Design of a Pressure-Sensitive Cell and Model Studies of Pressures in a Flexible Pavement Subgrade

T. F. McMahon, *Associate Professor in Civil Engineering, University of Kansas;** and
E. J. Yoder, *Associate Professor in Civil Engineering, Purdue University*

This paper reports the design and development of a pressure-sensitive cell and the use of this cell in making pressure measurements in homogeneous and two-layer model pavement systems.

The pressure cell is of the diaphragm type, 1½ in. in diameter and ⅜ in. thick. SR-4 strain gages are used to measure the deflection of the diaphragm as pressure is applied to the cell. A study was made of the action of the cell in clay-soil and in sand media, as compared to its performance during calibration under air pressure. It was determined that the performance in the clay-soil was very similar to that in air, but that in sand the cell behavior was erratic.

Pressures were measured under three different size plates, on a homogeneous compacted clay fill, and on the same fill when varying thicknesses of the upper portion of the clay had been replaced with a compacted crushed limestone base. These measured pressures have been compared with the theoretical pressures, as determined by the Boussinesq and the Burmister methods. They have also been compared with pressure measurements made by U. S. Army Engineers Waterways Experiment Station. A fair correlation of measured and theoretical pressures has been made by using a modification of the Boussinesq method, called the "equivalent plate method." However, it is necessary to have the magnitude of the interface pressure to establish this correlation.

The following are some of the conclusions that have been made during this study:

1. The pressure cell designed and developed as part of the project measured the pressures within the subgrade with an accuracy that should make it a very helpful tool in furthering knowledge of pressure distributions.
2. The stress distribution within a homogeneous soil mass, under a semi-rigid plate, is similar to the Boussinesq pattern of distribution for a uniformly loaded area.
3. The stress distribution within a homogeneous soil mass is affected but little by a considerable change in strength of the mass.
4. The measured stresses in a two-layer system under the center of a semi-rigid plate appear to be higher than the Boussinesq or the Burmister theory would indicate for a uniformly loaded area.
5. The stress distribution in a two-layer system depends to a large extent upon the strength and thickness of the upper layer.

* Formerly with Joint Highway Research Project, Purdue University.

• ALTHOUGH FLEXIBLE PAVEMENTS have been constructed for hundreds of years, the design of such pavements is still based on empirical methods. Pavement thicknesses are still determined through personal experience, by service characteristics, or by empirical formulas that correlate service records with measurable qualities of pavements and subgrades.

These methods have proved satisfactory where performance data and pavement and subgrade qualities are well correlated. However, in areas where correlation is inadequate, or where load and use characteristics must be changed, these methods are of little value. Thus, it is apparent that some rational means of pavement design must be formulated in order that a more economical use may be made of natural resources and a better pavement performance insured.

Webster defines the word rational as "having reason or understanding." Hence, before a rational method of design can be established, it is necessary that the function of a pavement be fully understood.

In the design of any structure, on a rational basis, it is necessary that the applied forces, the stress distributions, and the physical properties of the materials be known and understood. In highway design the total applied load, the tire pressures, and the contact areas are usually known. The load distribution over the tire contact areas has been studied by the Civil Aeronautics Administration (*2*) and the Bureau of Public Roads (*41*). If this distribution is found to be of importance in a rational method of design, it should be possible to establish values for tire sizes, tire pressures, and gross loads. Recent advances in soil mechanics and mechanics of materials enable adequate measurement of the physical properties of paving and subgrade materials for use in a rational method of design if the test conditions are known. The transition from a loaded area to a stress in a given paving material, especially when the system is multilayered, as are all pavements, is one of the important factors in establishing such a design method.

Ever since Boussinesq (*4*) presented his classic solution of stress distributions in 1885, mathematicians and engineers have been applying his solution, or modifications of his solution, to pavement design. It is only in recent years that any attempt has been made to rationalize this method to some extent by the use of factors which consider the effects of the various strengths of the materials in the layered system.

Attempts have been made to measure the pressure distribution within the pavement mass (*13, 14*), and other investigators are presently concerned with this subject (*13*). Most of these projects have been carried out under costly conditions, using large-size measuring devices and prototype methods. Also, the greater portion of the investigations has dealt with one-layer systems only.

In the study of stress distributions, it is essential to have an accurate pressure measuring device, or devices, which will be small enough to minimize its effect on the actions of the materials but large enough to measure average pressures rather than localized stresses. A major purpose of this study was to develop such a device.

The Civil Aeronautics Administration (*27*) and Spangler (*39*) have measured with some success pressures transferred through pavements to the subgrade. As yet, except for the present large-scale project of the Corps of Engineers (*13*), no one has undertaken a complete investigation of the distribution of pressures within the subgrade, or the effect of the component parts of the pavement on these pressures.

In order to further the knowledge concerning stress distributions, the pressure measuring device was used in a model study of pressure distributions in a compacted subgrade under several layered systems. The objective of these latter measurements was to contribute to the eventual formulation of a rational method of flexible pavement design.

PURPOSE AND SCOPE

In order to determine to what extent the present theories of pressure distribution were applicable to the rational design of flexible-type pavements, a three-fold study was undertaken.

The first phase of the investigation consisted of the design and development of a small inexpensive device for measuring the pressures transmitted through a soil mass.

The second phase was a laboratory study in which the limitations and uses of the cell were studied and model investigations were made.

The third phase was a field model study in which pressure measurements were taken for comparison with theoretical values. These measurements were of the pressure distributions under rigid plates on a nearly homogeneous section and of the changes in this distribution as various layers of base material were substituted for an equal thickness of the homogeneous section.

DEVELOPMENT OF A PRESSURE CELL

In the development of any device it is essential to know the factors which control the functioning of the device and the limitations within which the device will perform with the specified precision. With due cognizance of prior efforts, a device may then be designed which will best perform the purpose for which it is intended. This approach was used in the design and development of the pressure cell used in this investigation.

Limitations of Cell

It is only reasonable to expect that the introduction of a foreign object having radically different elastic properties into a soil mass of assumed homogeneity will disturb the distribution of pressure in the vicinity of the object.

Kögler and Scheidig (*29*) first called attention to the difficulties of measuring soil pressures accurately with a pressure cell. They pointed out that a cell which is more rigid than the soil would indicate pressures greater than those present in the soil and, conversely, a cell more compressible than the soil would give pressure readings which were less than those in the soil. There can be little question as to the correctness of this reasoning; the natural inference is that if a device is to indicate true soil pressures it must possess in itself the same elastic properties as those of the surrounding soil. The cell must deform in all directions to the same extent as the soil. The possibility of providing a cell with these characteristics is small; therefore, it behooves the researcher to develop a measuring device which will disturb the pressure patterns as little as possible and yet provide a precise means of measuring these pressures. The extent to which the indicated pressure might deviate from the true pressure will probably vary as some function of the thickness or of the cross-sectional area of the cell and with the applied stresses. If it is assumed that the forces imposed on a pressure cell are essentially the same as those resisting the penetration of a body into the soil, it would be expected that the pressure indicated by cells of different size would vary with the area, and the indicated pressures would be different in cohesive and in granular soils. It seems reasonable that the presence of a rim around the pressure-responsive area would disturb the pressure-area relationship, because it would tend to alter the distribution of pressure on the central area. There is also the possibility that difficulty may be experienced in providing the same intimacy of contact over both the rim and the diaphragm.

Benkelman and Lancaster (*3*) observed that with the rim-type pressure cell there was considerable variation in the readings obtained with differing types of material and differing methods of embedment. They also determined that the type of soil entered into the degree to which readings corresponded to the theoretical values. In plastic clays the physical dimensions of the cells did not produce a significant deviation in the pressure indications.

Many of the limitations of the pressure cell have been determined by research at the Army Engineers Waterways Experiment Station. In this report (*11*) it is suggested that cells mounted on a wall or a rigid base should have a diameter-projection ratio greater than 30; the diameter-deflection ratio of the cell should be greater than 1,000; and cells embedded within a sand mass should have a diameter-thickness ratio greater than 5. It was also indicated that pressure measurements were in most cases larger than the applied stresses.

Design Considerations

It is evident from the literature that although little is known of the actual stress distributions around a pressure cell it is best to design within certain size ratios in order to minimize the deviation of the cell readings from the theoretical values. It was the intent in this investigation to design a pressure measuring device which would deviate from these limits as little as possible, yet would be small enough and of low enough cost that it could be used with convenience in making measurements at various positions below plates of moderate size.

The major limitation on the smallness in size of the cell is the necessity of providing means of measuring deflections of the cell diaphragm and of transferring these measurements to pressure readings. After a study of this problem, it was decided that the use of SR-4 strain gages would provide the most accurate and convenient means of measuring the deflections of a small size diaphragm. To obtain maximum sensitivity it was decided to use two SR-4 gages, one at the center of the diaphragm and another near the edge, connected in series. It was determined by trial that two SR-4 type 18a strain gages could be attached to a 1-in. diameter diaphragm; therefore, this size diaphragm was chosen for the design.

An important facet of the design was the determination of the diaphragm thickness. This thickness must be commensurate with the sensitivity desired and the diameter-deflection ratio established by the Waterways Experiment Station. The thickness computations were made by the use of Timoshenko's equation for the deflection of a circular plate fixed at the edges (*42*):

$$w = \frac{q\,a^4}{64\,D} \tag{1}$$

in which

w = deflection at center of plate;
q = applied uniform pressure;
a = radius;
D = $E\,t^3/12(1-\mu^2)$
E = modulus of elasticity;
t = diaphragm thickness; and
μ = Poisson's ratio.

Use of Eq. 1 in a trial-and-error process made it possible to select a diaphragm thickness which would best fit the criteria

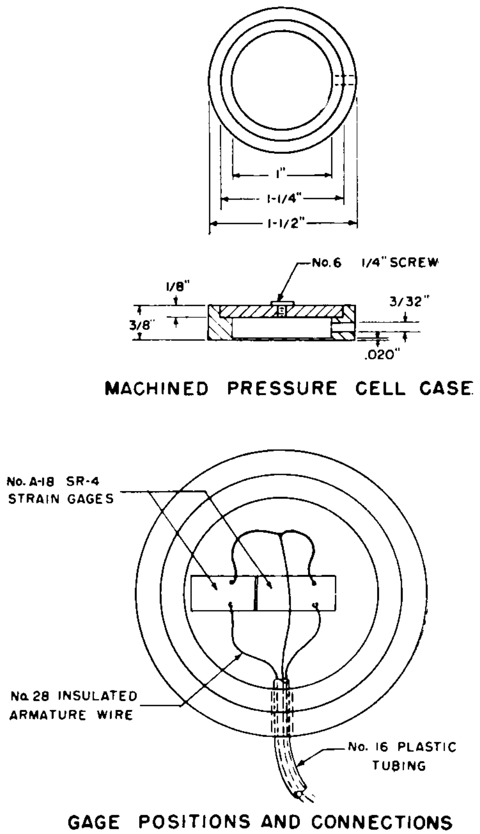


Figure 1. Pressure cell details.

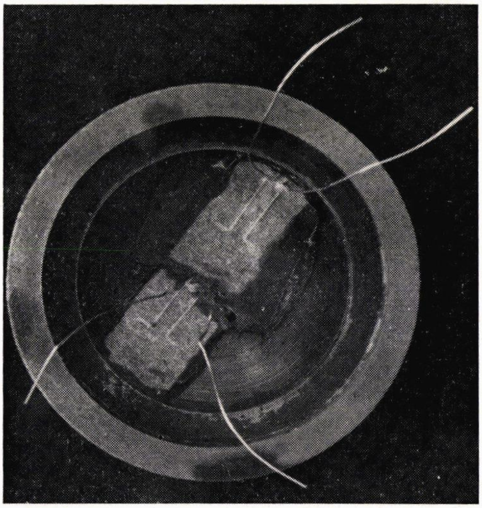


Figure 2. Pressure cell interior after placement of gages.

of the Waterways Experiment Station and still retain the desired sensitivity. A diaphragm thickness of 0.02 in. was chosen and used in the first series of cells. Later, cells with a diaphragm thickness of 0.018 and 0.015 in. were constructed for measurement of the smaller pressures at greater depths below the plate.

Stainless steel was chosen as the cell construction material. It is a high yield strength material with excellent elastic properties and is resistant to corrosion during long periods of contact with moist soil.

The details of the cell are shown in Figure 1. Because of the difficulty of securing the diaphragm to the body of the cell, the cell and diaphragm were machined as an integral unit from round stock. The design thickness, determined by the depth necessary for gage installation and wiring, provided a diameter-thickness ratio of 4, which was lower than is recommended by the Waterways Experiment Station. This, however, will produce only a slight deviation of the readings in sand and will have no effect in plastic soils (*3*).

The gages were attached to the diaphragm with a metal adhesive (Fig. 2).

Instrumentation

Initial calibration readings were obtained with Brush recording equipment, consisting of an analyzer and a pen recorder. This equipment was chosen in order that a record of dynamic loading might be taken, if so desired. This recording system had many desirable features but did not possess the sensitivity and stability required in this research. Accordingly, a Baldwin SR-4 type L strain indicator was substituted for the Brush equipment. The strain indicator afforded an increase in the sensitivity of measurements and in the stability of the circuit. A battery-powered strain indicator was used in order that both laboratory and field readings might be made with the same instrument. When measurements were made with more than one cell a switching device was employed.

Cell Calibration

Many measurements were made in order to establish calibration procedures which would be valid under field conditions. The first calibration tests were per-

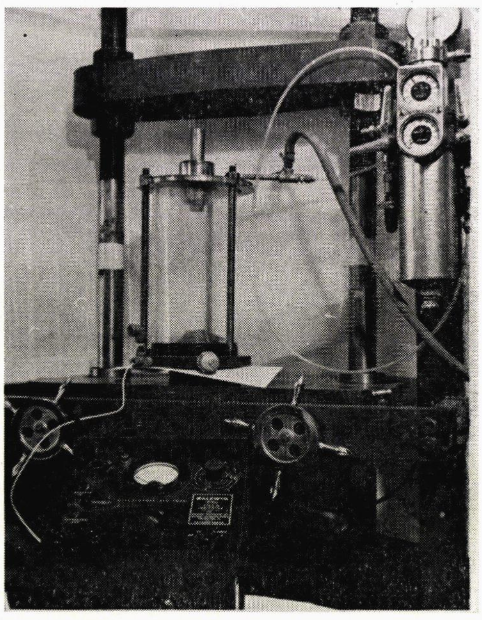


Figure 3. Triaxial cell used in pressure cell calibration.

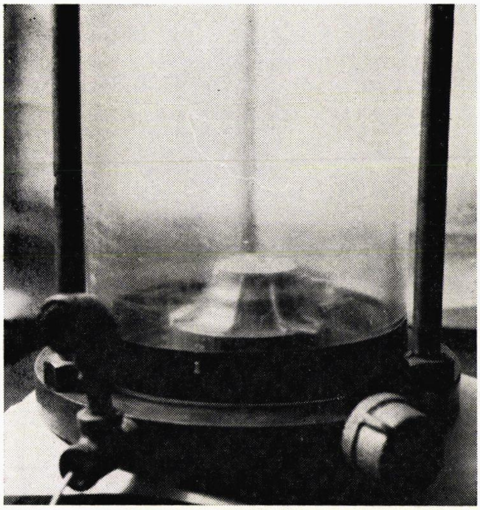


Figure 4. Pressure cell under air pressure.

formed in the triaxial equipment shown in Figure 3. The pressure cell was placed on the base within the triaxial cell and covered with a flexible membrane, which was then clamped between the lucite cylinder and the base of the triaxial cell. Compressed air entering the triaxial cell forced the flexible membrane against the diaphragm of the cell (Fig. 4), thereby causing a deflection of this diaphragm. The air pressure in the triaxial cell was measured by means of a large mercury manometer and correlated with the deflections of the diaphragm as measured by the strain gages. This method was later adopted as the procedure to be used for all cell calibration.

In order to study the effect of the confining medium on the action of the pressure cells, several of the cells that had been calibrated in the air pressure device were re-calibrated in a clay-soil and in a sand medium. The cells were buried in whichever medium was being used in the test, in a brass sleeve which was placed in the triaxial cell (Fig. 5). A flexible membrane was placed over the top of the material in the sleeve and again clamped between the lucite cylinder and the base. Air pressure was admitted to the cell, forcing the membrane against the soil. The deflections of the diaphragm were again correlated with the air pressure to provide a calibration curve.

The calibration data obtained with a clay medium surrounding the cell compared well with the calibration data obtained with the air. When sand was used as the surrounding medium, the data were very erratic and the correlations were very poor (*3*).

In order that there would be no doubt as to the validity of the air calibration for the clay soil medium of the investigation, several of the cells were placed in compacted clay-soil triaxial specimens upon which triaxial compression tests were run. The specimens were 6 by 12 in. in size. The cells were placed at the center of the specimen, horizontally and vertically. Readings were taken of the pressures transmitted to the cell during the test. In each test the cell was placed in a different plane within the specimen. Representative triaxial data are shown as a Mohr Circle diagram in Figure 6.

As a result of this study it was concluded that the measurements made with the cells in the triaxial specimen were a good representation of the actual stresses within the soil. There seems to be little

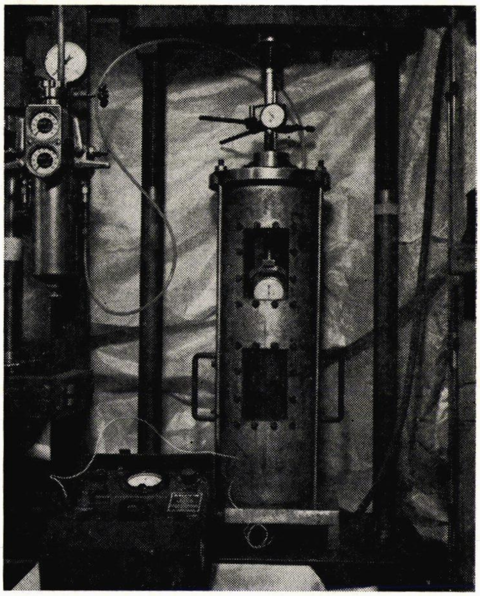


Figure 5. Triaxial equipment for check calibrations.

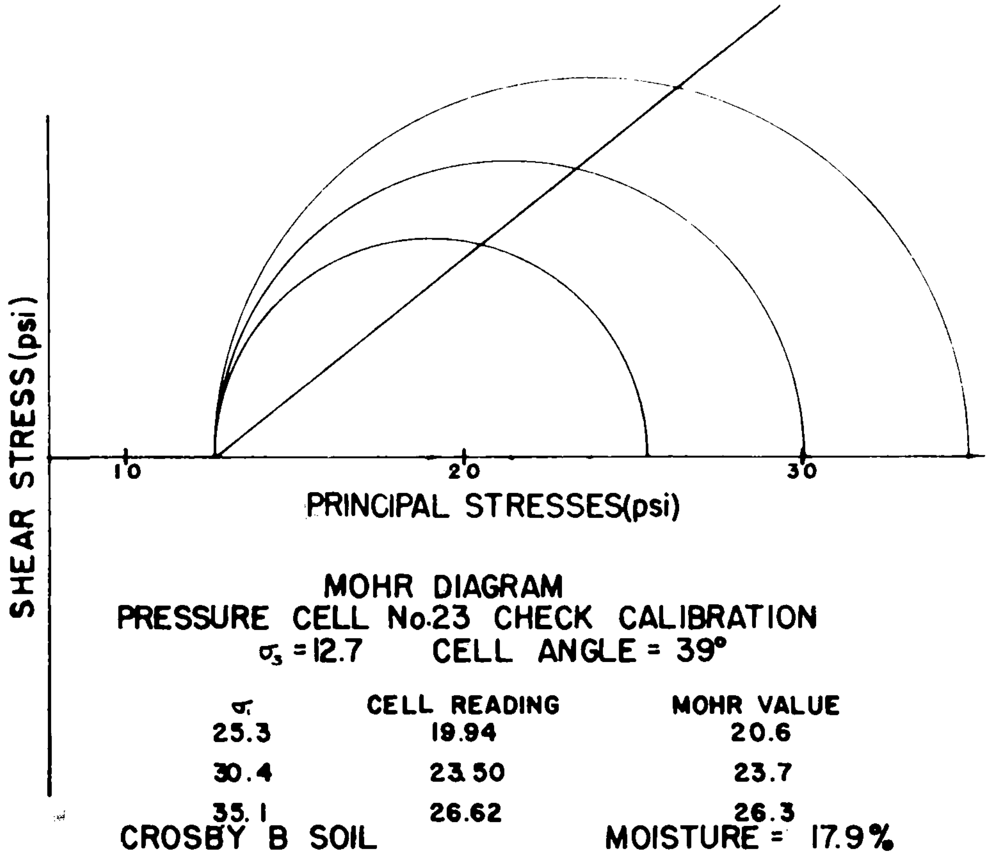


Figure 6. Mohr diagram pressure cell check calibration.

possibility that the cells have over-evaluated the stresses. There is, however, a possibility that the cells have registered values that were slightly lower than the existing values.

LABORATORY PRESSURE MEASUREMENTS

The laboratory measurements were made as pilot studies to enable the development of techniques of testing and to study the limitations of the cell. Therefore, this portion of the investigation has been omitted from this paper.

FIELD PRESSURE MEASUREMENTS

The preliminary proposals of this study were based on the premise that all testing would be done in the laboratory. However, the results of the pilot studies indicated serious side effects from the small box. To eliminate the side effects for the large size plates it would have been necessary to use a box so large that the available testing equipment would have been inadequate. Therefore, it was decided that the tests with the larger size plates would be performed in the field, in such a manner that side effects would be minimized or completely eliminated.

Pressure Cell Installations

The plan for this section of the investigation called for the measurement of pressures at various depths within the soil mass under several transmitting systems. In order to work above ground, to minimize flooding of the project, and to

Figure 7. Compaction of soil in test pit.

be able to change the thickness and type of cover readily, the arrangement shown in Figure 7 was designed and constructed. A pit 3 ft deep and 8 by 8 ft in plan, was excavated in an area of Crosby B soil at the Purdue University School of Civil Engineering test road site. The material removed from the pit was placed on and under canvas to minimize loss of moisture during the construction period. A retaining structure made with 4- by 4-in. timbers was erected to a height of 1 ft above ground level. This structure was arranged so that by removing or adding successive side members the contained materials could be reduced or increased by 2-in. increments of depth. This arrangement provided a variation in depth of cell cover of 1 ft, in 2-in. increments, thereby allowing a number of pressure determinations for each cell installation.

The soil removed from the excavation was replaced by compacting it in 2-in. lifts with the gasoline-powered vibrator. The moisture content of the soil was such that the material was within the lower limit of the plastic range. Consistency control was maintained by the use of a Proctor needle. The first group of pressure cells was placed exactly 3 ft below the top of the timber frame and 1 ft above the interface between the compacted and the natural subgrade. The cells were placed in holes drilled with an extension bit and carefully covered with compacted soil before the next layer of soil was placed. Cells were placed in the same manner at 2 ft and 1 ft 4 in. below the top of the framework. This arrangement of cells provided for pressure measurements at three levels for each thickness of cover used. The use of several thicknesses of cover made it possible to obtain a good distribution of measurements throughout the soil mass. A plastic moisture barrier was placed between the fill and the wooden frame.

Load Test Apparatus

To enhance the possibilities of establishing relationships of pressure, area, and depth, three sizes of plates were used for applying load to the surface of the system. The plates were $7\frac{3}{16}$, 12, and 18 in. in diameter. Loads were applied to the plate by jacking against a soil-test load test frame with a hydraulic jack. The jack was calibrated before the start of the testing and several times during the testing period. Ames dials were used to measure the vertical deformations of the plate due to load. Pressure determinations were again made by measuring the deflections of the cell diaphragms with the strain indicator. The entire test area was enclosed in canvas as soon as construction was completed. The equipment used for compacting the soil and base material is shown in Figure 7. The testing equipment is shown in Figure 9.

Field Procedures

To obtain as much information as possible, the testing procedures were carefully planned. Tests were run on each of the three plates, on each exposed surface of the clay-soil subgrade, and on each cover layer of compacted base course material.

Figure 8. Cells at 2-ft depth, Series I.

The first tests were run on the compacted clay-soil surface at the maximum depth of cover, 16 in., over the upper group of pressure cells. The largest plate was used first, then the smaller ones in order of size. This provided a smooth, level surface for the contact area for each plate. There is no doubt that there was some change in density of the material because of this method of testing, but the effect was small in most instances. After the tests with the three plates had been run and pressure cell measurements taken, 4 in. of soil was removed and the tests repeated. Before the next 4 in. of soil was removed, a 4-in. layer of crushed limestone base material was compacted on this surface, by vibration, and the tests were run on the surface of the limestone. The base material was then removed, another 4-in. increment of the soil was taken off, and the tests were repeated. In both series of tests, 8-in. layers of base were also included. In the second series of tests a 12-in. layer of base was placed and tested.

The tests were run as load tests, using the standard load test equipment. The load was applied to the plates with a hydraulic jack, in increments of 500 lb on the small plate and 1,000 lb on the two larger plates. After application of each increment of load a strain indicator reading was taken on each cell. The readings were taken immediately after the load application, over a period of approximately 5 min. The pressure exerted on the cell was determined by averaging four differences between full load and zero load.

Results

Representative results are presented in Figures 10 through 13. The curves pre-

Figure 9. Field test equipment.

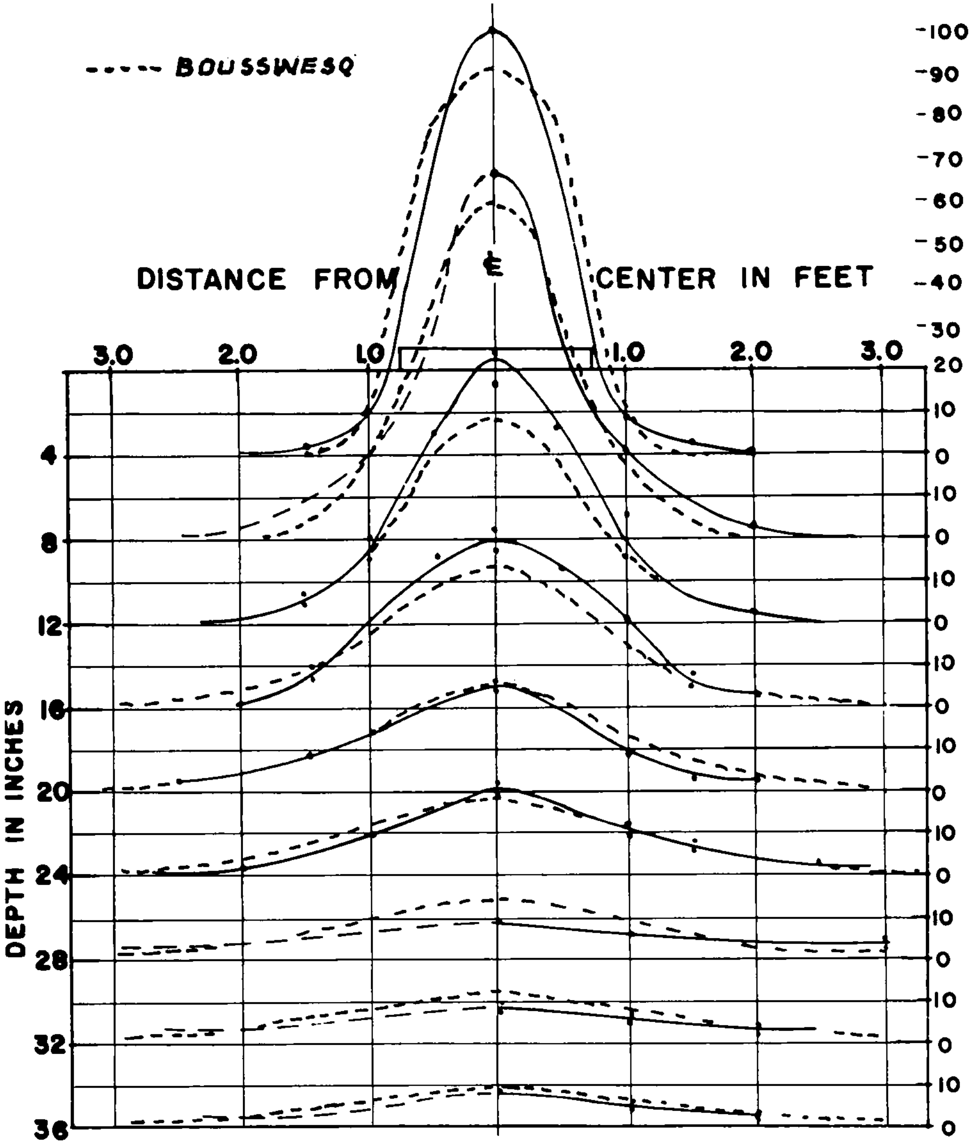
sent the vertical pressure distributions, as determined by the pressure cell measurements, in terms of percent of the stress applied at the surface.

There was some variation in the moisture content and density of the subgrade in Test Series I. This material was placed during a period of excessive rainfall. The fill was flooded and absorbed moisture, with a resultant softening of the material. The excessive moisture also resulted in failure of several of the cells during the test period. The subgrade of Test Series II was much more uniform and of higher strength.

The crushed limestone base, compacted by vibration, seemed to produce a dense surface of fairly high strength. However, the base for Series I proved to be rather weak; therefore, it was decided that in the second series the compacted base should be allowed to stand at least 24 hours before being tested.

Discussion of Results

The pressure distribution data obtained with the 18-in. plate in four test conditions are presented in Figures 10 through 13. A comparison of these curves indicates several trends in the data. There is a definite reduction in the measured pressures at the shallower depths as the base thickness is increased. However, the 12-in. base effects a reduction only slightly greater than that for the 8-in. base. At the greater depths the base seems to have little effect on the pressure distributions. The curves for the homogeneous condition (Fig. 10) are as much as 18 percent higher than the theoretical curves at the shallower depths, but are lower at the



MEASURED PRESSURES
AS PERCENT OF APPLIED STRESS
18" DIAMETER PLATE
SUBGRADE ONLY

Figure 10.

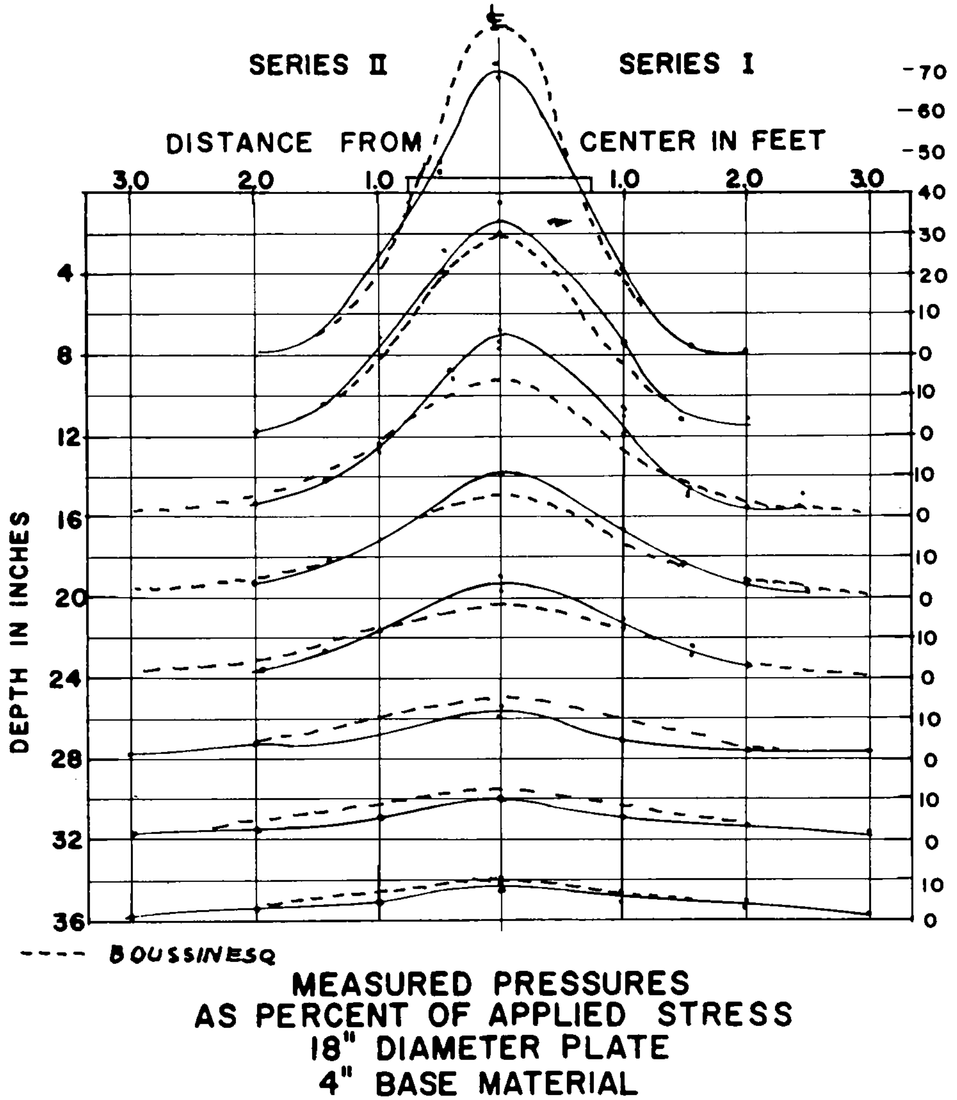


Figure 11.

greater depths. This same trend is apparent in the pressures under the base courses in the other figures, except that near the interface the pressures seem to be less than the Boussinesq theory would indicate. It can be said, however, that the shapes of the curves, and even the magnitude of the curves, do not depart in a major sense from the Boussinesq theory. It must be remembered that the Boussinesq curves are for a uniformly loaded area, whereas the measured values relate to the distribution for semi-rigid plates used in the test.

Figures 14 to 17 present the data for the pressures measured under the centers of the plates at various depths for the four test conditions. The curves of Figure 14 are representative of the pressures measured in the homogeneous subgrade

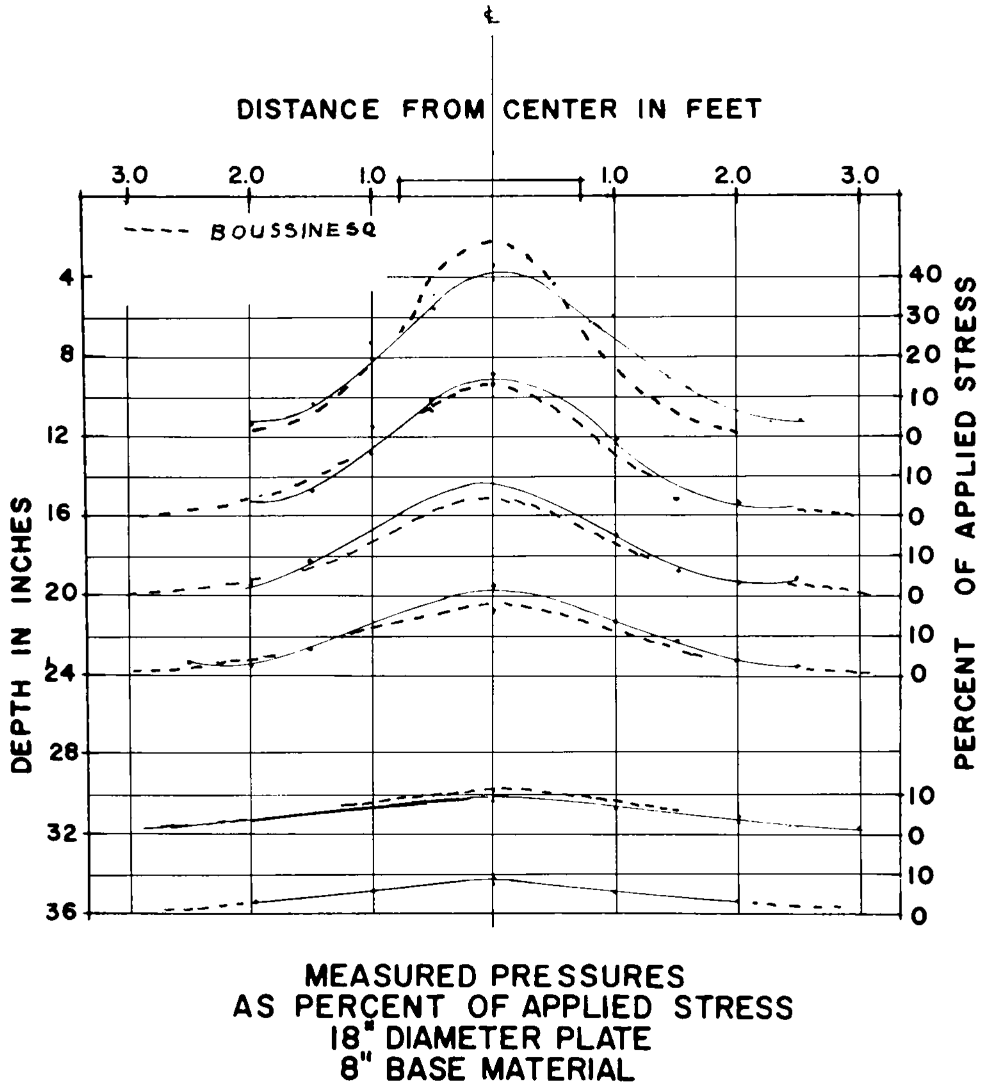
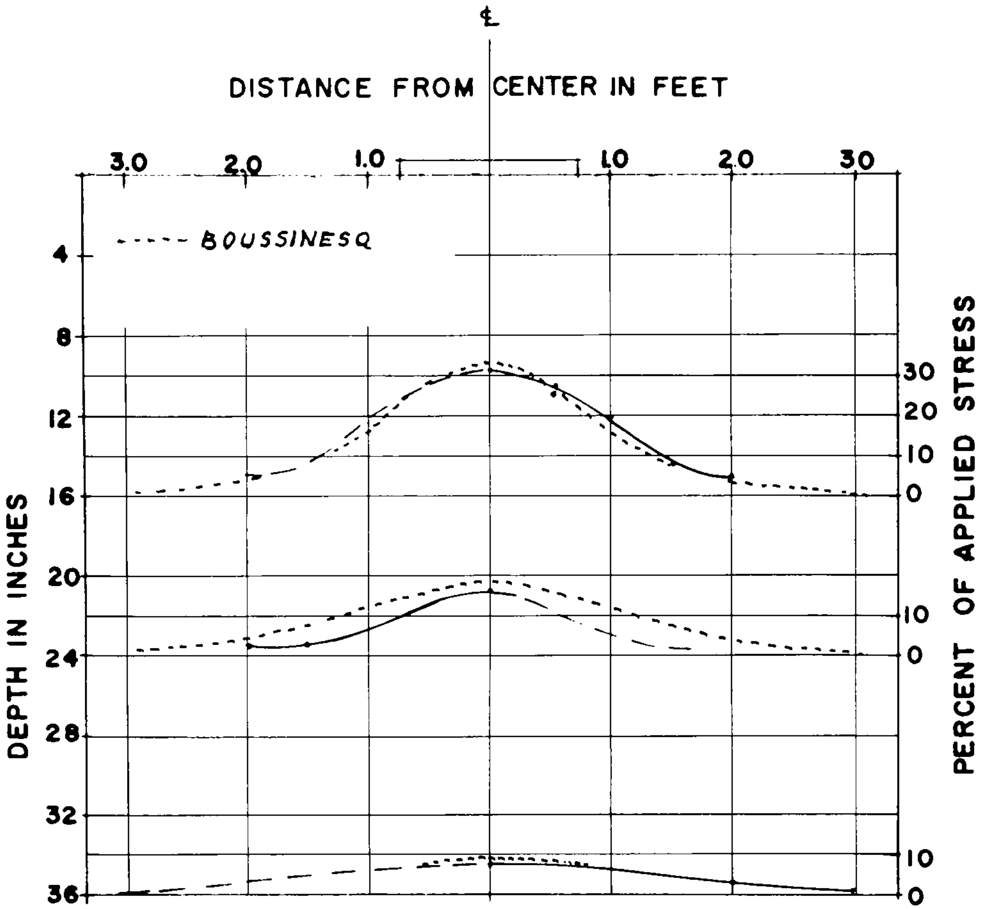


Figure 12.

under the centers of the three plates for both series of tests. Although there is a slight scattering of points, it is evident that the change in strength of the subgrade had little, if any, effect on the measured pressures. A correlation of pressure with strength, as indicated by E-values calculated from the load test data, was attempted, but no definite trend could be established. There was, however, a slight indication that with the higher strength conditions the measured pressures tended to be lower. A range of E-values from 400 to 1,000 produced a variation of only 2 to 5 percent in the measured pressures. It is apparent that the measured pressures are considerably higher than the Boussinesq distribution for a uniform load, especially at the intermediate depths. The limited data available may produce an erroneous appearance here, but it would seem that the



MEASURED PRESSURES
AS PERCENT OF APPLIED STRESS
18" DIAMETER PLATE
12" BASE MATERIAL

Figure 13.

values at the center of the plate might be considerably higher than the average of the applied load, although this is contrary to theory. This would tend to produce the higher stresses in the upper areas, and the lower stresses with depth, that are depicted by these curves. All three plates behave in a similar manner.

The curves of Figure 15 are drawn to best fit the available data when the loaded plate rested on the surface of a 4-in. layer of crushed limestone base. In these curves it is evident that the strength of the base material plays an important part in the magnitude of the induced stresses. The calculated ratios of the modulus E of the base to the modulus E of the subgrade vary from 1 to 14. The pressure values measured under the weaker bases are higher than the values measured when

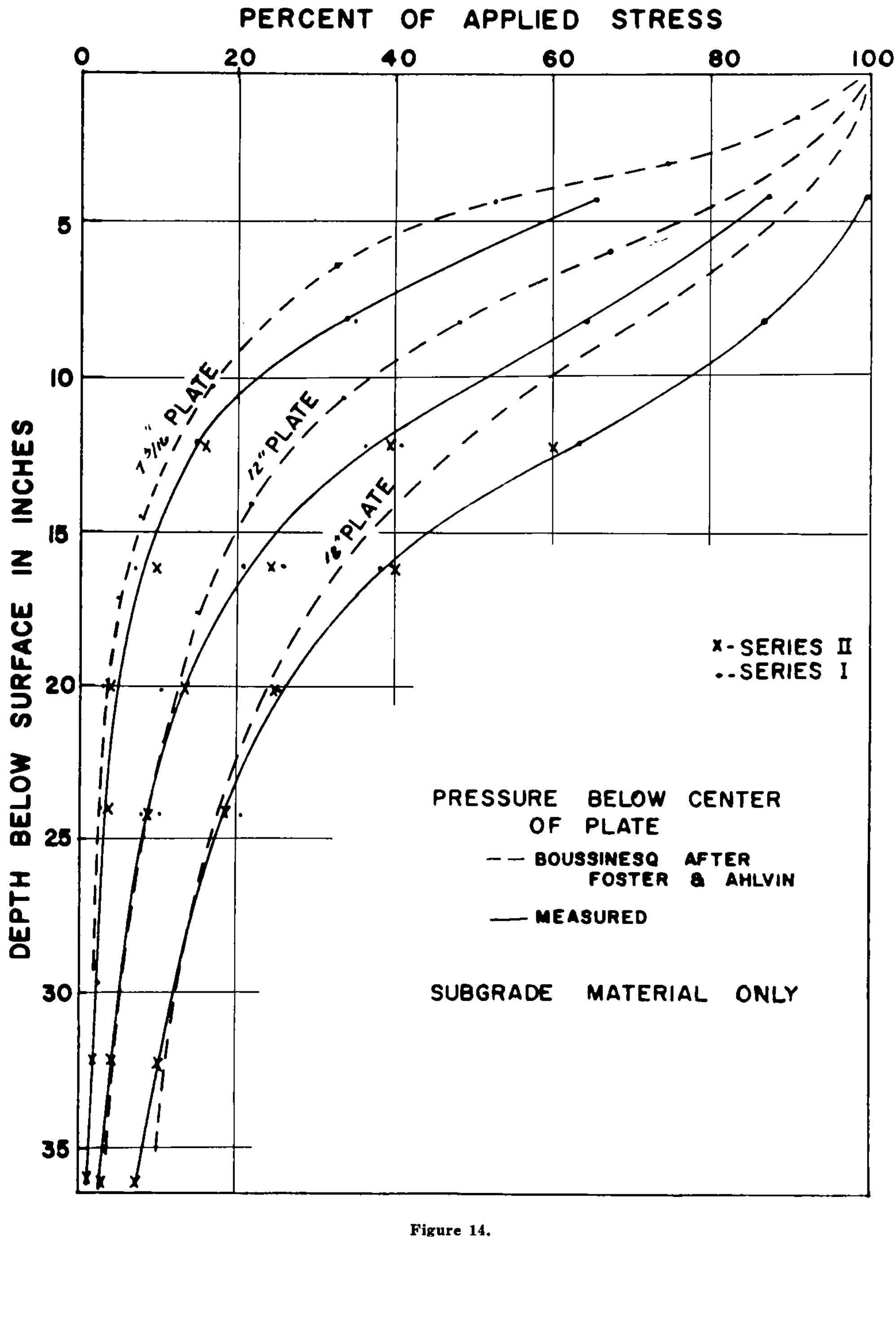

PERCENT OF APPLIED STRESS
0
20
40
60
80
100
DEPTH BELOW SURFACE IN INCHES
5
10
15
20
25
30
35
7 5/16" PLATE
12" PLATE
18" PLATE
x - SERIES II
• - SERIES I
PRESSURE BELOW CENTER OF PLATE
— — BOUSSINESQ AFTER FOSTER & AHLVIN
—— MEASURED
SUBGRADE MATERIAL ONLY

Figure 14.

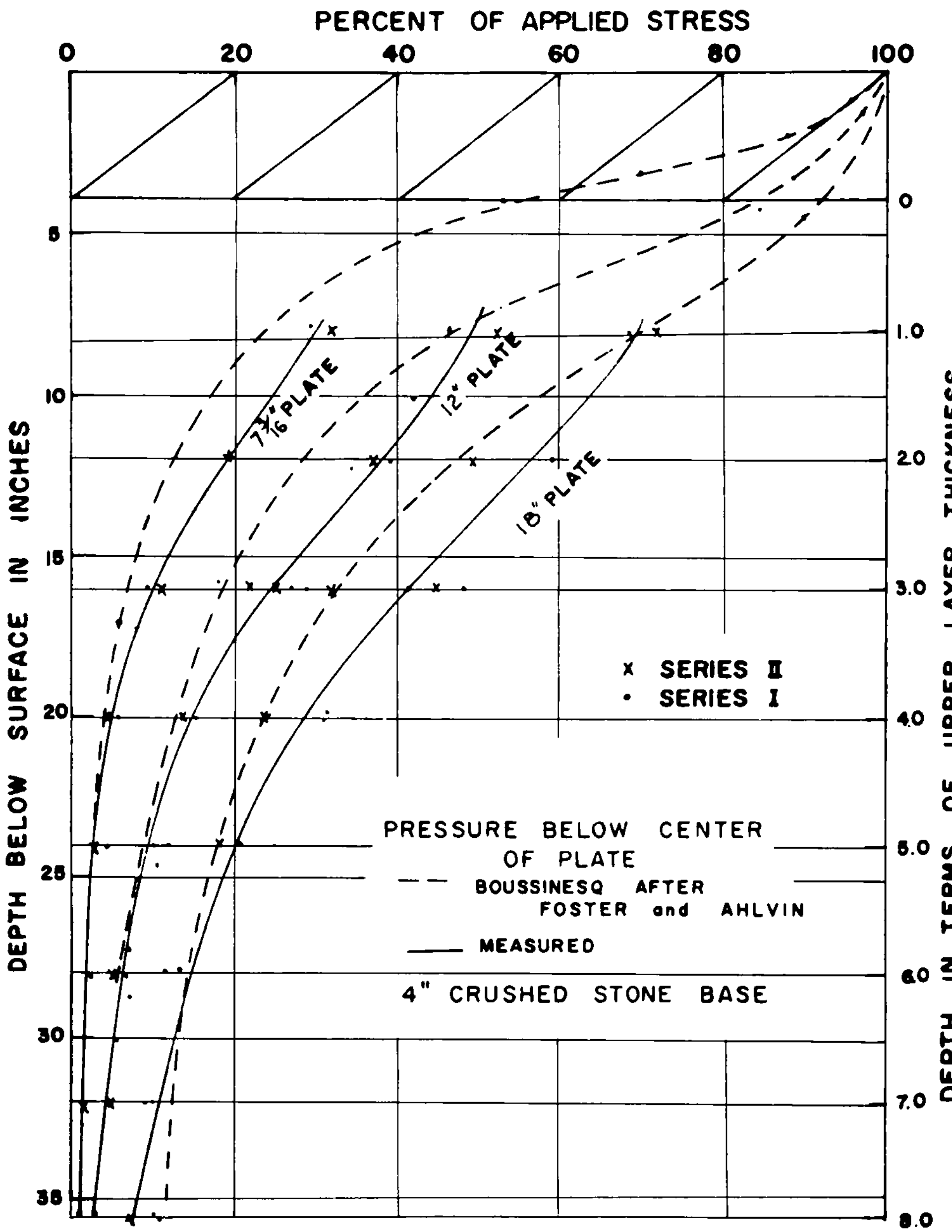

PERCENT OF APPLIED STRESS
0
20
40
60
80
100
DEPTH BELOW SURFACE IN INCHES
5
10
15
20
25
30
35
DEPTH IN TERMS OF UPPER LAYER THICKNESS
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
7 1/16" PLATE
12" PLATE
18" PLATE
x SERIES II
• SERIES I
PRESSURE BELOW CENTER OF PLATE
BOUSSINESQ AFTER FOSTER and AHLVIN
MEASURED
4" CRUSHED STONE BASE

Figure 15.

the bases were stronger. This is shown quite well by the difference in the pressure measurements for Series I and Series II. It is also apparent that the strength relationships are much more critical for the larger plates. The points depicting the values obtained in Series II, under the 18-in. plate, nearly coincide with the theoretical curve of Boussinesq for a uniformly distributed load, while the points for Series I are not greatly different from the curve for the homogeneous condition. The data for the 12-in. plate are somewhat scattered, but the values obtained under the 7-in. plate have not been affected. The values of all the curves are greater, over most of their length, than those of the theoretical curves, and in some places are even greater than for the homogeneous condition. However, near the bottom of the base the pressures seem to be considerably lower than the theoretical values.

The curves of Figure 16, for the 8-in. base condition, exhibit much the same features as those for the 4-in. base condition. It can be seen that the values have been reduced and more nearly approach the theoretical values. Here again, as in Figure 15, there is a strong indication that the values near the interface are much less than in the homogeneous condition.

The curves of Figure 17 are for the limited data of the 12-in. base condition. They also exhibit the characteristics discussed in the 4- and 8-in. base conditions. It is, however, evident that the percentage decrease in pressure is less between the 8- and 12-in. than it was between the 4- and 8-in. conditions. This would substantiate the theory that the stresses in the subgrade approach those of the homogeneous condition as the ratio of the base thickness to the radius of the plate increases.

The stress distributions under the center of each plate for the four test conditions are presented in Figures 18, 19 and 20. Several important features of the stress distributions are indicated in these curves. For the plate sizes used in the investigation, the base thickness does not affect the magnitude of the pressures to any great extent below a depth of 18 in. The point that the base course affects stresses primarily at the base-subgrade interface is again noted. These curves also indicate an optimum base thickness for each plate size. It would seem that this thickness might be approximately equal to the radius of the plate.

In Figure 21 data from a report published by the Corps of Engineers (*13*) are presented as a curve of stress distribution with depth. The points along the curve are data from the current investigation. A correlation between the two sets of data exists in spite of the differences in the test conditions. The Corps of Engineers in their investigation used a 1,000-sq in. flexible plate to apply loads of much greater magnitude than were used in this study. The data from both investigations are for homogeneous soil conditions. The data from both projects have similar trends; namely, the values for both are higher than the theoretical values of Boussinesq, and both also indicate that the pressure under the center of the plate was higher than it would be for a uniform distribution, which is to be expected for the flexible plate.

In the previous discussion the comparisons of measured values with the theoretical values have been made using the Boussinesq theory for a uniformly loaded plate. In Figures 22 to 24 a comparison has been made of the values obtained in this investigation with values computed by Fox (*17*) using the Burmister Two-Layer Theory. This comparison has been made by methods described by Burmister (*5*). Load test curves have been used to determine E_2, the modulus of the subgrade; E_1, the modulus of the combined system; and F_w, Burmister's settlement coefficient. The calculated value of F_w is used in the chart by Burmister (*5*) to determine the value of E_2/E_1, the ratio of the modulus of the lower layer to the modulus of the upper layer. The data for the tests of Series II have been used for this comparison as the modulus ratio for this data was near or above the 1/10 ratio used by Fox. A perfectly rough interface was assumed in the computation of the Fox values. It

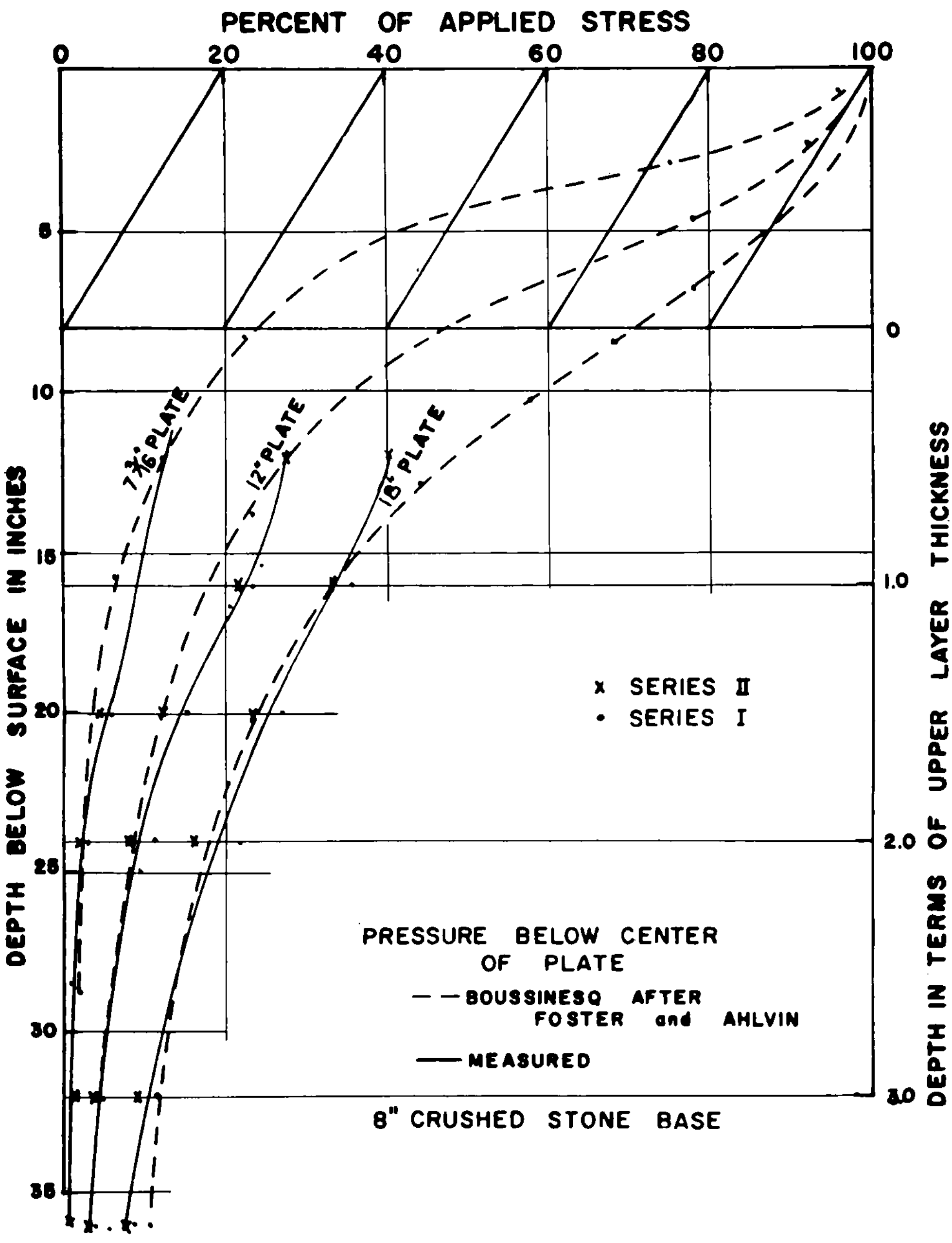

PERCENT OF APPLIED STRESS
0
20
40
60
80
100
5
10
15
20
25
30
35
DEPTH BELOW SURFACE IN INCHES
0
1.0
2.0
3.0
DEPTH IN TERMS OF UPPER LAYER THICKNESS
7 3/16" PLATE
12" PLATE
18" PLATE
x SERIES II
• SERIES I
PRESSURE BELOW CENTER OF PLATE
— — BOUSSINESQ AFTER FOSTER and AHLVIN
—— MEASURED
8" CRUSHED STONE BASE

Figure 16.

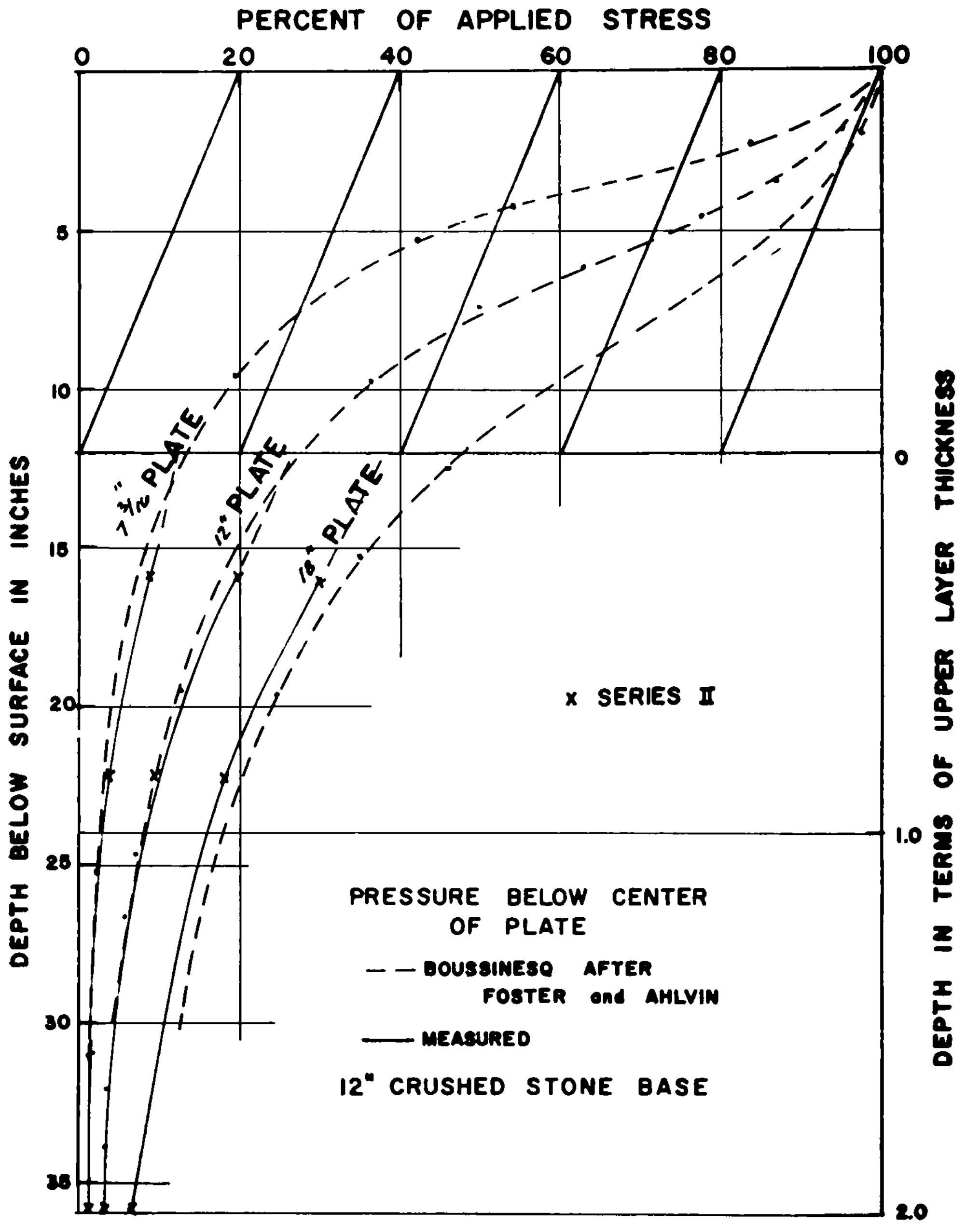

PERCENT OF APPLIED STRESS
0
20
40
60
80
100
5
10
15
20
25
30
35
DEPTH BELOW SURFACE IN INCHES
0
1.0
2.0
DEPTH IN TERMS OF UPPER LAYER THICKNESS
7 3/16" PLATE
12" PLATE
18" PLATE
x SERIES II
PRESSURE BELOW CENTER OF PLATE
— — BOUSSINESQ AFTER FOSTER and AHLVIN
—— MEASURED
12" CRUSHED STONE BASE

Figure 17.

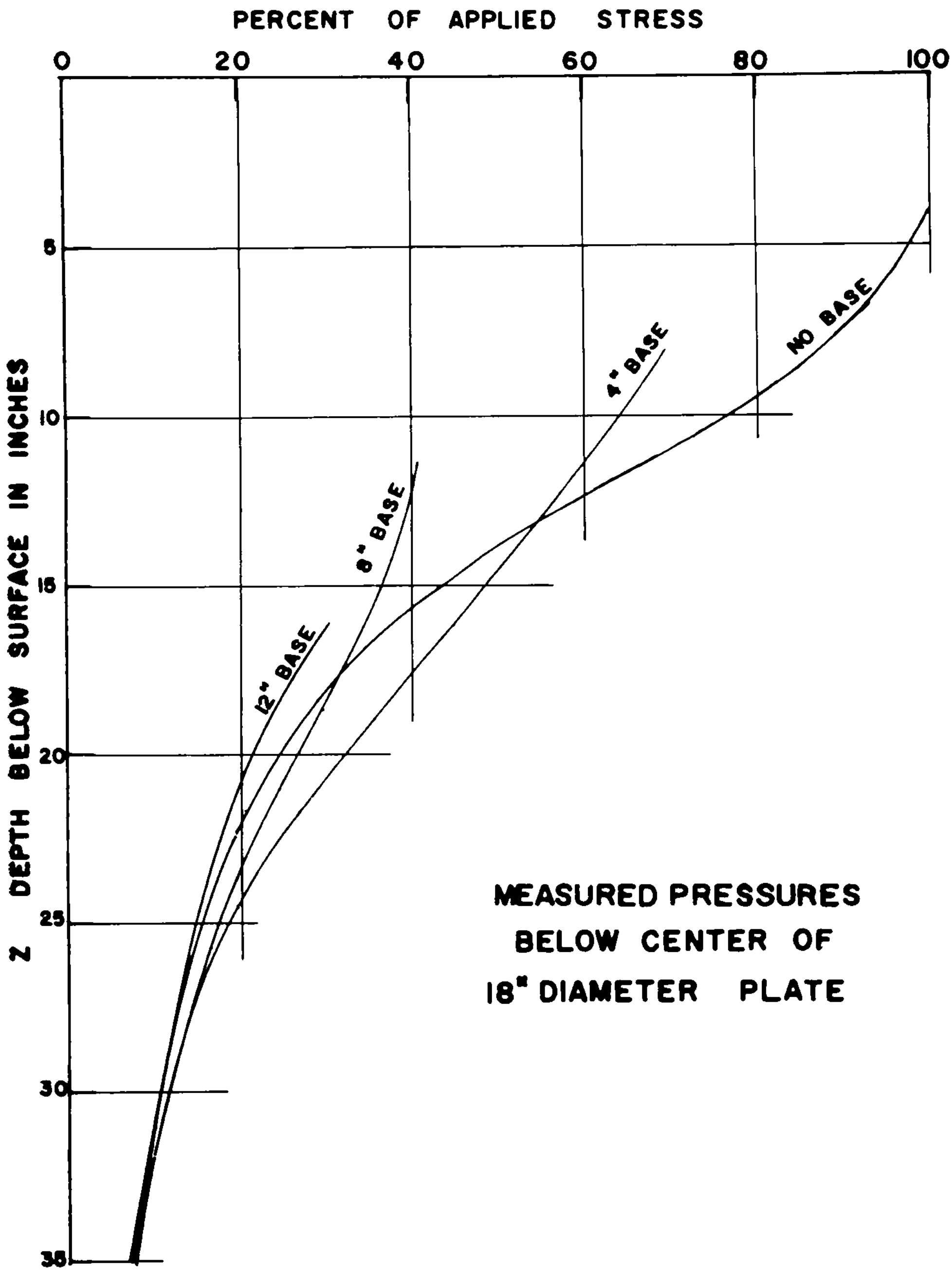

PERCENT OF APPLIED STRESS
0
20
40
60
80
100
Z DEPTH BELOW SURFACE IN INCHES
5
10
15
20
25
30
35
NO BASE
4" BASE
8" BASE
12" BASE
MEASURED PRESSURES
BELOW CENTER OF
18" DIAMETER PLATE

Figure 18.

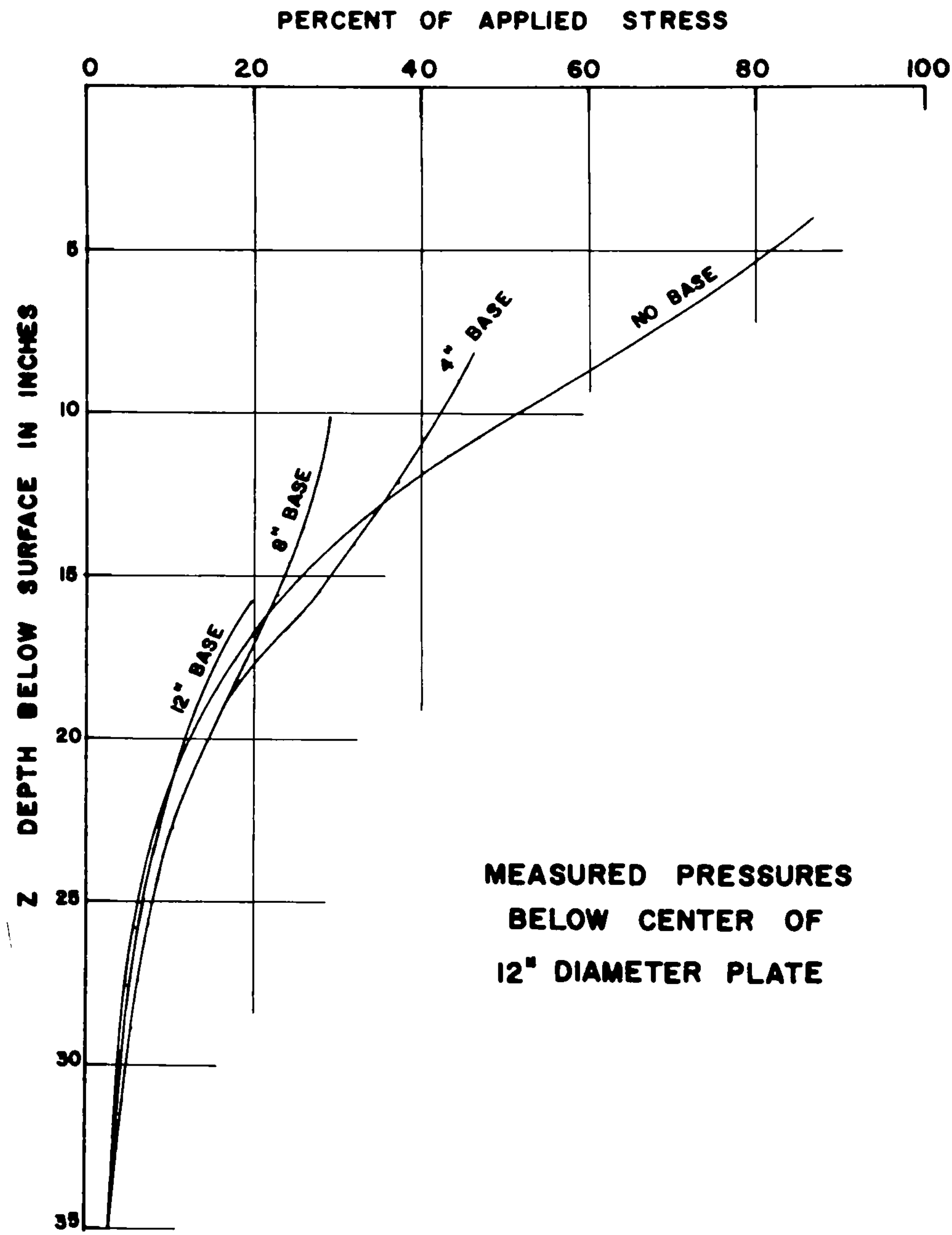

PERCENT OF APPLIED STRESS
0
20
40
60
80
100
5
10
15
20
25
30
35
DEPTH BELOW SURFACE IN INCHES
Z
NO BASE
4" BASE
8" BASE
12" BASE
MEASURED PRESSURES
BELOW CENTER OF
12" DIAMETER PLATE

Figure 19.

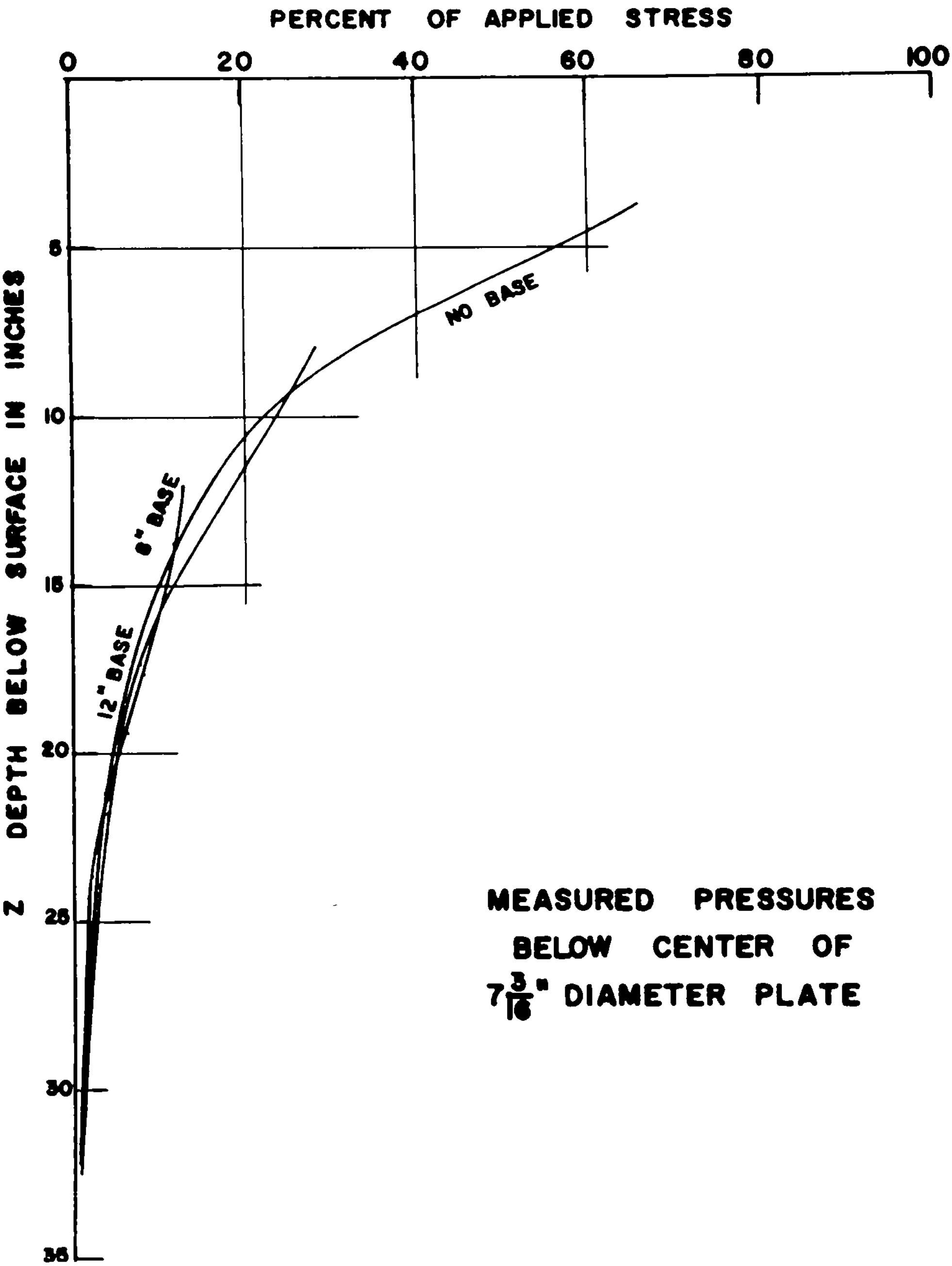

PERCENT OF APPLIED STRESS
0
20
40
60
80
100
5
10
15
20
25
30
35
Z DEPTH BELOW SURFACE IN INCHES
NO BASE
6" BASE
12" BASE
MEASURED PRESSURES BELOW CENTER OF $7\frac{3}{16}$" DIAMETER PLATE

Figure 20.

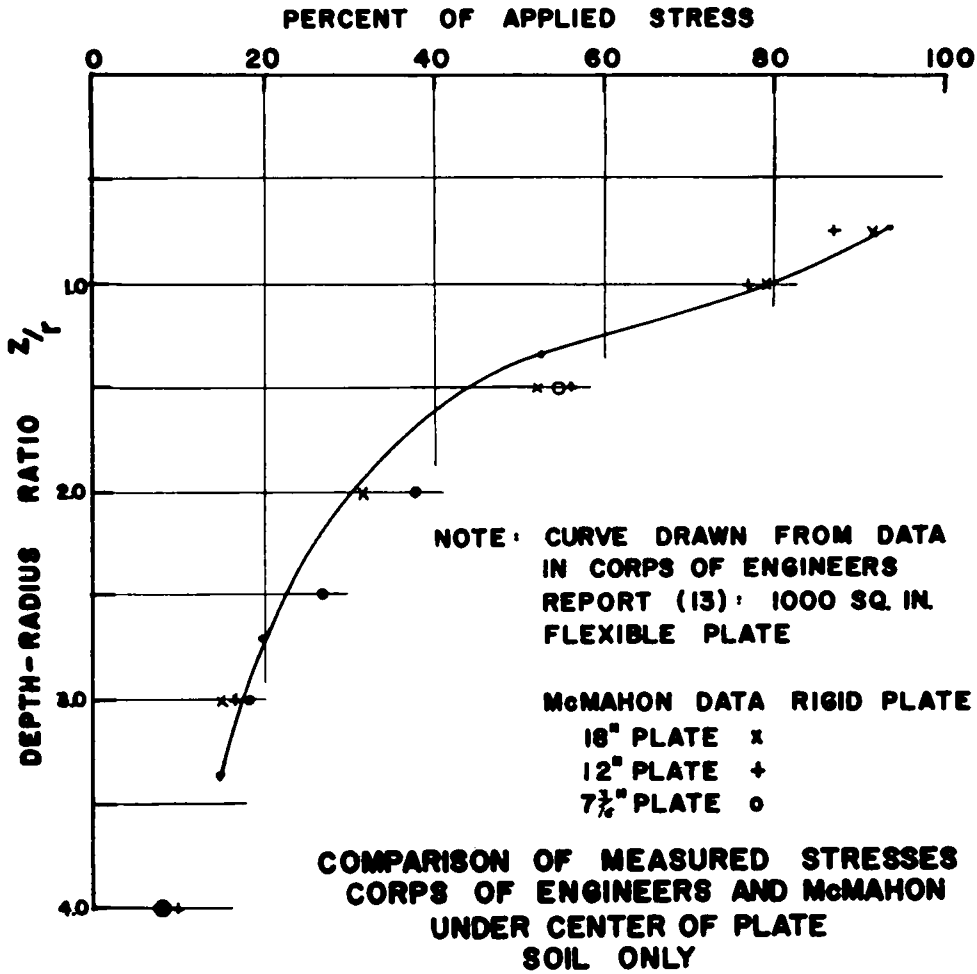


Figure 21.

is evident that the values obtained in the investigation are considerably higher than those computed by the Burmister Two-Layer Theory. However, as the strength of the base was so low, it was felt that this comparison was questionable.

The test data suggest that the effect of the base course in reducing stresses is primarily at the base-subgrade interface. Thus, it would be reasonable to assume that the stresses below the base follow the theoretical values if the true stresses at the interface were used as the surface pressure. To test this hypothesis the curves of Figures 15 and 16 are again presented in Figures 25 and 26, upon which are superimposed points of stress that have been calculated by an Equivalent Plate Method. These points have been determined in the following manner: the curves of the measured pressures were extended to intersect with the interface of the system. It was then assumed that this intercept was the average percent of applied stress on a plate, composed of a circular section of the base, of a size to have a uniform stress of this magnitude. The points were then calculated using the charts of Foster and Ahlvin (*16*). It is evident from Figures

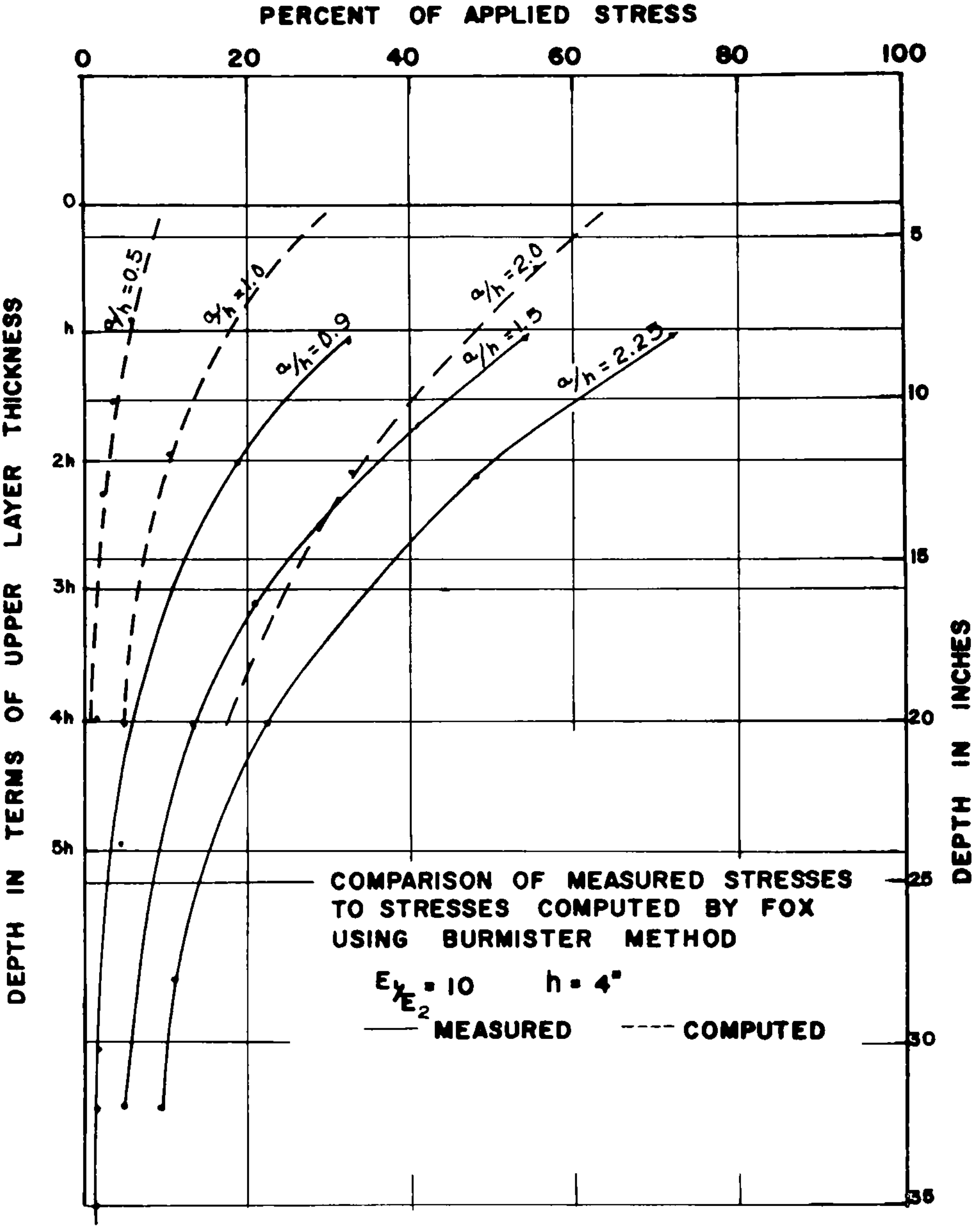

PERCENT OF APPLIED STRESS
0
20
40
60
80
100
0
h
2h
3h
4h
5h
DEPTH IN TERMS OF UPPER LAYER THICKNESS
5
10
15
20
25
30
35
DEPTH IN INCHES
a/h = 0.5
a/h = 1.0
a/h = 0.9
a/h = 2.0
a/h = 1.5
a/h = 2.25
COMPARISON OF MEASURED STRESSES
TO STRESSES COMPUTED BY FOX
USING BURMISTER METHOD
E1/E2 = 10
h = 4"
MEASURED
COMPUTED

Figure 22.

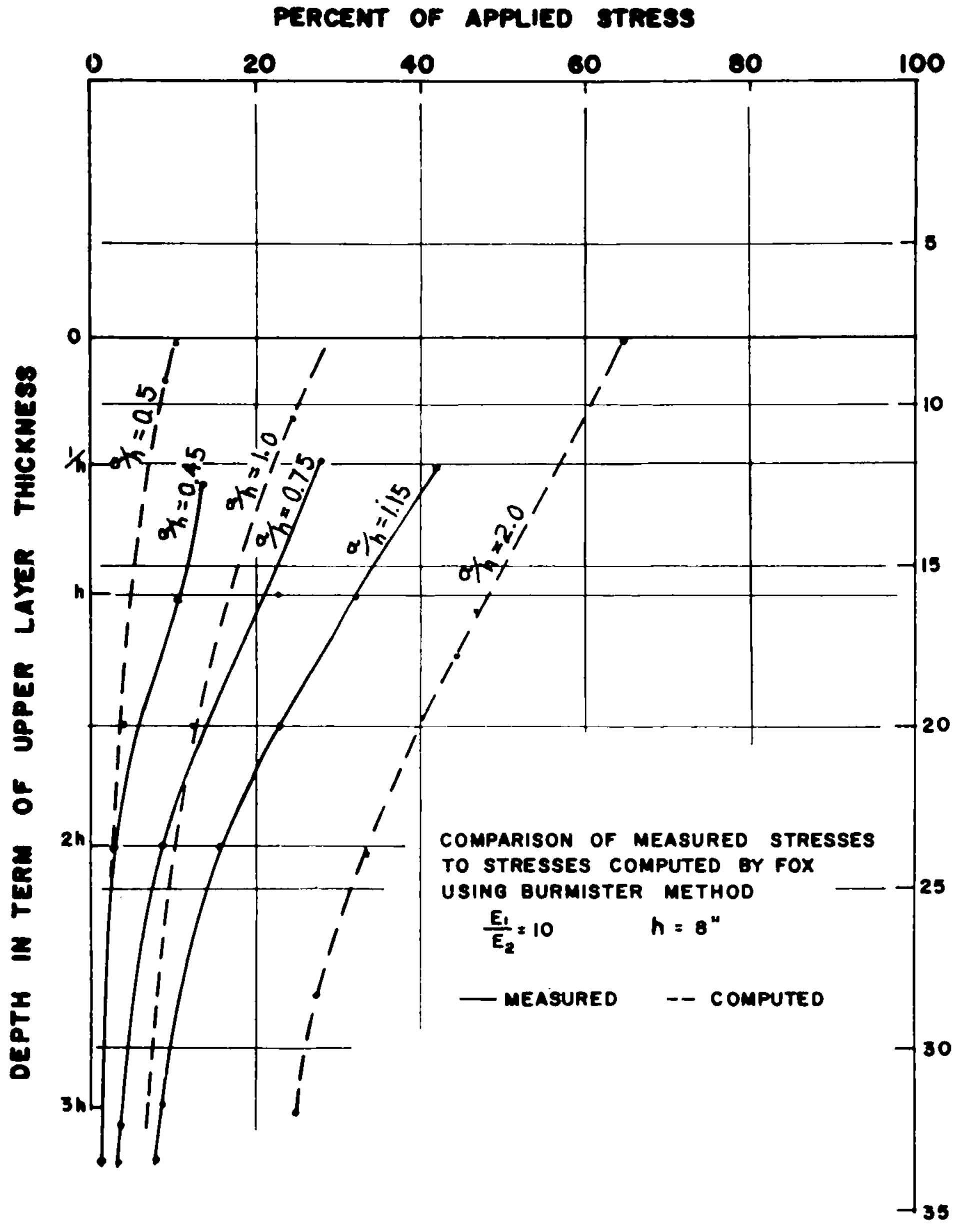

PERCENT OF APPLIED STRESS
0
20
40
60
80
100
DEPTH IN TERM OF UPPER LAYER THICKNESS
0
½h
h
2h
3h
DEPTH IN INCHES
5
10
15
20
25
30
35
a/h = 0.5
a/h = 0.45
a/h = 1.0
a/h = 0.75
a/h = 1.15
a/h = 2.0
COMPARISON OF MEASURED STRESSES
TO STRESSES COMPUTED BY FOX
USING BURMISTER METHOD
E1/E2 = 10
h = 8"
MEASURED
COMPUTED

Figure 23.

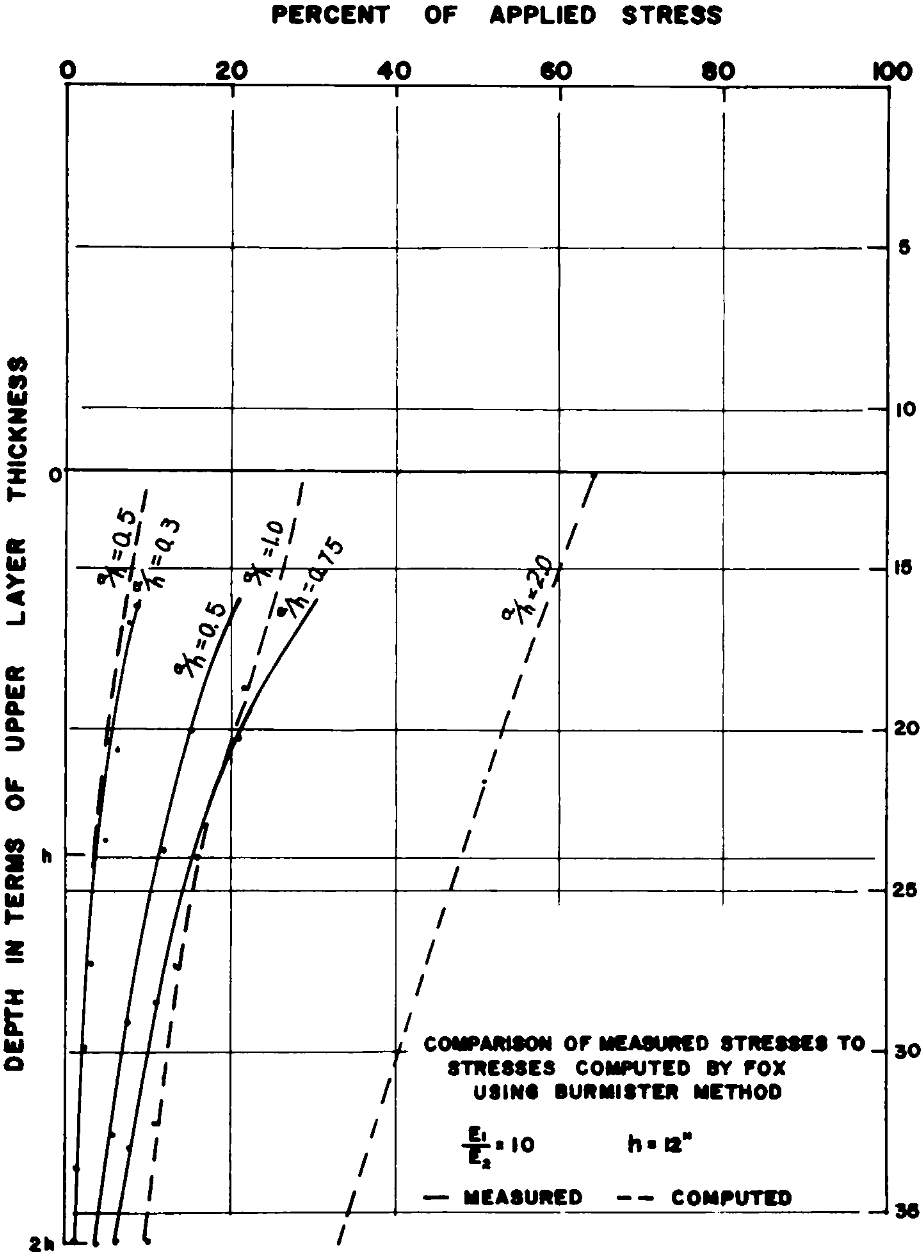

PERCENT OF APPLIED STRESS
0
20
40
60
80
100
DEPTH IN TERMS OF UPPER LAYER THICKNESS
DEPTH IN INCHES
5
10
15
20
25
30
35
0
h
2h
a/h=0.5
a/h=0.3
a/h=0.5
a/h=1.0
a/h=0.75
a/h=2.0
COMPARISON OF MEASURED STRESSES TO
STRESSES COMPUTED BY FOX
USING BURMISTER METHOD
E1/E2 = 10
h = 12"
— MEASURED
-- COMPUTED

Figure 24.

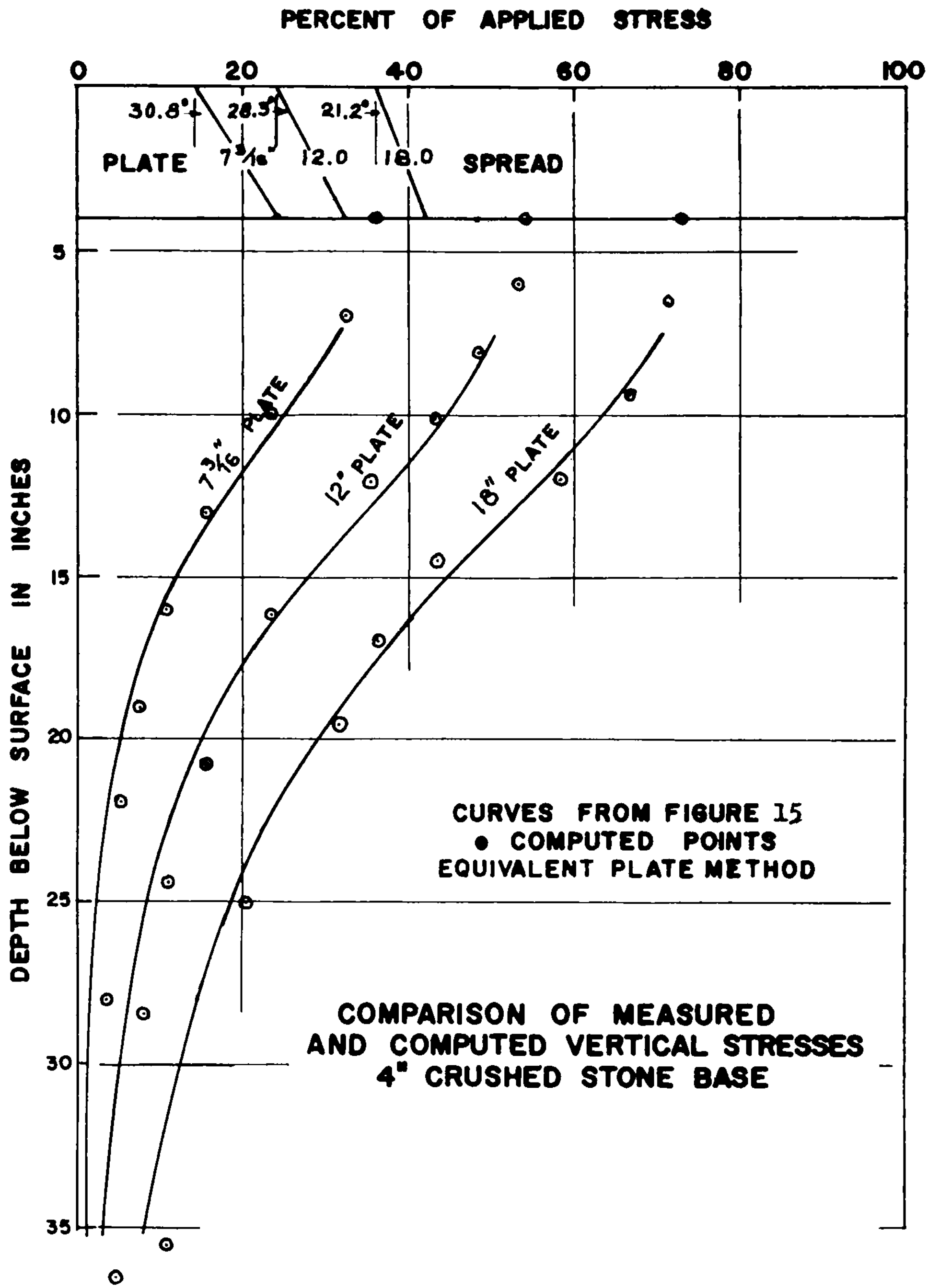

PERCENT OF APPLIED STRESS
0
20
40
60
80
100
30.8°
28.5°
21.2°
PLATE 7 3/16" 12.0 18.0 SPREAD
5
10
15
20
25
30
35
DEPTH BELOW SURFACE IN INCHES
7 3/16" PLATE
12" PLATE
18" PLATE
CURVES FROM FIGURE 15
• COMPUTED POINTS
EQUIVALENT PLATE METHOD
COMPARISON OF MEASURED
AND COMPUTED VERTICAL STRESSES
4" CRUSHED STONE BASE

Figure 25.

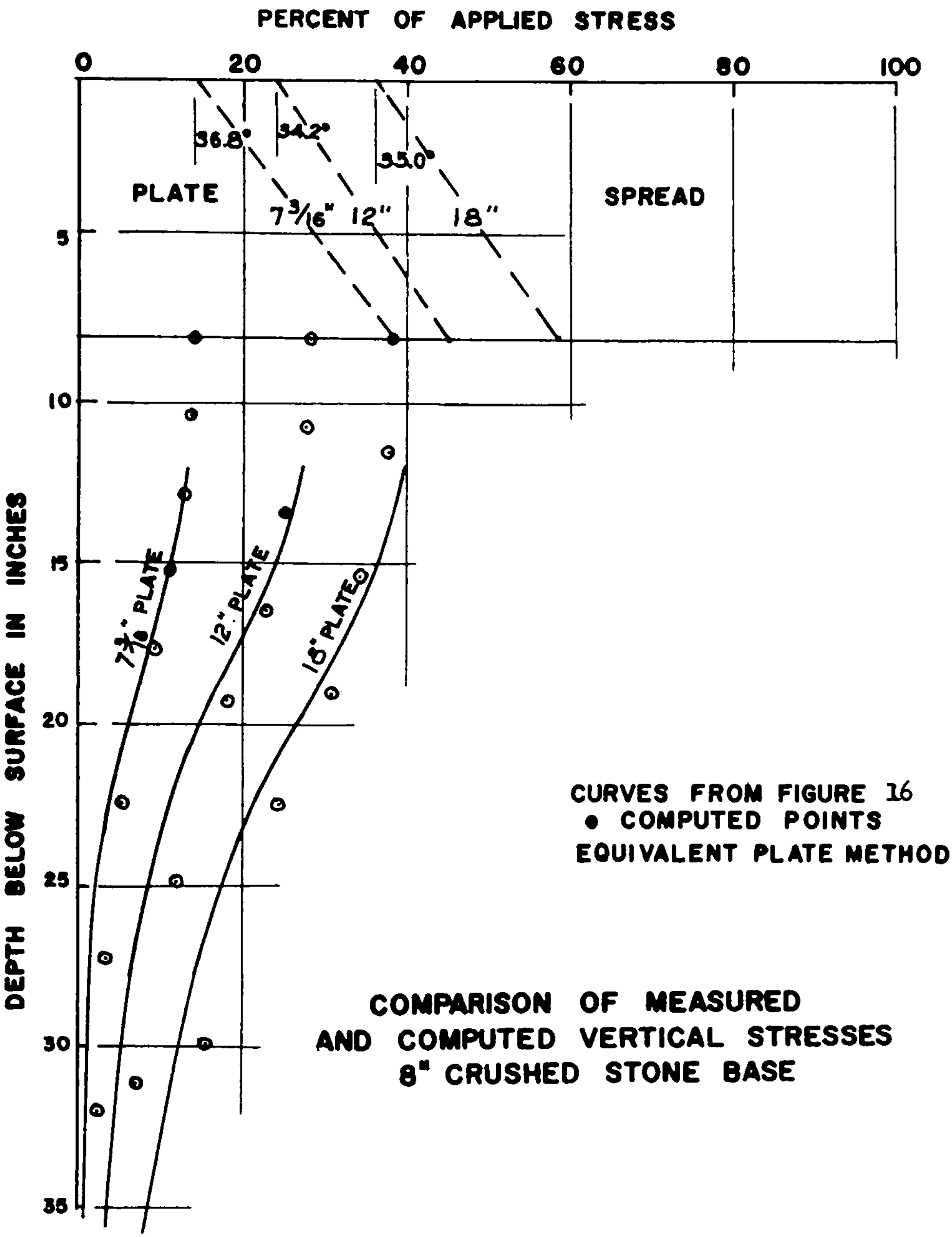

PERCENT OF APPLIED STRESS
0
20
40
60
80
100
36.8°
34.2°
35.0°
PLATE
7 3/16" 12" 18"
SPREAD
5
10
15
20
25
30
35
DEPTH BELOW SURFACE IN INCHES
7 3/16" PLATE
12" PLATE
18" PLATE
CURVES FROM FIGURE 16
• COMPUTED POINTS
EQUIVALENT PLATE METHOD
COMPARISON OF MEASURED
AND COMPUTED VERTICAL STRESSES
8" CRUSHED STONE BASE

Figure 26.

25 and 26 that there is a marked similarity between the results of this method and those of the investigation. It is also evident that this stress is somewhat higher than the actual uniform stress on a plate of this size at this position. This feature is made evident by the departure of the points from the Boussinesq distribution at the greater depths. However, the curves represent measured data, and therefore may not be representative of a uniform stress on a plate. The curves of Figure 16 indicate that the stresses at the center of a plate on a clay-soil subgrade are greater than the average applied stress. The work of the Civil Aeronautics Administration (*2*) also indicates that the stress transmitted to the subgrade through a base is considerably higher in the central zone of the affected area. With this factor in mind, it is not unreasonable to assume that the measured stresses near the interface will be higher than would be commensurate with a uniform distribution. It is possible that if the calculated points were made to fit the lower portion of the theoretical curve, the intersection of the calculated curve with the interface would indicate the true magnitude of a uniform pressure over an equivalent plate.

It is also apparent from Figures 25 and 26 that the spreading of the load is not a constant for all conditions of the base material. It is evident that the strength of the base course influences the spread of the load. The angle of spread determined for the 18-in. plate on the 4-in. base is only 21.2 deg. The modulus calculated for this material is even less than that for the soil alone. The spread angles of 28.3 and 30.8 deg for the 12-in. and 7-in. plates, respectively, can be explained by the sequence of loading used during the testing. The 18-in. plate was applied first. This resulted in a compaction and a strength increase in the base, which is reflected in the spread angles of the smaller plates. The spread angles for the 8-in. base are reasonably uniform. The data of the 12-in. base were not considered to be adequate for a like analysis. However, the spread effect, as calculated for the 7-in. plate, is 43 deg.

SUMMARY

Results

The major findings of the research may be summarized under topical headings of the various phases of the investigation in the following manner.

Design and Development of a Pressure Cell

A pressure cell was designed and developed as a portion of this study. The available literature was studied to ascertain the extent of the knowledge of the design of a cell and its limitations in use. The design was based on the criteria established by the Corps of Engineers, using the theory of elasticity to calculate the required dimensions.

The cell was tested to establish its behavior characteristics in air, clay, and sand media. It was determined that the functioning of the cell in the air was very similar to that in the clay medium.

The cell was also inserted in several clay-soil triaxial specimens and the measured stresses compared with theoretical stresses computed by the Mohr Circle method. It was determined that the degree of accuracy of the cell, as delineated by this comparison, was in all cases within an accuracy of ± 5 percent, and usually much less.

Laboratory Pressure Cell Measurements

Two series of pressure measurement tests, involving 17 separate loading conditions, were made in an 18 x 18 x 18-in. box, under loads applied with a 5¼-in. diameter plate. Measurements were made within homogeneous systems and within layered systems.

The stress pattern formed by the measured pressures appeared to follow the theoretical pattern of Boussinesq. However, the magnitude of the measured stresses deviated from the computed values. In a homogeneous system the stresses were smaller and in a layered system larger than those predicted by the Boussinesq theory. It was felt that the side effects of the small box were significant and that arching effects within the homogeneous mass were contributing to the reduction in the measured values.

Field Pressure Cell Measurements

Two series of field pressure measurement tests involving 53 separate loading conditions were made in an 8 x 8-ft model. Three plate sizes were used in these series of tests $7\frac{3}{16}$, 12, and 18 in. in diameter. Tests were performed with homogeneous systems and with two-layer systems. In the two-layer systems, 4, 8, and 12 in. of the homogeneous material were replaced by the same thickness of crushed stone base material. The results of these tests were compared with values calculated by known theories.

The pattern depicted by the field measurements again followed the Boussinesq theory for a uniformly distributed load in form. However, with the elimination of the side effects the measured pressures were greater in magnitude than the computed values, in both the homogeneous and the two-layer systems.

The base in the two-layer systems appeared to act as a load spreading medium. There was a definite reduction of stress in the zone directly below the base-soil interface. However, this reduction became negligible within a distance of r or less below the interface and the measured pressures again became higher than the theoretical values of Boussinesq for a uniformly loaded area. The measured pressures at intermediate depths were even higher than they were for the homogeneous condition.

A comparison was made between the measured pressures and the corresponding stresses computed by the Burmister theory under the center of the plates. The Burmister values were definitely lower than those measured in this investigation. However, the pattern of the measured distribution near the interface is similar to that predicted by Burmister, but at the greater depths it does not show a compatible reduction in stress. However, the low values of E of this investigation made it difficult to compare these distributions.

Calculations were made of the stresses which would be induced in the subgrade by a plate having a uniform load and an area compatible with the stress indicated at the interface, by an extrapolation of the curves of measured pressure. This plate was positioned at the interface and used as an equivalent area of base material. The calculated values, determined by the Boussinesq theory, correlated well with the measured values.

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