DESIGN OF LARGE SLABS ON GRANULAR MATERIAL

CALCUL DES DALLES LARGES SUR MATERIAUX GRANULAIRES
РАСЧЕТ ПЛИТ БОЛЬШОГО РАЗМЕРА НА СЫПУЧЕМ ГРУНТЕ

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SYNOPSIS: An equation is developed relating settlement of a large slab on granular soil to in situ stresses, loading conditions and soil characteristics. The equation uses a modulus-confining pressure relationship based on laboratory tests and in situ stresses inferred from plate load tests. Soil-structure interaction is accounted for by using an iterative process involving the theory of subgrade reaction. Subgrade modulus values determined from pressure-settlement relations based on the derived equation were used in the design of a 400-foot wide base slab for an electric generating plant. The modulus values predicted are significantly smaller than values previously associated with granular materials, but agree with the results of recently published field studies. Average settlements predicted using the derived equation are in agreement with those being measured during construction of the electric generating plant.

INTRODUCTION

A key factor in the design of large heavily loaded slabs on soil is the idealization of the soil in a manner which insures proper evaluation of soil-slab interaction. Recent field studies (Bjerrum and Eggestad 1963, D'Appolonia et. al 1968, Schmertmann 1970), indicate that procedures previously used to
653 predict the behavior of large slabs sometimes give results which are non-conservative. Because existing procedures do not explicitly account for variations in soil compressibility with in situ and applied stress, and because it was necessary to account for these factors in the design of a 400-foot wide, 500-foot long, 6-foot thick slab for an electric generating plant, a new procedure, meeting these requirements, was developed. The development and application of this procedure are the subject of this paper.

The slab, for which this settlement and modulus prediction procedure was developed, will support Units 1 and 2 of the Bruce Mansfield Electric Generating Plant in Shippingport, Pennsylvania, U.S.A. The Station, which was designed by Commonwealth Associates, Inc., of Jackson, Michigan, is being constructed by the Central Area Power Coordination Group (CAPCO), a group of five investor owned utility companies in the north-central United States. The plant site is a high level terrace on the south shore of the Ohio River. The terrace consists of dense sands and gravels deposited by the river during the Wisconsin continental glaciations. Most of the area occupied by the slab had been quarried for sand and gravel aggregate over the past 20 years forming a pit extending 60 feet below slab elevation. To support the slab this pit was filled with sand and gravel compacted to a dense state. Due to the slope of the rock surface the total depth of natural sand and gravel plus fill beneath the slab varies from 40 to 100 feet.

Settlement predictions for structures on granular materials are generally made using theoretical equations with a constant modulus of elasticity or empirical equations using either standard penetration values (Meyerhoff 1965) or results of plate load tests (Terzaghi and Peck 1948). Modulus of subgrade reaction values are usually obtained as follows: Plate load tests or tables (Teng 1962) are used to determine modulus values for small plates. These results are modified using empirical equations to account for foundation width and embedment (Terzaghi 1955, Teng 1962). Elastic theory is only occasionally used to estimate modulus of subgrade reaction values.

Because the modulus of elasticity of a granular material is not constant with depth and stress level, and because standard penetration values cannot account for variations in foundation size, etc., procedures based on these factors alone are not suitable for accurate estimates of settlement. In situations which differ from those used in developing Terzaghi and Peck's (1948) empirical equation, recent field studies indicate that measured settlements may significantly exceed those predicted using this equation. Because the slab at the Bruce Mansfield Plant is much larger than those studied by Terzaghi and Peck, a more general equation was developed.

Modulus of subgrade reaction is by definition a ratio of stress to settlement, and some of the same difficulties encountered in predicting settlement are met in estimating modulus values. A graphic illustration of these difficulties is presented in Fig. 1, where values of k/k_1 (determined from published field studies) are plotted against corresponding values of footing width, B.

uniquely related to footing width. Therefore, a procedure accounting for other factors is required.

RELEVANT PARAMETERS

The basic factors governing the deformation of a soil mass are the loading conditions (including initial stresses), the bounding geometry, and the constitutive relations governing soil behavior. Because loading on a large slab may not be uniform the distribution of pressure transmitted to the soil by the slab will depend on the relative stiffness of the slab. Therefore slab flexibility should be included in specifying loading conditions. Parameters involved in estimating initial stresses include soil unit weight, residual stresses due to previous loading (including compaction), and coefficient of lateral earth pressure. Most design problems involve soil layers of large lateral extent; in these cases thickness is the only significant soil dimension.

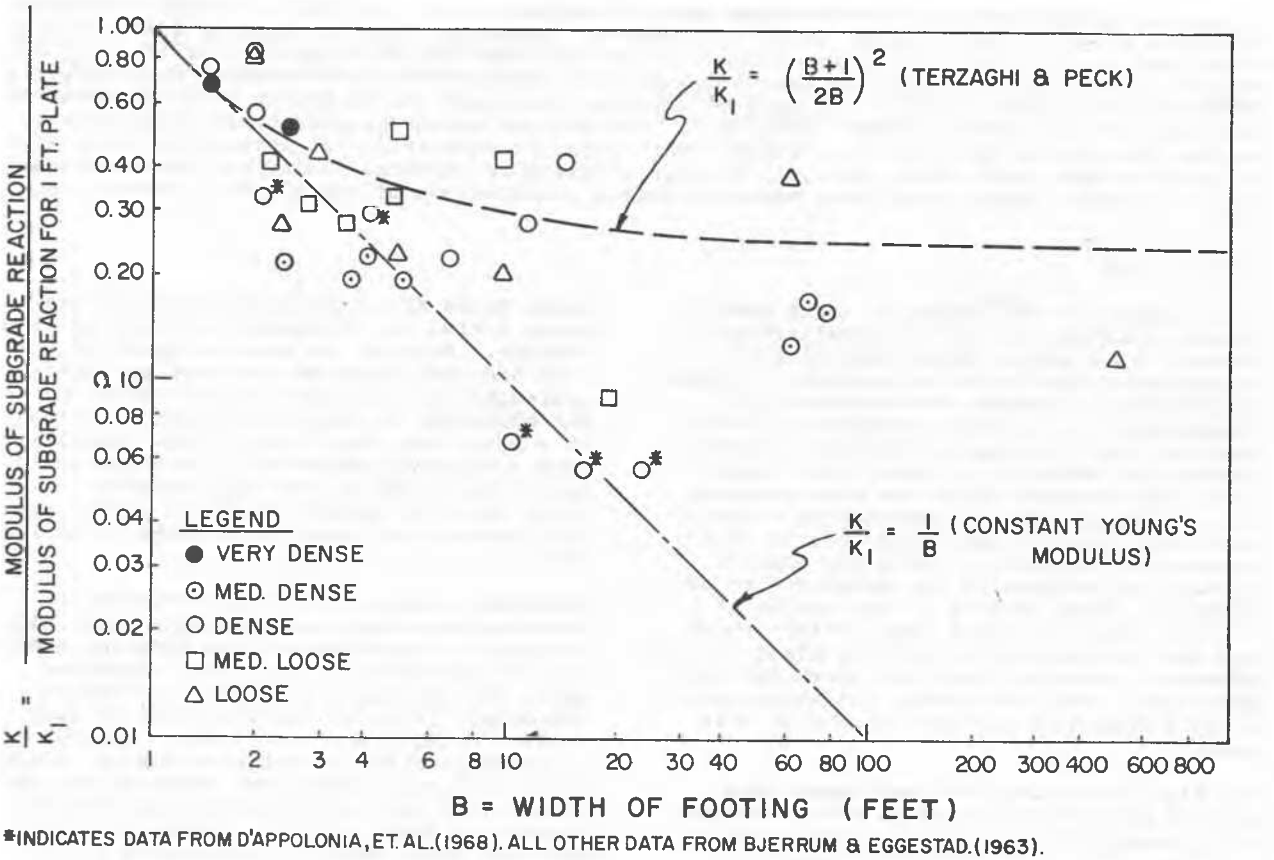

FIG. 1 SUBGRADE MODULUS RATIOS FOR SANDS AND GRAVELS

Considering the wide scatter of data it is clear that neither Terzaghi and Peck's empirical equation nor a theoretical equation based on constant Young's modulus can satisfactorily predict subgrade modulus values for all situations as the ratio k/k_1 is not

A variety of constitutive relations have been proposed for granular soils; however, recent evidence (Vesic and Clough 1968) indicates that for many granular materials, an elastic modulus which varies with confining pressure according to the relationship

$$E = E_1 \sigma_3^{\,n} \qquad (1)$$

satisfactorily represents soil behavior.

In order to check the ability of this relationship to represent the behavior of the sand and gravel used to support the slab at the Bruce Mansfield Plant, six-inch diameter samples were subjected to triaxial tests using various confining pressures. Each stress-strain curve obtained was approximated by a straight line and elastic moduli were computed. The data are satisfactorily represented by equation 1 provided E_1 = 1,250 pounds per square inch and n = 0.5.

In order to check the parameters E_1 and n obtained from the triaxial tests, settlements predicted using these parameters and the procedures developed herein were compared to the results of field plate load tests performed at various levels in the fill and natural soil. Four-foot square plates were tested; four pressure-settlement curves, representative of those obtained, are shown in Fig. 2. In order to generate curves falling in the range shown,

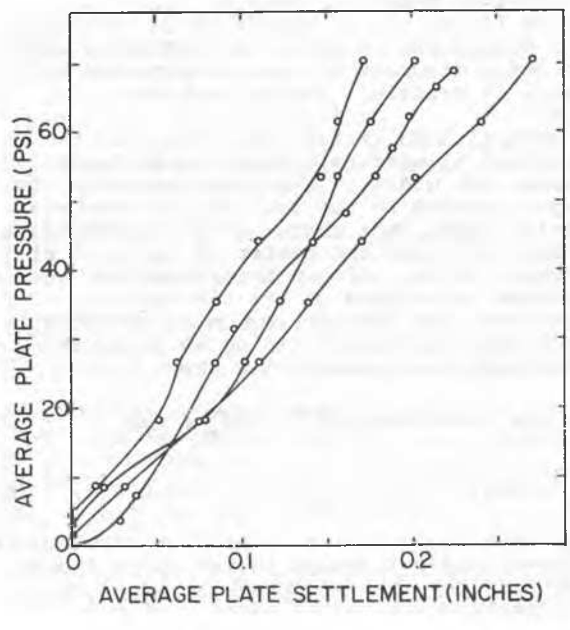

FIG. 2 PRESSURE-SETTLEMENT CURVES FROM PLATE BEARING TESTS

using the E_1 and n values given above and the procedures developed herein it is necessary to assume residual lateral soil pressures (due to compaction) of the order of 80 to 100 pounds per square inch. Because these values are unreasonable, the procedures used to obtain the E_1 and n values were re-examined.

Because each triaxial test involved loading at a constant value of σ_3, whereas a plate load test involves conditions in which σ_3 varies during loading, confined compression tests were performed as follows: Six-inch diameter samples were compacted and tested in a rigid mold approximately six inches high. Because of the lateral restraint the confining pressure increased during loading in a manner similar to that occurring just below the center of the plate loaded in the field. Four stress-strain curves, typical of those obtained, are shown in Fig. 3.

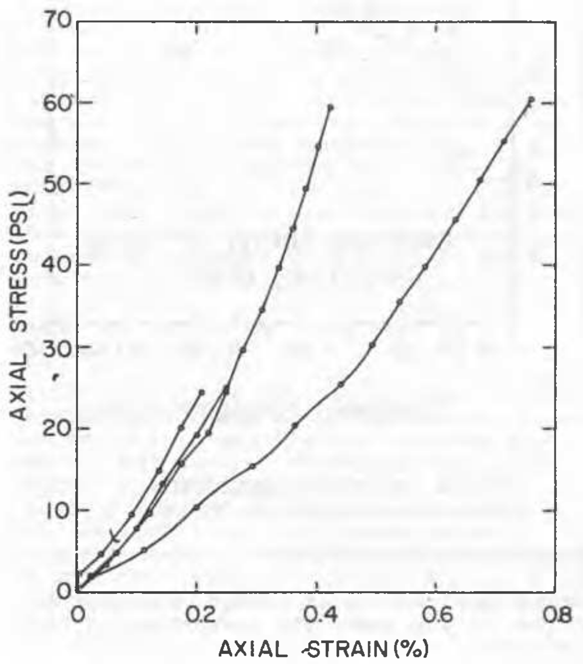

FIG. 3 STRESS-STRAIN CURVES FROM CONFINED COMPRESSION TESTS

Tangents to the curves obtained were drawn at various points and moduli determined. Confining pressures were not measured, but each was assumed equal to the corresponding vertical pressure as a conservative approximation. In this manner, Fig. 4 was prepared relating E and σ_3. As indicated in this figure, equation 1 satisfactorily represents the data provided E = 3,600 pounds per square inch and n = 0.5. Using these parameters and a residual lateral soil pressure of five pounds per square inch, a pressure-settlement curve which falls near the center of the range of field plate load curves presented in Fig. 2 was obtained. Because this residual pressure and the E_1 and n values obtained are reasonable and correlate well with the field results, they were used in the analysis of the slab at the Bruce Mansfield Plant.

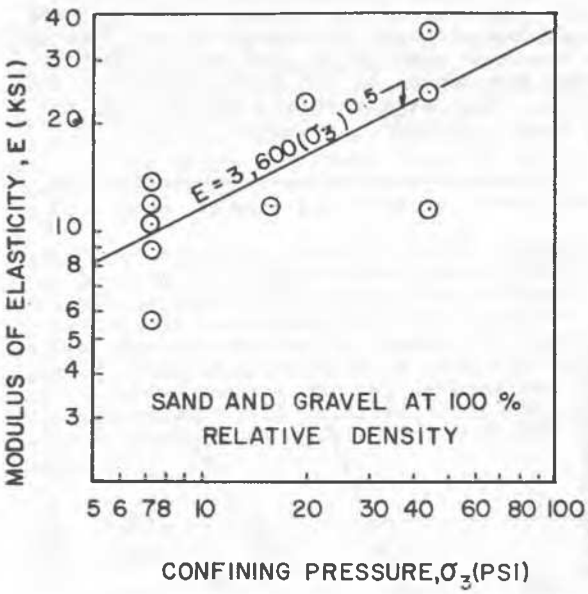

FIG. 4 ELASTIC MODULI FROM CONFINED COMPRESSION TESTS

THEORETICAL RELATIONSHIPS

Confining pressures in a soil mass can be related to the governing parameters by the equation:

$$\sigma_3 = K\gamma z + \sigma_r + K\Delta\sigma_v \quad (2)$$

In this equation

K = coefficient of lateral soil pressure

γ = unit weight of soil

z = depth below base of slab,

σ_r = residual confining pressure due to precompression and compaction, and

$\Delta\sigma_v$ = increase in vertical stress at depth z due to pressure applied to soil surface.

Assuming that the modulus, E, given by equation 1 is equal to the ratio of the changes in vertical stress $d\sigma_v$ and vertical strain $d\varepsilon_v$ below the center of the loaded portion of a soil layer of thickness H, the settlement of the center of the area will be given by the equation:

$$s = \int_0^H \int_{\sigma_{v_1}}^{\sigma_{v_2}} \frac{1}{E}\, d\sigma_v dz \quad (3)$$

Substituting from equations 1 and 2,

$$S = \int_0^H \frac{[\sigma_r + K(\gamma z + \Delta\sigma_v)]^{1-n} \quad [\sigma_r + K\gamma z]^{1-n}\, dz}{(1-n)\, E_1 K} \quad (4)$$

In order to compute settlements for a given loading situation it is necessary to substitute an appropriate expression relating $\Delta\sigma_v$ and z into equation 4. For plate load tests the expression:

$$\Delta\sigma_v = \Delta q\, [1 - z^3 (b^2 + z^2)^{-1.5}] \quad (5)$$

was substituted into equation 4 and utilized (with a numerical integration procedure) to develop the pressure-settlement curve used to evaluate E_1, n, and σ_r, as discussed above. (This expression, which is based on the theory of elasticity (Timoshenko and Goodier, 1951) gives the increase in vertical stress at depth, z, due to a pressure, Δq, applied to a plate of width, 2b, on a material of constant modulus. Because stress distribution is not highly sensitive to variation in modulus, the equation is considered sufficiently accurate for the computation of stress in practical design problems.)

At several load levels, the slab will be subjected to uniformly distributed loads. Because the width of the slab (400 feet) is large compared to the soil depths involved (40-100 feet), the change in vertical stress in the soil near the center of the slab will be equal to the uniform stress applied to the slab regardless of its flexibility. Therefore, the identity $\Delta\sigma_v = \Delta q$ was substituted into equation 4 giving an integrable expression which simplifies to:

$$s = [(\sigma_r + K\gamma H + K\Delta q)^{2-n} - (\sigma_r + K\gamma H)^{2-n} - (\sigma_r + K\Delta q)^{2-n} + (\sigma_r)^{2-n}][(1-n)(2-n)E_1 K^2 \gamma]^{-1} \quad (6)$$

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This equation was used to predict settlements and pressure-settlement curves for uniform slab loading. The slope of the pressure-settlement curve is the modulus of subgrade reaction governing behavior at the stress level involved.

At other load levels, more complex loading conditions prevail and the pressures transmitted to the soil surface will depend on the slab flexibility. For example, at several locations large concentrated loads will be applied to the slab. An indication of the pressures developed below such a load is given in Fig. 5. As a reasonable approximation, the curve presented in this figure has been replaced by the straight line shown; i.e., the pressure is assumed to vary linearly from a peak value directly under the load to zero in a distance $R = 3r_o$, where:

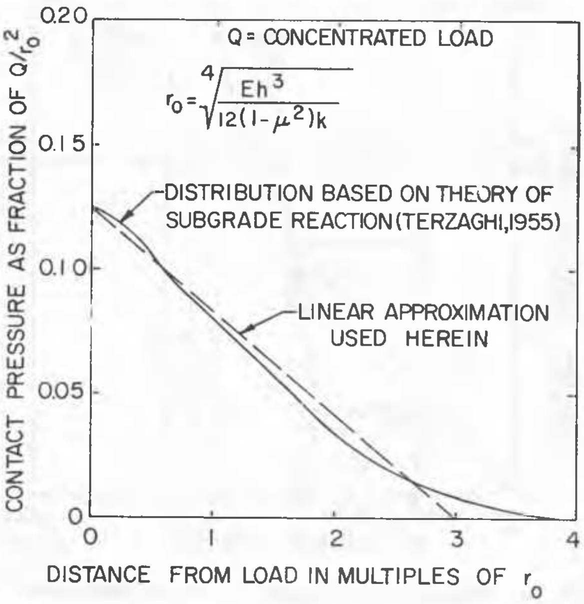


FIG. 5 DISTRIBUTION OF CONTACT PRESSURE BELOW SLAB SUPPORTING CONCENTRATED LOAD

$$r_o = [E_c h^3/(12(1-\nu_c^2)k)]^{1/4} \qquad (7)$$

r_o = radius of relative stiffness (Westergaard, 1926),

E_c = modulus of elasticity of slab,

h = thickness of slab,

ν_c = Poisson's ratio of slab, and

k = coefficient of subgrade reaction.

This pressure distribution forms a cone of stress applied to the soil surface. Therefore the expression:

$$\Delta\sigma_v = \Delta q_{max}[1-z(R^2 + z^2)]^{-0.5} \qquad (8)$$

was substituted into equation 4 and used to develop pressure-settlement curves for portions of the slab subjected to concentrated loads. This expression, which is based on the theory of elasticity (Harr and Lovell, 1963) gives the increase in vertical stress at depth z, due tb a pressure cone of height Δq_{max} and base radius R. The interrelation between R and k is considered later in this paper.

At locations where line loads are to be applied to the slab it is assumed that the pressures transmitted to the soil surface will vary from a peak value directly under the load to zero in a distance $R = 3r_o$ where r_o is the radius of relative stiffness given by equation 7. This pressure distribution forms a wedge of stress applied to the soil surface. Therefore, an expression, taken from Scott (1963):

$$\Delta\sigma_v = \Delta q_{max}\ [(2/\pi)\tan^{-1}(2R/z)] \qquad (9)$$

was substituted into equation 4 and used to develop pressure-settlement curves for portions of the slab subjected to line loads.

APPLICATION OF PREDICTION PROCEDURE

Slab settlements caused by uniformly distributed loads may be computed using equation 6. The equation is most accurate when applied to points near the center of the slab. For points near the edge of the slab the equation should be modified to account for the fact that $\Delta\sigma_v < \Delta q$ below points away from the slab center. For the Bruce Mansfield Plant slab, elastic theory was used to estimate soil stresses below these points. A lateral pressure coefficient of 0.5 and a soil unit weight of 135 pounds per cubic foot were used in the analyses.

Because soil depth was not uniform, different pressure-settlement relations were obtained even for points equidistant from the slab center. For design convenience the slab subgrade was divided into zones and a representative pressure-settlement curve developed for each zone. The zones selected and the pressure-settlement relations developed for uniform loading are shown in Figs. 6 and 7. The modulus of subgrade reaction values

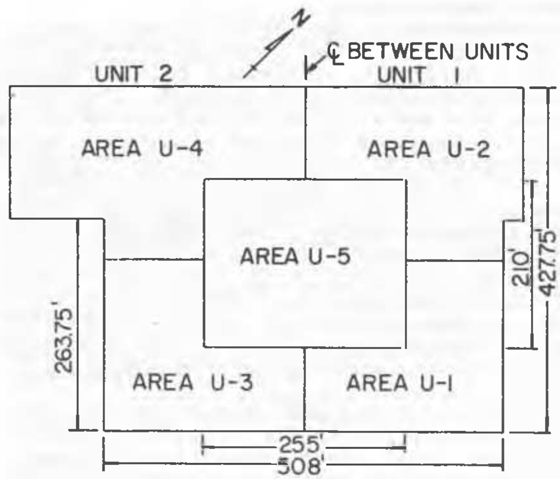


FIG. 6 SUBDIVISION OF SLAB FOR STUDY OF UNIFORM LOADING

defined by the pressure-settlement relations given in Figure 7 (20-30 pounds per cubic inch) are significantly smaller than values usually associated with dense granular materials. However, recent field studies on large slabs have indicated settlements

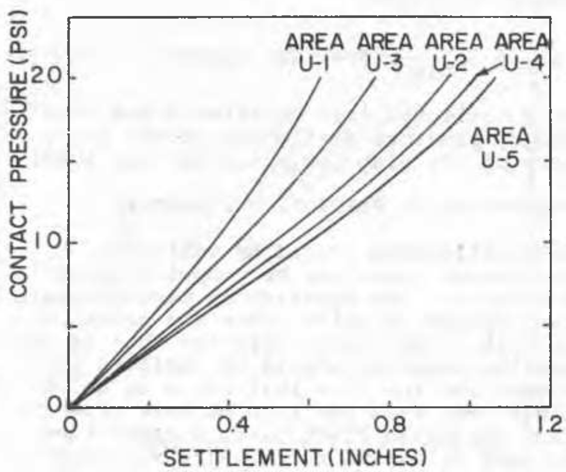


FIG. 7 PRESSURE-SETTLEMENT RELATIONSHIPS FOR UNIFORMLY LOADED AREAS - UNITS 1 & 2, BRUCE MANSFIELD PLANT

corresponding to modulus values of this magnitude. (Bjerrum and Eggestad, 1963).

In order to estimate settlements caused by concentrated loads it is necessary to perform computations using equations (4), (7), and (8) starting with assumed values of k (or r_o) and h. For the problem under consideration initial values of k = 300 pounds per cubic inch and h = 6 feet were assumed. For these values r_o is 9 feet and R is 27 feet. Substituting R = 27 feet and H values corresponding to the points of application of large concentrated loads into equations 4 and 8, pressure-settlement relationships for these points were developed. Two of the curves defined in this way are presented in Fig. 8. Straight line approximations to the curves presented in Fig. 8 define k values of 30 to 40 pounds per cubic inch. These values differ significantly from the value used in computing r_o. Therefore the new k value for curve C-1 was substituted into equation 7 giving r_o = 15 feet. Using the corresponding value of R and equations 4 and 8, a new pressure-settlement curve and a new k value were developed. This process was repeated until convergence was achieved.

Curves C-1 and C-2 are unique, as they are the result of loading by a single column. For other areas the stresses from adjacent columns and machinery foundations overlap, complicating the analysis. In order to study this situation, the Bruce Mansfield Plant slab and the expected slab loading were modeled mathematically as described elsewhere (Hiorth, 1972). In the initial phase of this study values of k = 300 pounds per cubic inch and h = 6 feet were assumed. Based on these parameters, contact pressure contours for one-half of the slab (Unit 1) are presented in Fig. 9.

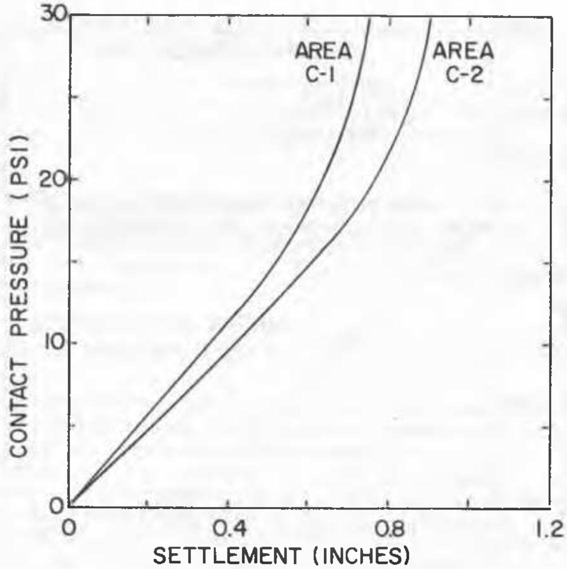


FIG. 8 PRESSURE-SETTLEMENT RELATIONSHIPS FOR AREAS SUPPORTING CONCENTRATED LOADS - UNITS 1 & 2, BRUCE MANSFIELD PLANT

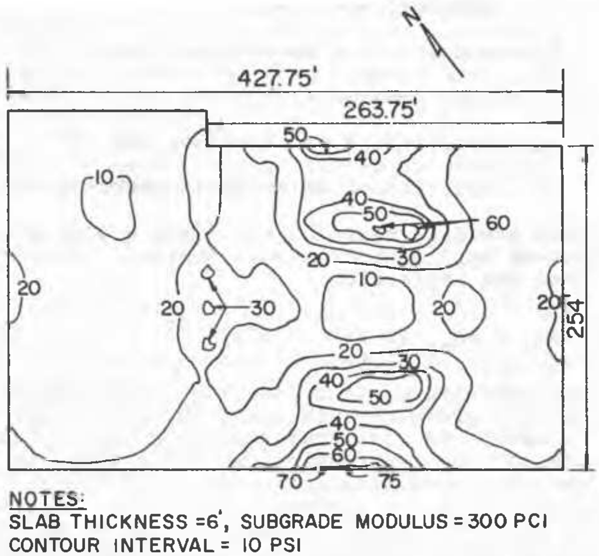


FIG. 9 PRELIMINARY ESTIMATE OF DISTRIBUTION OF CONTACT PRESSURES - UNIT 1, BRUCE MANSFIELD PLANT

The stress distribution presented in Fig. 9 was idealized as shown in Fig. 10, and additional subdivisions were specified as indicated in Fig. 11. In this case, Area C-1

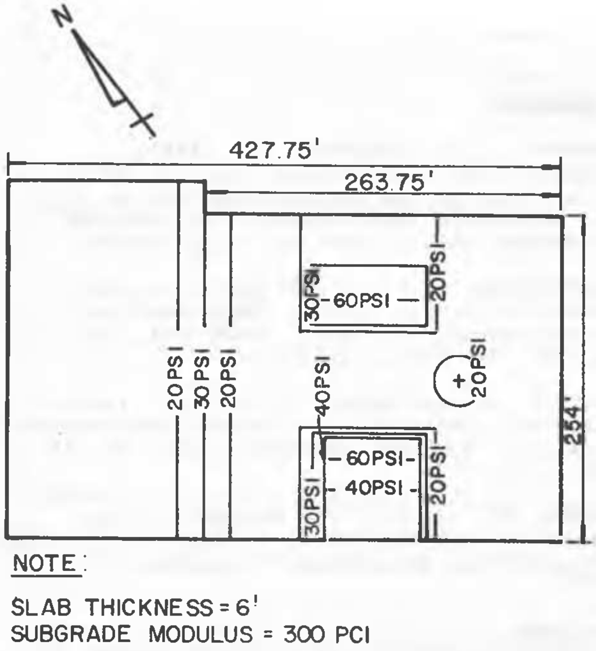


FIG. 10 IDEALIZATION OF DISTRIBUTION OF CONTACT PRESSURES - UNIT 1, BRUCE MANSFIELD PLANT

is subjected to a concentrated load, Areas L-1 through L-5 to line loads and Areas U-1, U-2 and U-5 to uniform loads as indicated in

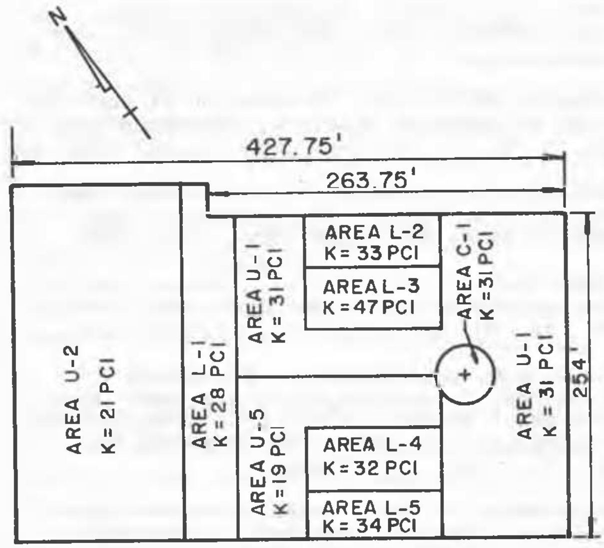


FIG. 11 PRELIMINARY SUBDIVISION OF SLAB FOR STUDY OF NON-UNIFORM LOADING - UNIT 1, BRUCE MANSFIELD PLANT

the figure. Using the dimensions and loads shown in Figs. 10 and 11, and equations 4, 8, and 9, pressure-settlements curves were developed for each of Areas C-1, L-1 through L-5, and U-1, U-2 and U-5. Straight line approximations to the curves developed were used to compute k values for the expected load ranges. The area dimensions and k values were then modified as described below.

The iteration study conducted for Area C-1 indicated that the correct diameter for this area is approximately 50 per cent larger than that given in Fig. 11 and the correct k value about 25 per cent less than that defined in Fig. 8. On this basis, revised dimensions and corresponding modulus of subgrade reaction values were developed for each slab area. The modulus values varied from 19 to 47 pounds per cubic inch as shown in Fig. 11.

SETTLEMENTS MEASURED DURING FILL PLACEMENT

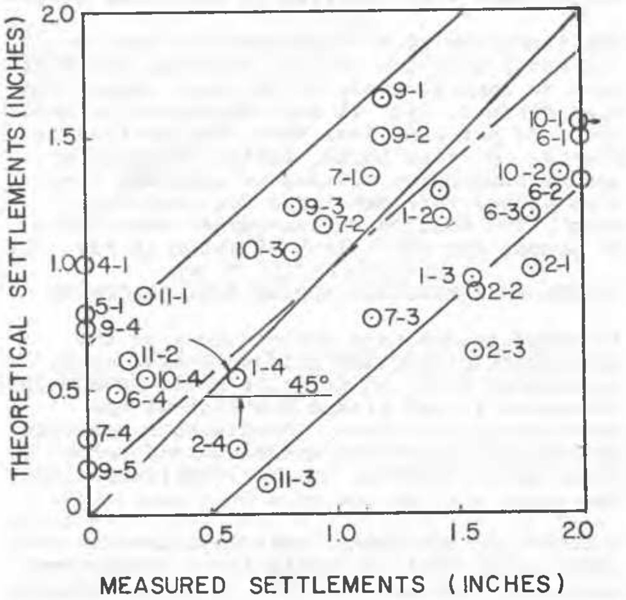
In order to evaluate the accuracy of the settlement prediction procedure developed, settlement pins and pressure cells have been installed in and around the slab at the Bruce Mansfield Plant. Settlements measured during fill placement are discussed below. Other data collected during construction of the plant will be analyzed when available.

During fill placement, settlements were measured at various levels in the compacted material. Because the fill covers a large area in a relatively uniform fashion, equation 6 was used to predict settlements at the various measuring stations. The σ_r, K, γ, n and E_1 values used were those which correlate with field plate bearing tests as described above. The parameters H and Δq were adjusted for each measuring point to account for the thickness of soil and fill found below and above the point respectively.

The settlements calculated using equation 6 are plotted against the corresponding measured settlements in Fig. 12. If the theoretical settlements were equal to the corresponding measured settlements, all points in Fig. 12 would fall on the 45° line shown. Instead the points are scattered in a band centered near this line. The centerline of this band indicates that the theory slightly over-predicts small settlements and slightly under-predicts large settlements. On the average, however, agreement between theory and experience is satisfactory.

CONCLUSION

Using a modulus-confining pressure relationship based on laboratory tests, an equation has been developed linking settlement of a large slab with in situ stresses, loading conditions, and soil characteristics. In situ stresses at a particular site were inferred from plate load tests, and soil-structure interaction for an electric generating plant was idealized using the theory of subgrade reaction. Modulus of subgrade



LEGEND
⊙ 7-3 = SETTLEMENT PIN NO.7, FLANGE NO. 3

NOTE:
ARROW INDICATES OFF - SCALE POINT

FIG. 12 COMPARISON OF THEORETICAL AND MEASURED SETTLEMENTS, UNITS 1 & 2, BRUCE MANSFIELD PLANT

reaction values predicted using the procedure developed are significantly smaller than values usually associated with granular materials, but agree with the results of recent field studies. Average settlements predicted using the procedure described herein are in agreement with those measured during placement of fill at the plant which is currently under construction.

ACKNOWLEDGEMENTS

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