearing capacity, $q_u$ (kPa), is calculated from general equations

For a circular footing:       $q_{uc} = cN_c \, 1.3 + qN_q + 0.3 \, \gamma'BN_\gamma$    (2a)

For a square footing:       $q_{us} = cN_c \, 1.3 + qN_q + 0.4 \, \gamma'BN_\gamma$    (2b)

For a rectangular footing:     $q_{ur} = cN_c(1+0.3 \frac{B}{L})+qN_q+0.4 \, \gamma'BN_\gamma$    (2c)

where c is the cohesion of soil (kPa), $N_c$, $N_q$, and $N_\gamma$ are the dimensionless bearing capacity coefficients, and L (m) is the length of the rectangular footing.

For undrained conditions, such as those existing on a lake bottom, the angle of internal friction, $\phi$, is considered to be zero and, consequently, $N_c$=5.7, $N_q$=1.0, and $N_\gamma$=0, and equations (2a, b, c) simplify to

$$q_{uc} = 7.4c + \gamma'D \qquad (3a)$$

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[1]According to Terzaghi's definition, a shallow footing is the one in which the depth of the bottom of the footing, D, is less than the least dimension of the footing, B (see Figure 3).

$$q_{us} = 7.4c + \gamma'D = q_{uc} \tag{3b}$$

$$q_{ur} = 5.7c \left(1 + 0.3\frac{B}{L}\right) + \gamma'D \tag{3c}$$

The penetration D can be determined from equations (3a, c), provided that values of $q_u$, c, and $\gamma'$ (all of which generally vary as functions of D) are known. In this method, it is assumed that the footing continues to penetrate into the soil until the applied footing pressure becomes equal to the available bearing capacity of the soil. Gemenhardt and Focht (1972) used a very similar approach and reported very good agreement between predicted and observed penetrations of jack-up rig footings at 120 offshore locations in the Gulf of Mexico.

## 4.0 COMPUTED PENETRATIONS

The computation of footing pressures is summarized in Table 1 below.

**TABLE 1** Footing Pressures for the Anchor and the Profiling Winch and Some Other Quantitites.

|  | Anchor | Profiling Winch |
|---|---|---|
| Weight, kN | 3.336 | 1.323 |
| Footing Area, $m^2$ | 0.66 | 2.25 |
| Specific Gravity (assumed) | 7.86 | 7.86 |
| Submerged Weight, kN | 2.9'5 | 1.155 |
| Footing Pressure, kPa | 4.415 | 0.513 |

The geotechnical properties of interest are the submerged unit weight of soil, $\gamma'$, and the cohesion of soil, c. Examination of values determined in the laboratory on samples from Borehole 13163 shows that both $\gamma'$ and c increase with depth at approximately uniform rates (Figure 4).

For the point set of 12 $\gamma'$ values, the linear regression results in an equation

$$\gamma' = 2.200 + 1.448 \, D \tag{4a}$$

$$r^2 = 0.978 \tag{4b}$$

where $r^2$ is the coefficient of determination.

Similarly, the point set of 11 c values yields

$$c = 0.327 + 0.305 \, D \tag{5a}$$

$$r^2 = 0.933 \tag{5b}$$

For the present calculation, it is assumed that the c value, which is to be used in Equations 3a and 3c, is the one measured at the depth B/2 below the footing base. Furthermore, the average submerged unit weight above the footing base is used in these equations.

## 4.1 Penetration of Anchor

$$\frac{B}{2} = 0.455 \text{ m}$$

Therefore, at an arbitrary depth of the footing base D, the following equations are to be used

$$\gamma'_D = 2.2 + 0.724D \tag{6}$$

$$c_D = 0.466 + 0.305D \tag{7}$$

The relationship between the bearing capacity and the depth of penetration can be now expressed by a quadratic equation

$$q_{uc} = 0.724D^2 + 4.457D + 3.448 \tag{8}$$

The positive root of this equation for $q_{uc}$=4.415 kPa (the applied footing pressure) is then the estimated penetration depth of the anchor

$$\underline{D = 0.21 \text{ m.}}$$

## 4.2 Penetration of Profiling Winch

$$\frac{B}{2} = 0.60 \text{ m}$$

$$\gamma'_D = 2.2 + 0.724D \tag{6}$$

$$c_D = 0.510 + 0.305D \tag{9}$$

$$q_{ur} = 0.724D^2 + 4.286D + 3.448 \tag{10}$$

Since $q_{ur}$ for D=0 exceeds the footing pressure of 0.513 kPa, <u>no penetration is expected.</u>

The results and the bearing capacity vs penetration curves for the anchor and the profiling winch are plotted in Figure 5.

## 5.0    CONSOLIDATION THEORY

As an independent check on results obtained in 4.1 and 4.2, the problem is treated as that of time-dependent one-dimensional consolidation, using the well-established Terzaghi theory (Terzaghi and Peck, 1967).

### 5.1    Total Settlement

Using the empirical Equation 4a for $\Upsilon'$, the vertical profile of the existing overburden pressure, $p_o$ (kPa), is estimated to be

$$p_o = \Upsilon' D = 2.2D + 1.448 \, D^2 \tag{11}$$

This relationship is plotted in Figure 6.

Now, we want to compute $\Delta p$ (kPa), which is the increased pressure intensity, distributed nonlinearly with depth, due to the applied footing pressure. The computation of $\Delta p$ is carried out graphically by means of the Boussinesq method and the Newmark influence chart (Terzaghi and Peck, 1967). The results obtained for the anchor and the profiling winch are shown in Figure 7.

The amount of expected settlement in the underlying layer of the post-glacial silty clay can be computed from the equation

$$S = \int_0^H m_v \, \Delta p \, dD \tag{12}$$

where S is the settlement (m), $m_v$ is the coefficient of compressibility (1/kPa), and H is the thickness of the soil stratum (m), which experiences the increase in pressure $\Delta p$ due to the applied load.

Within the surficial stratum (depth 0-3 m) only three $m_v$ values are available from the laboratory consolidation tests on samples from Borehole 13193. A parabolic fit to these three points yields an interpolated curve (Figure 7)

$$m_v = 0.006D^2 - 0.041D + 0.071 \tag{13}$$

The total amount of settlement can be now computed by determining the shaded areas in Figure 8. The application of Simpson's rule for numerical integration yield the following results

- 6 -

For the anchor: $\qquad$ $S \approx 0.17$ m

For the profiling winch: $\qquad$ $S \approx 0.03$ m

i.e., the results, obtained by a completely different approach, agree quite closely with the penetration estimates in 4.1 and 4.2.

## 5.2 Rate of Settlement

The rate of settlement can be estimated from the solution of the second-order partial differential equation for one-dimensional consolidation

$$\frac{\partial u}{\partial t} = c_v \frac{\partial^2 u}{\partial D^2} \qquad (14)$$

where u is the excess pore pressure (kPa), t is time and $c_v$ (cm$^2$/s) is the coefficient of consolidation.

Of present interest is to find the degree of consolidation, U%, in relationship to the length of time, t (e.g. months), measured from the installation of the anchor and the winch.

According to the Terzaghi theory, this relationship is expressed by

$$U\% = f(T_v) \qquad (15)$$

$$t = \frac{H^2 T_v}{c_v} \qquad (16)$$

where $T_v$ is the dimensionless time factor. The relationship between U% and $T_v$ has been tabulated and plotted for principal practical situations (Terzaghi and Peck, 1967; Leonards, 1960). In the present computation, it is assumed that the initial excess pore pressure, $U_o$, decreases linearly with depth and becomes zero at the depth D=H. The results are plotted in Figure 9, which also shows the amount of settlement as a function of time.

The estimated time to reach 95% consolidation is

For the anchor: $\qquad$ $t_{95} = 26.1$ months

For the profiling winch: $\qquad$ $t_{95} = 11.6$ months

The assumed $c_v$ value used in the computation is $1.5 \times 10^{-3}$ cm$^2$/s.

Because of the number of assumptions made, the computation of the rate settlement has the character of a very crude estimate. The results are

particularly sensitive to selected $c_v$ values. For example, if $c_v$ is chosen to be 2 x $10^{-4}$ cm$^2$/s (which represents another test value on a sample from Borehole 13193), the results change drastically. In this case,

For the anchor: $t_{95}$ = 16.3 years

For the profiling winch: $t_{95}$ = 7.26 years.

In view of these uncertainties, a more refined theoretical analysis appears unjustified.

## 6.0　CONCLUSIONS

The railway wheel anchor is estimated to sink into the lake bottom 17-21 cm   The result is in agreement with the hindcast field experience of Technical Operations personnel who reported settlements less than 0.6 m based on the mudline on chains and the force required to recover it from the bottom.

The settlement of the profiling winch should not exceed 3 cm.   The winch was previously deployed in Kootenay Lake where it settled less than 10 cm, as evidenced by winch operation and lack of sediment in mechanism on recovery.

The settlement of anchor is expected to occur over the period of two-three years.   The time required to achieve 95% consolidation for the winch is about one year.   Both results represent very crude estimates, primarily due to uncertain values of the coefficient of consolidation in the post-glacial silty clay stratum.

# 7.0 REFERENCES

Gemenhardt, J. P. and J. A. Focht, Jr., 1970. "Theoretical and Observed Performance of Mobile Rig Footings on Clay". 2nd Annual Offshore Technology Conference, Houston, Paper No. OTC 1201, 10 p.

Leonards, G. A 962. "Foundation Engineering". McGraw-Hill Book Company, New York.

Lewis, C.F.M., 1966. "Sedimentation Studies of Unconsolidated Deposits in the Lake Erie Basin". Unpublished Ph.D. thesis, University of Toronto.

Lewis, C.F.M., A E. Wootton, and J. B. Davis, 1972. "Stratigraphic and Engineering Studies of Unconsolidated Sediments in Central Lake Erie near Erieau, Ontario". In Report of Activities, Geol. Survey Can. Paper 73-1A, pp. 205-210.

Sly, P G. and C.F.M. Lewis, 1972. "The Great Lakes of Canada - Quaternary Geology and Limnology". XXIV International Geological Congress Excursion A43.

Terzaghi, K. and R. B. Peck, 1967. "Soil Mechanics in Engineering Practice". 2nd edition, John Wiley and Sons, Inc.

BUOY
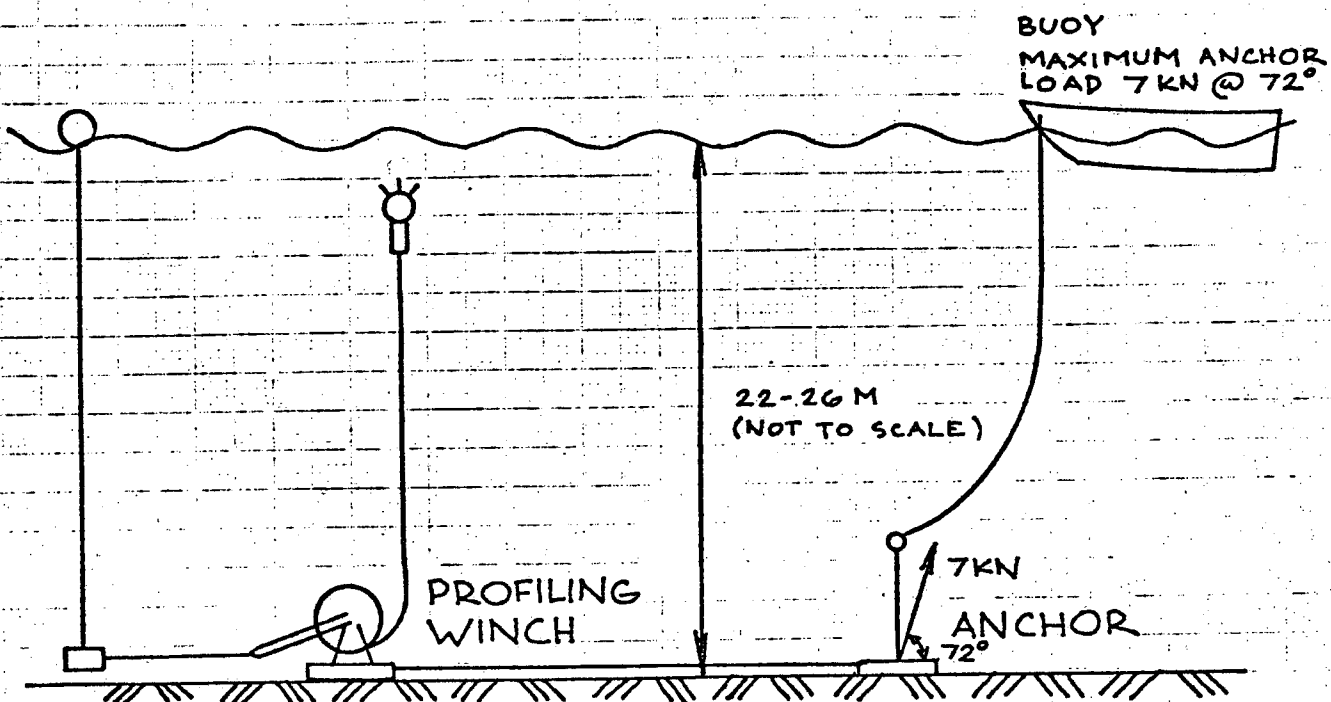MAXIMUM ANCHOR
LOAD 7 KN @ 72°

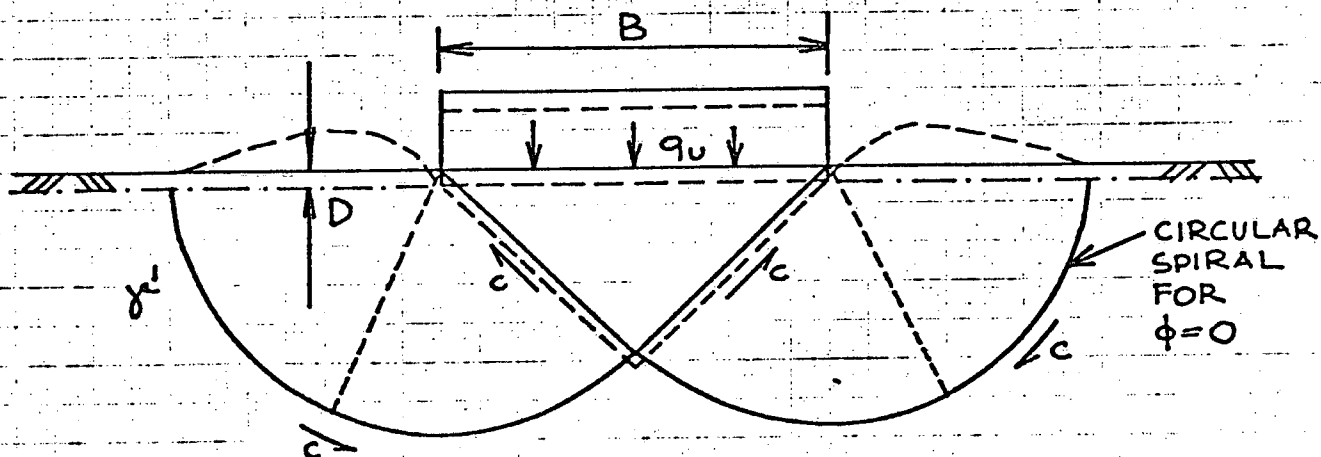22-26 M
(NOT TO SCALE)

7KN
ANCHOR
72°

PROFILING
WINCH

FIGURE 1. PROPOSED MOORING CONFIGURATION

B

$q_u$

D

$\gamma'$

c

c

c

c

CIRCULAR
SPIRAL
FOR
$\phi = 0$

FIGURE 3. MODE OF BEARING FAILURE (AFTER TERZAGHI)

LEGEND

- M — post-glacial mud; soft grey silty clay
- SM — soft grey mud with some sand; may range from continuous soft sandy mud to discontinuous clean sand and/or mud zones
- S — sand and/or gravel in offshore areas sand occurs commonly as a thin deposit over glacial clay sediments
- Gl — glacial sediments; semi-consolidated clay till or glaciolacustrine clay, commonly veneered with lag sand and/or gravel deposits
- R — bedrock, undifferentiated; in places covered with thin sand, mud or glacial deposits

lake erie
bottom sediment distribution
compiled by c.f.m. lewis
based on surveys by great lakes institute, 1960-64
cwrc 1967 (near shore)
ohio geological survey 1957-67
lundie 1933-6
pegrum 1929

⊕ PROPOSED LOCATION FOR MOORING

⊞ LOCATION FOR WHICH GEOTECHNICAL DATA AVAILABLE

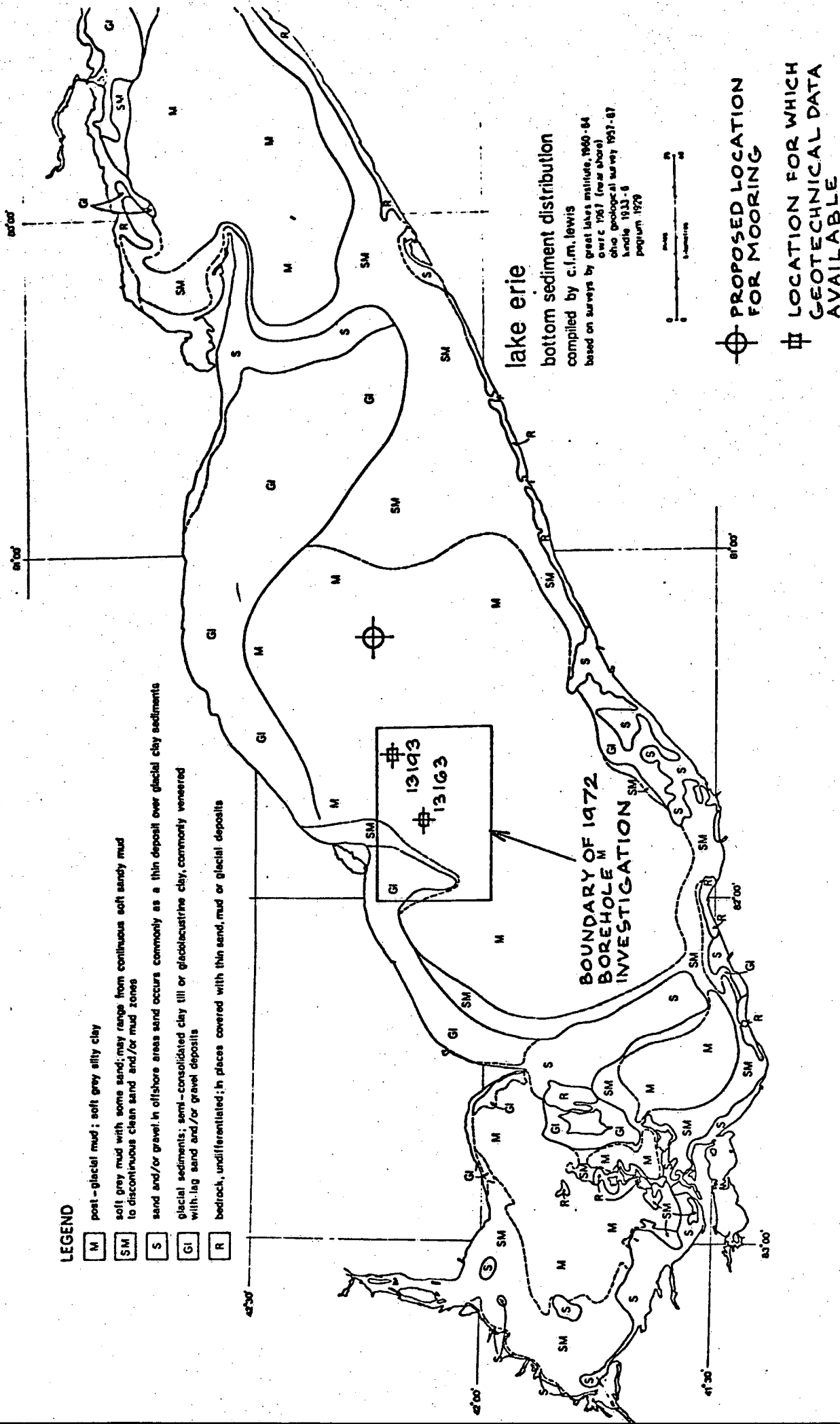BOUNDARY OF 1972 BOREHOLE INVESTIGATION

13193
13163

(SLY AND LEWIS, 1972)
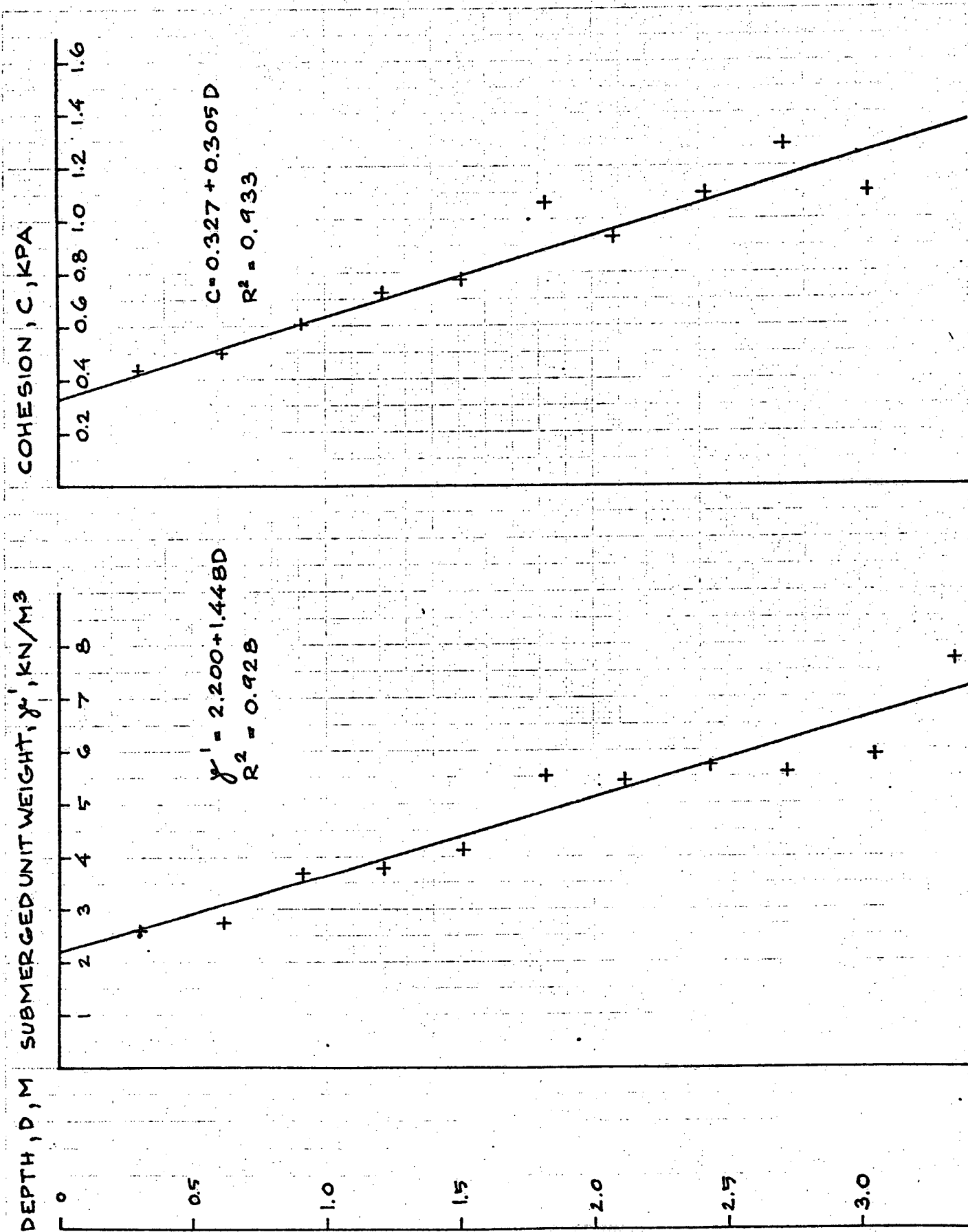
Fig. 2. Lake Erie bottom sediments.

FIGURE 4. SUBMERGED UNIT WEIGHT AND COHESION PROFILES IN BOREHOLE 13163
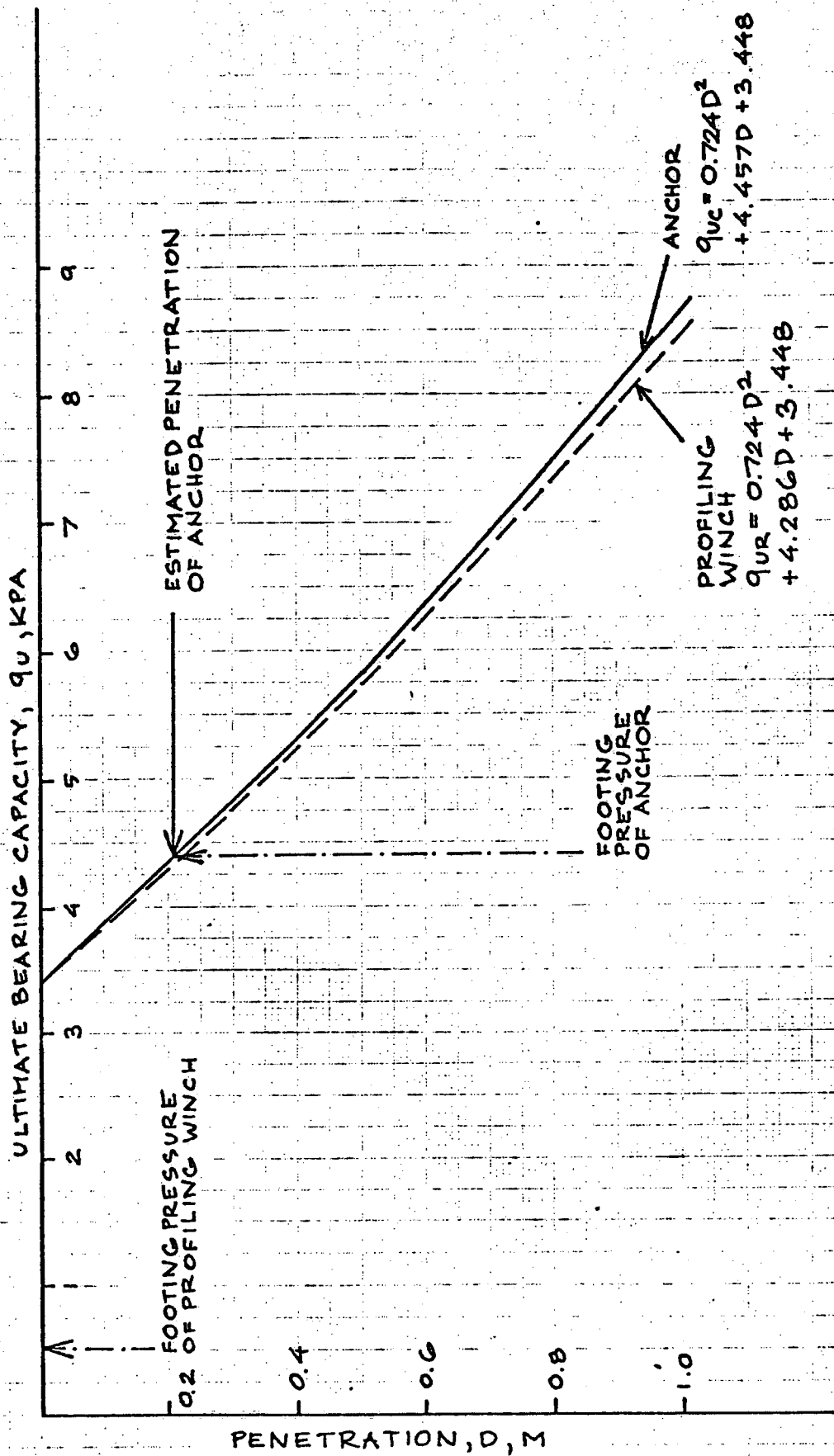
FIGURE 5.   RELATIONSHIP BETWEEN ULTIMATE BEARING CAPACITY AND FOOTING PENETRATION (FOR VALUES OF $\gamma'$ AND C AS PER FIGURE 4)
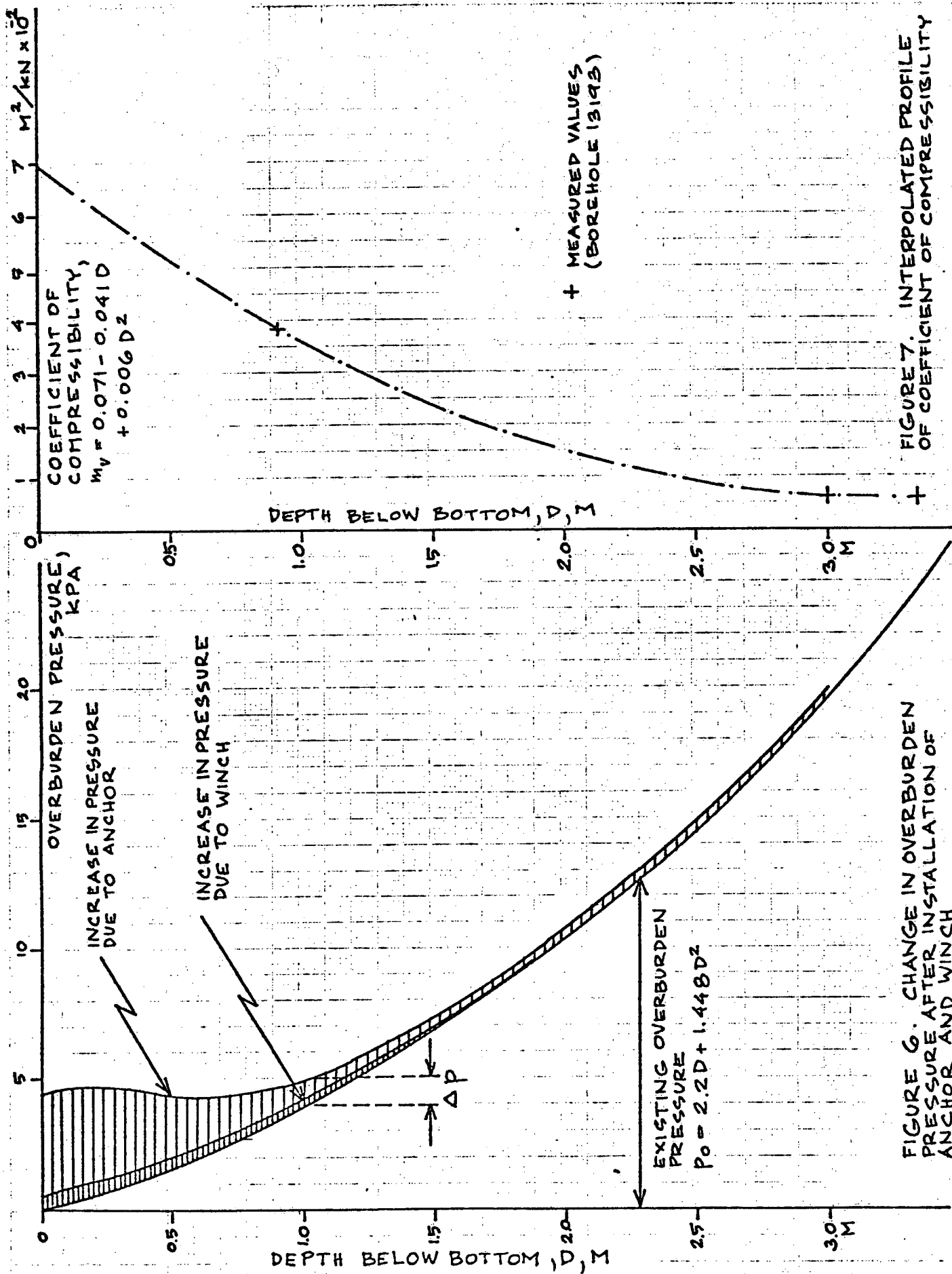
FIGURE 7. INTERPOLATED PROFILE OF COEFFICIENT OF COMPRESSIBILITY

COEFFICIENT OF COMPRESSIBILITY, $m_v = 0.071 - 0.041 D + 0.006 D^2$

+ MEASURED VALUES (BOREHOLE 13193)



FIGURE 6. CHANGE IN OVERBURDEN PRESSURE AFTER INSTALLATION OF ANCHOR AND WINCH

OVERBURDEN PRESSURE, KPA

INCREASE IN PRESSURE DUE TO ANCHOR

INCREASE IN PRESSURE DUE TO WINCH

EXISTING OVERBURDEN PRESSURE $P_0 = 2.2 D + 1.448 D^2$

$\Delta P$

DEPTH BELOW BOTTOM, D, M

PROFILING WINCH

$$S \approx \int_{0}^{2.0} m_v \Delta p \, dD \approx 0.03M$$

$m_v \Delta p \times 10^{-2}$

DEPTH BELOW BOTTOM, D, M

ANCHOR

$$S \approx \int_{0}^{3.0} m_v \Delta p \, dD \approx 0.17M$$

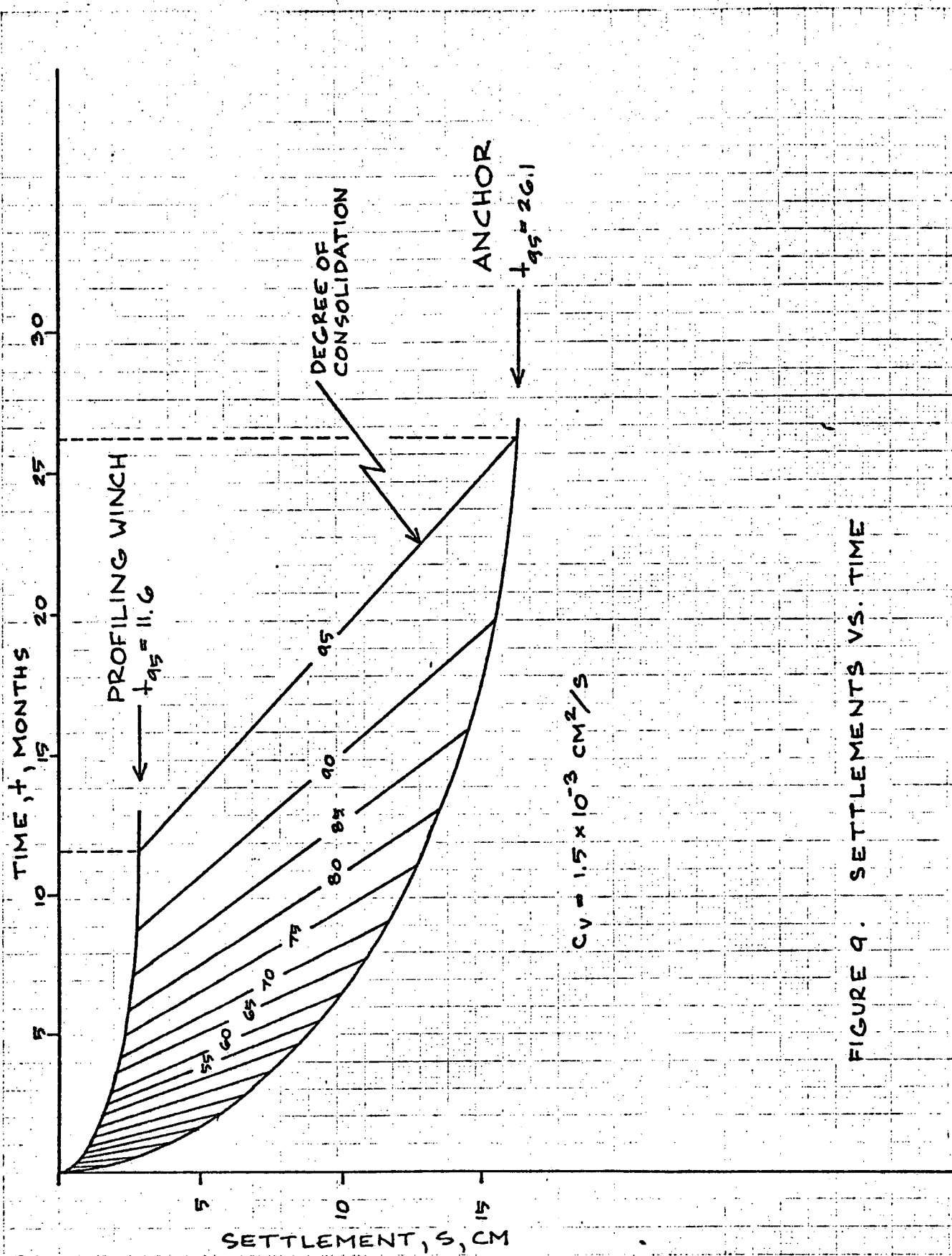$40 \, m_v \Delta p \times 10^{-2}$

DEPTH BELOW BOTTOM, D, M

FIGURE 8. ESTIMATED SETTLEMENTS OF ANCHOR AND WINCH

FIGURE 9. SETTLEMENTS VS. TIME

$C_V = 1.5 \times 10^{-3}$ CM²/S

DEGREE OF CONSOLIDATION

ANCHOR
$t_{95} = 26.1$

PROFILING WINCH
$t_{95} = 11.6$

TIME, $t$, MONTHS

SETTLEMENT, $S$, CM

95
90
85
80
75
70
65
60
55