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THE TRANSMISSION OF PRESSURE THROUGH SAND

BY

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AND
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May 24, 1912

This is to certify that the thesis of LEWIS NEBINGER FISHER and HARVEY FRANKLIN WAGNER entitled THE TRANSMISSION OF PRESSURE THROUGH SAND was prepared under my personal supervision; and I recommend that it be approved as meeting this part of the requirements for the degree of Bachelor of Science in Civil Engineering.

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Ira O. Baker.

Professor of Civil Engineering.

THE TRANSMISSION OF PRESSURE THROUGH SAND.

I. Introduction.

The safe unit loads which sand, earth, stone, and various other materials will bear have been pretty satisfactorily determined by experience; but the relative amount of this pressure which is transmitted through the material, and the direction and intensity of the lines of pressure have as yet been little studied, and engineers know very little about these questions. In this thesis and in the two preceding it an endeavor has been made to obtain reliable information on this subject, and to present it in such a manner that the results obtained may be of use.

The first experiments of this series were made in 1910 by K.A.Burnell. His aim as stated by him was "more for the determination of the best methods of procedure than as a complete solution of the problem". In 1911 W.C.Eells and J.Van Dervoort carried on an extended series of experiments on sand, using apparatus which was a great improvement over that devised by Burnell. In these experiments the ground was covered very thoroughly, and the results obtained were of great value in advancing the knowledge on this subject.

It is the purpose of the writers of this thesis:

1. To verify the results obtained by Eells and Van Dervoort with regard to, (a), the relation between the maximum unit load which can be sustained and the depth of sand, (b), the variation of maximum unit load sustained with the area of surface loaded,

and (c), the variation of the intensity of pressure with the depth of sand and distance from the center of concentration of the load.

2. To determine the coefficient of friction of sand, and find out what effect moisture has on this coefficient.

3. To determine by means of photographs the direction of motion of the grains of sand as a load is applied to the bed of sand.

The subject will be treated under the following heads:

II. Theory and Available Data.

III. Materials, Apparatus and Methods of Testing.

IV. Experimental Data and Discussion.

V. Conclusions.

II. Theory and Available Data.

An extended search of available engineering literature fails to show any record of work of a nature exactly similar to that of these experiments. Many and various kinds of experiments have been carried on in attempts to discover some formula or rule by which lateral earth pressure might be computed. Also, many experiments have been made to retermine the bearing power of soil, and of sand in its natural bed. Other experiments somewhat similar to the ones here reported are those of Jamieson on the bottom and lateral pressures in grain elevators; but in these cases the vertical pressure is relieved and carried by the side walls. With the exception of the work done by Burnell, and Eells and Van Dervoort, there is no record of any attempt to solve the questions outlined in the introduction.

When a load is applied to a circular plate resting on a bed of sand, pressure is transmitted through the sand to the supporting surface. It is generally thought that this pressure spreads out uniformly from the area in contact with the plate to a much larger area on the supporting surface beneath. A newer theory, the theory supported by the writers,is that the points of maximum pressure lie within a cone whose base is the bottom of the plate, and whose apex is directly below the center of the plate; and that outside of this cone is a region of smaller pressure which diminishes in intensity with the distance from the axis of the cone, and with the depth of sand.

For the calculation of the intensity of vertical pressure at a point in the axis of the cone mentioned above an empirical formula was developed by Eells and Van Dervoort which agreed

fairly well with the results of their experiments on a 13 1/2 inch plate. This formula is

$$p' = \frac{100p}{d^{1.84}},$$

in which p' = unit pressure in pounds per square inch on the supporting surface directly under the center of applied pressure, p = unit pressure in pounds per square inch applied on the plate, and d = depth of the sand in inches.

III. Materials, Apparatus, and Methods of Testing.

In these experiments a bed of sand on a reinforced concrete base was used. This base was 9 feet long, 8 1/2 feet wide, and 6 inches thick, heavily reinforced to carry localized loadings. Planks were placed around the base to prevent the sand from flowing off, but were not fastened so as to offer any appreciable lateral support to the sand. Near each end of the base a pair of 1-inch steel rods were placed in a vertical position with their lower ends securely fastened to two steel plates embedded near the bottom of the concrete. A 20-inch I-beam was suspended from the floor above between these rods, and held down by large 2-inch steel plates through which the rods passed. The upper ends of the rods were threaded, and large nuts were screwed down to a bearing on the plates. Under no load the I-beam was held in place by stirrups suspended from the floor above.

For measuring the applied load the apparatus used was that designed by Eells and Van Dervoort, and used by them with very satisfactory results. This apparatus was a heavy steel spring or dynamometer with an Ames dial to read the deflections. The dynamometer was built of two nickel steel plates 7 1/2 inches wide, 2 inches thick, and about 32 inches long, separated 3 inches by steel blocks near the ends of the plates, the whole being held together by bolts 28 inches apart center to center. The bolts were used without washers, the nuts being turned to a firm bearing. The Ames dial was fastened between the plates at the middle of the span. Load was put on the spring through knife-edges, two on each side of the spring. These knife-edges were of steel, 1/2 inch square, placed transversely across the

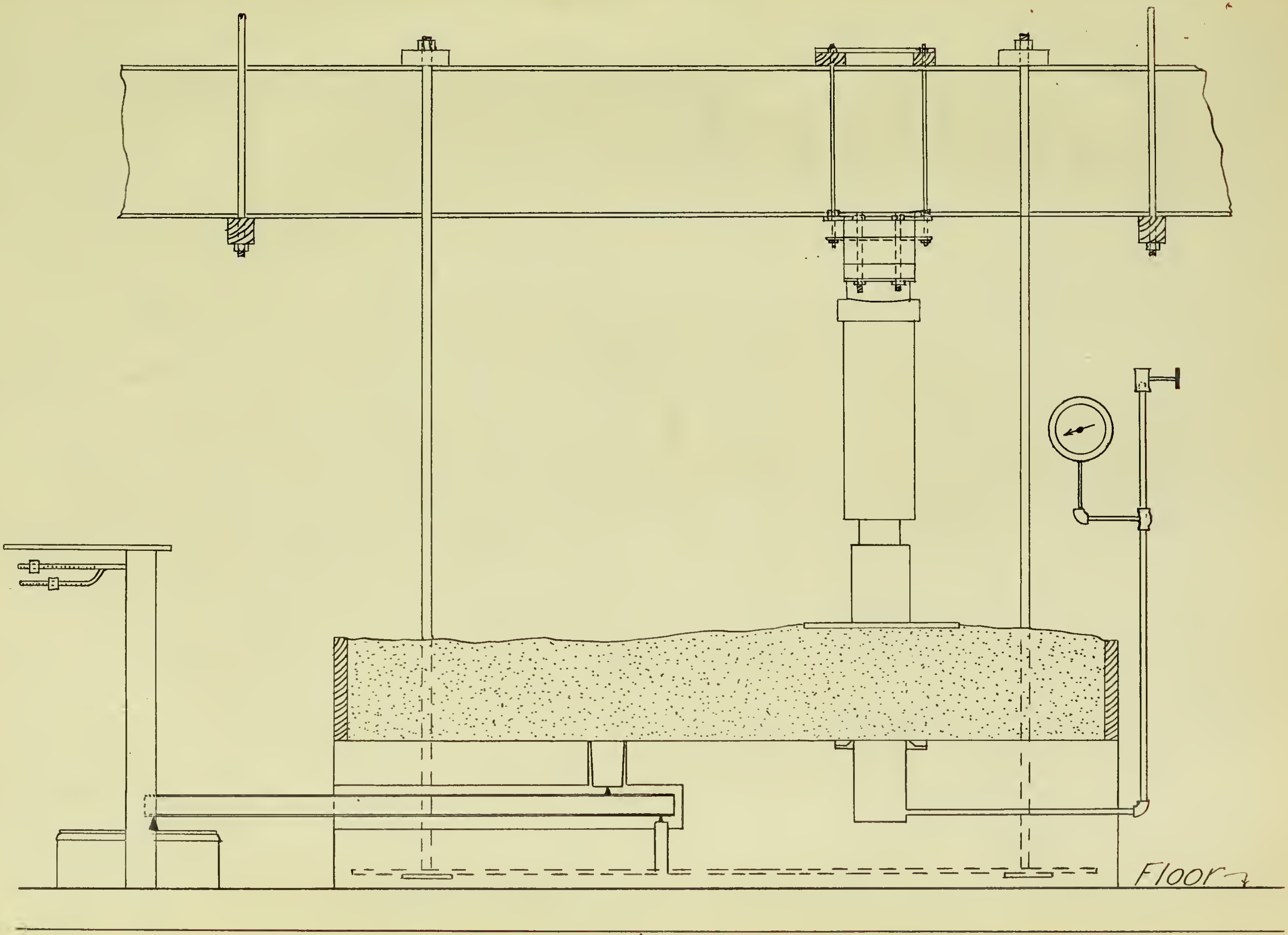


Fig. 1.

spring, each pair being 4 inches apart center to center, and equidistant from the center of the spring. The spring was calibrated in a testing machine, and found to be very dependable, since four calibrations with loads up to 50000 pounds agreed almost exactly. Since the deflections could be read directly to 0.001 inch, and estimated to 0.0001 inch, and a deflection of 0.001 inch corresponded to a load of about 170 pounds, the load on the spring could be easily ascertained within 30 pounds. The spring was held against the lower side of the I-beam by stirrups of 1/2-inch rods suspended from wood blocks across the top of the I-beam.

In previous experiments the pressure transmitted had been determined by means of a plug 4 inches in diameter in the base, free to move vertically, and supported by a lever the fulcrum of which was so placed that pressure on the plug could be measured by the load transferred to platform scales. Some doubt was felt as to the accuracy of this method. It was thought that as the plug must necessarily move downwards slightly as load was applied the pressure would be somewhat relieved by the arch action of the sand. This apparatus was also rather cumbersome, requiring much time and labor to take the readings. A diagram of this apparatus is shown in the lower left hand corner of Figure 1.

In view of these objections to the former method, and also in order to verify the results by a different method of measuring the transmitted pressure, it was decided that a pressure gauge would be used. Provision had been made for this means of measuring the pressure when the base slab of concrete was constructed, but owing to a lack of time the method had never been fully tested. A 6-inch iron cylinder,closed at the

bottom, was embedded in the concrete about 3 feet from one end of the base. A beveled flange was securely fastened to the top of this cylinder. A diaphragm made of two thicknesses of No. 16 packing rubber was used to close the cylinder. This diaphragm was held firmly in place by means of a beveled collar, which fastened to the flange with screws so as to make a water-tight joint. A 3/4-inch pipe led from the bottom of the cylinder out through one end of the concrete base, and up about 3 feet above the base, at which point was a valve at the end for closing it. A pressure gauge was attached about 1 foot below the end of the pipe. In filling this apparatus with water great care was taken to see that no air was entrapped in either the gauge, pipe, or cylinder. This apparatus was found to work well when the plate upon which pressure was applied was directly above the diaphragm, reading with the plate in this position as high as 135 pounds per square inch. But the rubber was so lacking in tensile strength that it burst at low pressures with off center loadings, for which reason very few data of this kind were obtained in these experiments. A stronger diaphragm could have been designed, but it was not thought advisable in this case as the time at hand could be more profitably employed in other phases of the work.

In applying the load to the sand the method used in all cases was to build up a well-packed bed of sand to a depth of 20 or 22 inches. This was carefully leveled off and a plate of the desired diameter placed upon it and centered by means of a plumb bob suspended from a center mark on the I-beam. The hydraulic jack was placed on the plate, and a 6" by 6" wooden post of sufficient length to reach from the jack to the bearing block put in place, supporting the bearing block which bore directly

on the two knife-edges on the lower side of the spring. The plate was then forced down until the depth of sand was 18 inches. No readings were taken with a depth of sand greater than 18 inches since the limited size of the base prevented the building of a good bed of sand to a greater depth than this. Pressure plates of 9, 13 1/2, and 21 inches diameter were used. In getting these data simultaneous readings were taken of the deflection of the spring as shown by the Ames dial, of the pressure on the diaphragm, read directly in pounds per square inch on the gauge, and of the depth of sand. The depth of sand was found by measuring the distance from the I-beam to the sand. After the bed of sand was built up for a set of readings the plate was forced down to the desired depth without disturbing the sand underneath, care being taken that the sand was at all times kept cleared away from the plate level with the top for a distance of about 2 feet on all sides.

The most interesting work done in connection with these experiments was the taking of the photographs which are shown herewith. As there seems to be nothing of exactly the same nature described in available engineering literature, the method used to secure these photographs will be quite fully described. The idea of taking these photographs originated from some photographs taken by Müller-Breslau in his experiments on lateral pressure against retaining walls. It was from these plates that the idea was obtained of taking a photograph of a granular material moving under load, by means of a long exposure of a photographic plate. Some experiments carried on for the American Railway Engineering Association and described in its Bulletin No. 136, gave further

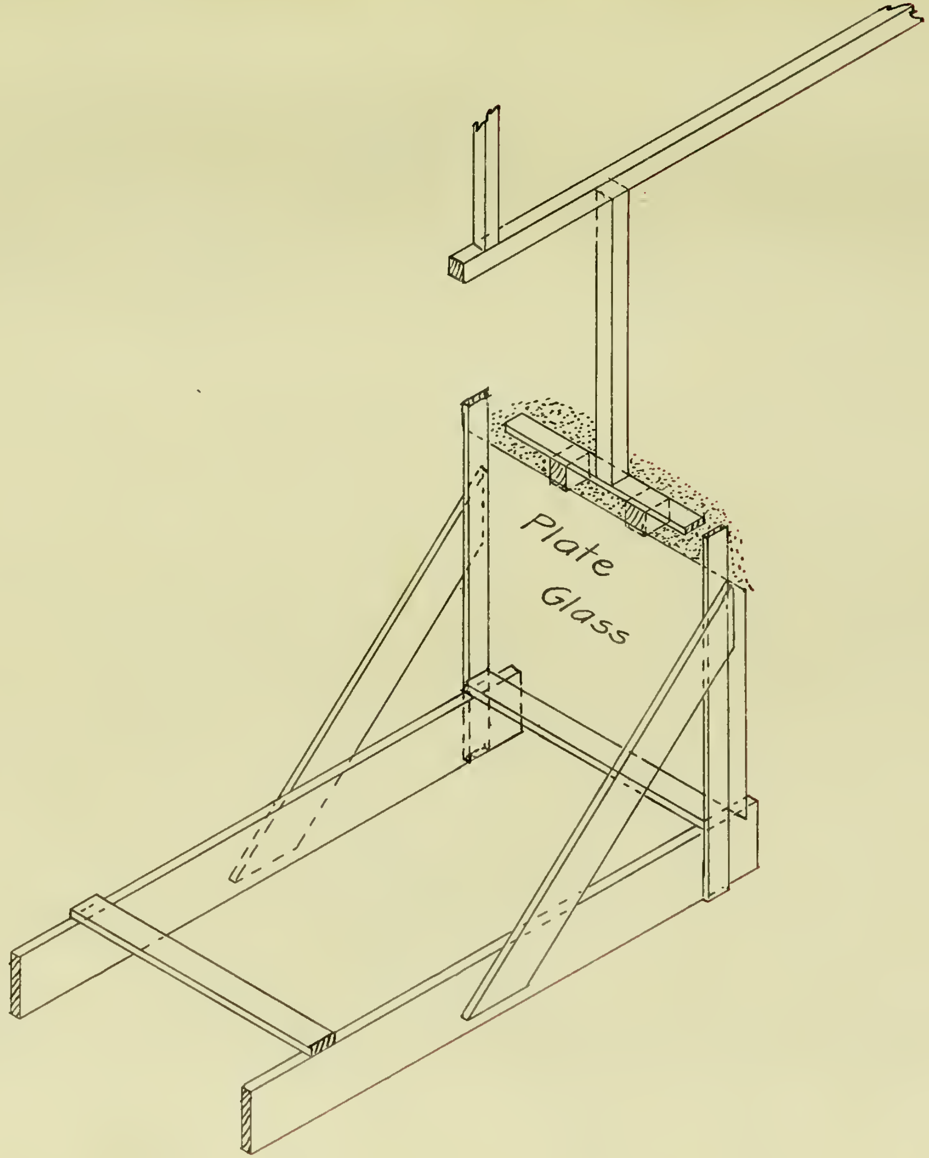


Fig. 2.

information. The result was the apparatus shown by Figure 2 and Plate 1. A wooden frame made of two 2" by 6" pieces of lumber with uprights and braces of 1" by 4" material near one end was used to hold the glass in a vertical position. The first glass used was ordinary window glass, but this was found to be too weak to stand sufficient lateral pressure to permit the desired vertical pressures to be applied, so a piece of plate glass 18" by 15" was secured. Sand was piled up on one side of the glass as high as the top. The sand next to the glass was screened to range in size of grains from 1/3 inch to 1/10 inch, but the main portion was the ordinary sand used in the previous experiments. Care was taken in heaping the sand around the glass and plate to make the pile symmetrical. As little sand was piled up as possible in order to make the resistance to the movements of the plates upon which the pressure was applied a minimum, since the glass was not strong enough to withstand much lateral pressure.

The plates upon which the pressure was applied were simply blocks of wood 2 inches wide, cut to the desired length; blocks 2, 4, 6, 9, and 12 inches long were used. In order to secure pressures similar to those given by railroad ties spaced at different distances apart, blocks of wood 2 inches square and 4 inches long were tacked to the lower side of a 2" by 4" piece 18 inches long. First two blocks were used and spaced successively 4, 6, 8, and 10 inches centers, and then three blocks were used, spacing them successively 4, 6, and 8 inches centers. For each photograph the blocks were slowly forced down, moving a total of about 2 inches in an interval of from a minute to a minute and a half. The camera was placed about 3 feet in front of the exposed

side of the glass, and the photographic plate exposed during the total time of movement of the sand. A good idea of the distribution of pressure in ballast under railroad ties may be had from those plates in which three blocks were used at once. To force the blocks down a piece of wood 2" by 2" and 8 feet long was used as a lever.

The apparatus used for determining the coefficient of friction of the sand was simply two wooden boxes 9 inches wide, 14 inches long, and 6 inches deep; four 25-pound weights, and a spring balance. These boxes were packed full of sand, one placed on the top of the other with their open sides together, and the force required to cause one to slide upon the other was measured with the spring balance. Sand enough was put into the boxes so that the edges would not touch. The force required to cause the upper box to slide on the lower was found, first with no load on the upper box, then with loads of 25, 50, 75, and 100 pounds, successively, on the upper box. In order to get the upper box in place full of sand, it was first filled in an upright position; a cover of sheet iron was placed on it, the box inverted, and the piece of sheet iron slipped out. Five samples of sand were taken, varying in percentage of moisture from practically dry sand in the first to completely saturated sand in the fifth sample. The coefficient of friction for each sample was determined by the average of four trials.

The sieve analysis of the sand was made by putting an average sample of sand through the indicated sieves. The sand used in these experiments was of medium coarseness, fairly clean, but very dry, containing only 1.25% of moisture.

IV. Experimental Data and Discussion.

In all of the following plates the results of the present series of experiments are shown in black lines. Curves drawn in red are reproduced from the thesis of Eells and Van Dervoort for purposes of comparison. In all cases "load on" indicates an increasing load, and "load off" a decreasing load.

Plate 1 is the calibration of the steel spring. This curve is the plotted average of four sets of readings, which agreed with other very closely. The deflections are slightly greater for "load off" than for "load on", due, very likely, to the slowness of the steel to exert its full resisting power. After over 100 applications of the load no permanent set of the steel could be observed.

The curves in Plate 2 show the total load in pounds sustained by the sand, using various sizes of plates and different depths of sand. The curves show that for each size of plate there is some depth of sand at which the supporting power of the sand ceases to vary with the depth, but is practically constant. This depth is not the same for all plates, however, but varies with the size of plates. Thus, for the 9-inch plate the load sustained is practically constant for all depths over 8 inches, while for the 13-1/2 inch plate this depth is about 12 inches, and for the 21-inch plate, about 30 inches.

On Plate 3 are plotted the depth of sand and unit load sustained for different sizes of plates. It shows that the unit load as well as the total load varies with the depth of sand. The values found by Eells and Van Dervoort are very much higher than those obtained in these experiments. A curious feature of

these curves is that in both sets the curves for the 13 1/2-inch and 21-inch plates cross each other at a point corresponding to a depth of about 15 inches. Just as in Plate 2 a point is reached beyond which the unit load sustained does not vary with the depth of sand, but is practically constant.

The curves plotted in Plates 4, 5, and 6 show the variation of unit pressure transmitted with unit pressure applied on a 13 1/2-inch plate for 6, 12, and 18 inches depth of sand, respectively. In all three cases the curve is approximately a straight line, showing that the unit pressure transmitted varies almost directly as the unit pressure applied; but the slope of the curve is different for the different depths. Thus, for the 6-inch depth the unit pressure transmitted is about twice the unit pressure applied, for the 12-inch depth the ratio is about one, and for the 18-inch depth the ratio is about one-half. The formula developed by Eells and Van Dervoort,

$$p' = \frac{100p}{d^{1.84}},$$

is apparently of the correct type. The constants will be verified later by the results of these experiments. It is seen that for 12-and 18-inch depths of sand the curves plotted from the two sets of experiments agree fairly well; but for the 6-inch depth of sand the value of the transmitted pressure found by Eells and Van Dervoort are very high, the ratio of the transmitted to the applied pressure running as high as 9. This can be partly explained by the fact that with the 13 1/2-inch plate and a 6-inch depth of sand it would be possible for the 4-inch plug used by them to be completely within the small cone of maximum pressure, and thus to receive practically all the applied load, while with

the much larger diaphragm used for these experiments this condition would not obtain. In all the curves of this character the values of the pressure transmitted are higher for "load off" than for "load on". This indicates that when the sand is being relieved of load it does not respond fully to the relief of pressure. However, some readjustment does take place, and the two sets of readings would agree more closely, if more time were allowed between readings.

On Plate 7 the ratio of the pressure transmitted to the pressure applied is plotted against the pressure applied for the 13 1/2-inch plate and for 6, 12, and 18 inch depths of sand. For sand 18 inches deep the average ratio is about 0.5; for the 12 inch depth, about 1.0; and for the 6 inch depth, about 2.4.

On Plates 8, 9, and 10 is plotted the variation of the unit pressure transmitted with that applied for the 9 inch plate and with 6, 12, and 18 inch depths of sand. These curves are of the same general nature as those shown in Plates 4, 5, and 6. The only difference is in the slope of the lines, or the ratios between the two unit pressures. Plates 11 and 12 are for the 21-inch plate and for 12 and 18 inch depths of sand. All curves showing variation of pressure transmitted with pressure applied are of the same general nature, but they vary both with the depth of sand and with the size of plate.

Plates 13, 14, 15, and 16 are curves showing the variation of unit pressure transmitted with unit pressure applied for a 13 1/2-inch plate 3 and 12 inches off center, and with depths of sand of 12 and 18 inches, respectively. Comparison of these curves with those of Plates 4, 5, and 6 shows that the pressure transmitted falls off very rapidly for off center loading. For on center loading the unit pressure transmitted was about the same as that applied

for the 12-inch depth, and about half as much for the 18-inch depth; but with the plate 3 inches off center and sand 12 inches deep the transmitted pressure was only about half of that applied, while for the 18 inch depth this ratio dropped to one third. For the plate 12 inches off center the ratio is about the same as for 3 inches off center with 12 inches depth of sand, but with the 18 inch depth of sand it is only half as great, or about one sixth.

On Plate 17 are plotted on logarithmic paper three sets of curves, one each for a 9-, 13 1/2-, and 21-inch plate; each set containing three curves, and each curve showing for a constant value of unit pressure on the plate the relation between the depth of sand and unit pressure transmitted. It has already been pointed out that the unit pressure varied almost directly with the unit pressure applied; that is, for a given plate and depth of sand, $p' = kp$, in which p' = unit pressure transmitted, p = unit pressure applied, and k = a constant. In these curves the depth of sand is introduced as a variable, and the relation between it and the other variables will now be sought. Eells and Van Dervoort plotted a set of similar curves for the 13 1/2-inch plate, and found them to be very nearly straight lines, and also almost parallel, indicating that p' varied with some constant power of the depth of sand. This exponent was given by the slope of the curves, and found to be -1.84. The formula adopted by them finally was then

$$p' = \frac{100p}{d^{1.84}},$$

in which d = depth of sand in inches, and p' and p meaning the same as before, expressed in pounds per square inch. In the sets of curves plotted from this series of experiments some curves approximate a straight line, while others are far from straight.

The slopes of these lines vary between 0.7 and 2.1, and therefore any formula of the type just given must be only very approximate.

However, in order to test Eells and Van Dervoort's formula, the average slope of the curves for the 13 1/2-inch plate was determined, and found to be -1.34. Then, substituting experimental values of p', p, and d in the formula, an average value of the coefficient of p was found to be 26, giving the approximate formula,

$$p' = \frac{26p}{d^{1.34}} ,$$

as agreeing fairly well with the results of the present series of experiments on the 13 1/2-inch plate.

While working with this formula an effort was made to make it general for all sizes of plates by putting it in the form

$$p' = \frac{26p}{d^{1.34}} \frac{A}{143} ,$$

A being the area of the plate in square inches, and 143, the area of the 13 1/2-inch plate for which the original formula was developed. This gives the formula in the final form,

$$p' = .182A\frac{p}{d^{1.34}} .$$

Comparisons were then made between the corresponding values of p' as computed by this formula, and as found by experiment, taking values of p and d such as to cover thoroughly the range of experimental values. A comparison of ten values for the 9-inch plate gave an average variation of 21.4% from the experimental values, with a maximum variation of 38%. This is as close as could be expected when the average variation of twelve comparisons of values for the 13 1/2-inch plate, from which the formula was developed was 14.5%, with a maximum of 28%. Similarly, the average variation in six comparisons of values for the 21-inch plate was 13.5%, with a maximum of 34%. The average variation of the computed from the

experimental values for the 28 comparisons was 16.7%, so it is safe to say that this formula will give the value of the transmitted pressure correct within 10%, for most cases lying within the ranges of the depths of sand and sizes of plates used in these experiments. These comparisons are shown in detail in Table I.

On Plate 18 are given the ideas of the authors as to the probable manner in which the pressure is distributed through the sand. The lines shown on the plate are contours of equal vertical unit pressure as determined by the pressure on the diaphragm for different depths of sand. Assuming the curves as correct, it will readily be seen that there is very little spreading out of the pressure over the base; that is, that most of the pressure is transmitted to an area directly under the plate, and that the unit pressure under the center of the plate for shallow depths is very much higher than the unit pressure on the plate.

Plate 19 is a sieve analysis curve of the sand used in the experiments. The curve is self-explanatory, and shows that the sand used was a very well-graded building sand.

A rather extended series of experiments was carried on to determine the coefficient of friction of sand, and to determine how this coefficient varied with the percentage of moisture in the sand, with the apparatus described in Art. III. It was thought that the coefficient of friction would vary considerably with the percentage of moisture; in fact, Dean M.S.Ketchum, of the University of Colorado, in his treatise on "Walls, Bins, and Grain Elevators", states that "if water be added to dry sand the angle of friction decreases, and approaches zero". The coefficient of

friction was found, however, to be practically constant for all percentages of moisture. The results of these experiments are shown in Tables 2 to 7, inclusive. The tangent of the angle of repose of sand with 1.25% of moisture was found to be 0.646, which is greater than any of the values found for the tangent of the angle of internal friction.

Photograph No.1 is a general view of the main apparatus. No.2 shows the steel spring used to measure loads. No.3 is a view of the apparatus used to secure the photographs of the grains of sand in motion. No.4 shows the arrangement of the grains of sand before any load was applied. Nos.5, 6, 7, and 8 show the movement of the sand particles when loads were applied to single blocks of different sizes as indicated. Nos. 9, 10, 11, and 12 show the movement of the sand particles when loads were applied to two 2" blocks spaced at the indicated distances apart. Nos. 13, 14, and 15 show the movement of the sand particles when loads were applied to three 2" blocks spaced at the indicated distances apart. These photographs are somewhat novel, and it is the hope of the authors that a study of these and similar photographs will lead to a better knowledge of "The transmission of pressure through sand".

V. Conclusions.

1. The unit load sustained increases as the area of the plate increases.

2. The load sustained by a plate increases with the percentage of moisture in the sand. The first experiments, which are not recorded in this thesis, were made on sand while it was yet very damp. The loads then sustained were considerably greater than those sustained after the sand had dried out.

3. The load sustained by a plate varies with the depth of sand. For the 9- and 13 1/2-inch plates the load increased very slowly from an 18-inch depth to a 10-inch depth, and very rapidly between the 10- and 6-inch depths. For the 21-inch plate the load increased very rapidly from the 18-inch depth to the 6-inch depth.

4. When the sand is unrestrained laterally, a depth of sand is reached for all plates at which an increase in depth does not affect the load sustained. This depth varies with the size of the plate, varying from about 8 inches for a 9-inch plate to about 30 inches for a 21-inch plate.

5. With a constant pressure on the plate the unit pressure transmitted varies inversely with some power of the depth of sand, this power being about 1.34 for the 13 1/2-inch plate, for the sand used in these experiments.

6. The pressure transmitted does not spread over as large an area as is generally supposed, but is largely transmitted vertically downward to an area not greatly exceeding that of the plate.

7. The unit pressure transmitted varies directly with the area of the plate for the depths of sand used.

8. The coefficient of internal friction of sand is practically constant for all degrees of moisture.

9. For all cases where transmitted pressure not exceeding 120 pounds per square inch is to be measured for an on center loading, the diaphragm and water gauge apparatus is much preferable to the plug and scales apparatus in ease of manipulation and reading, and is equally accurate. But for off center loadings, the eccentric loading on the diaphragm causes it to rupture at low unit pressures; therefore the plug and scales apparatus is preferable for off center loadings.

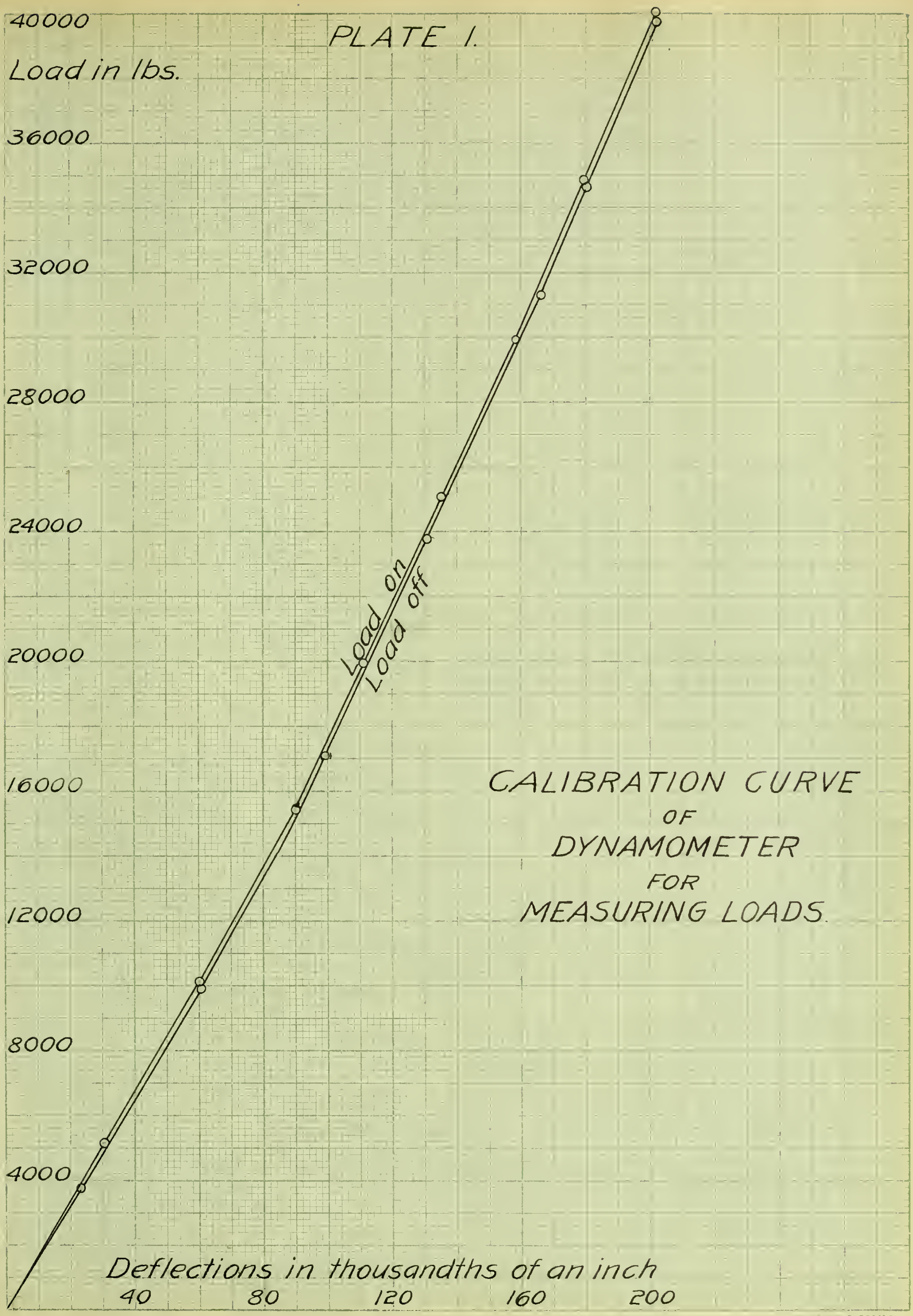
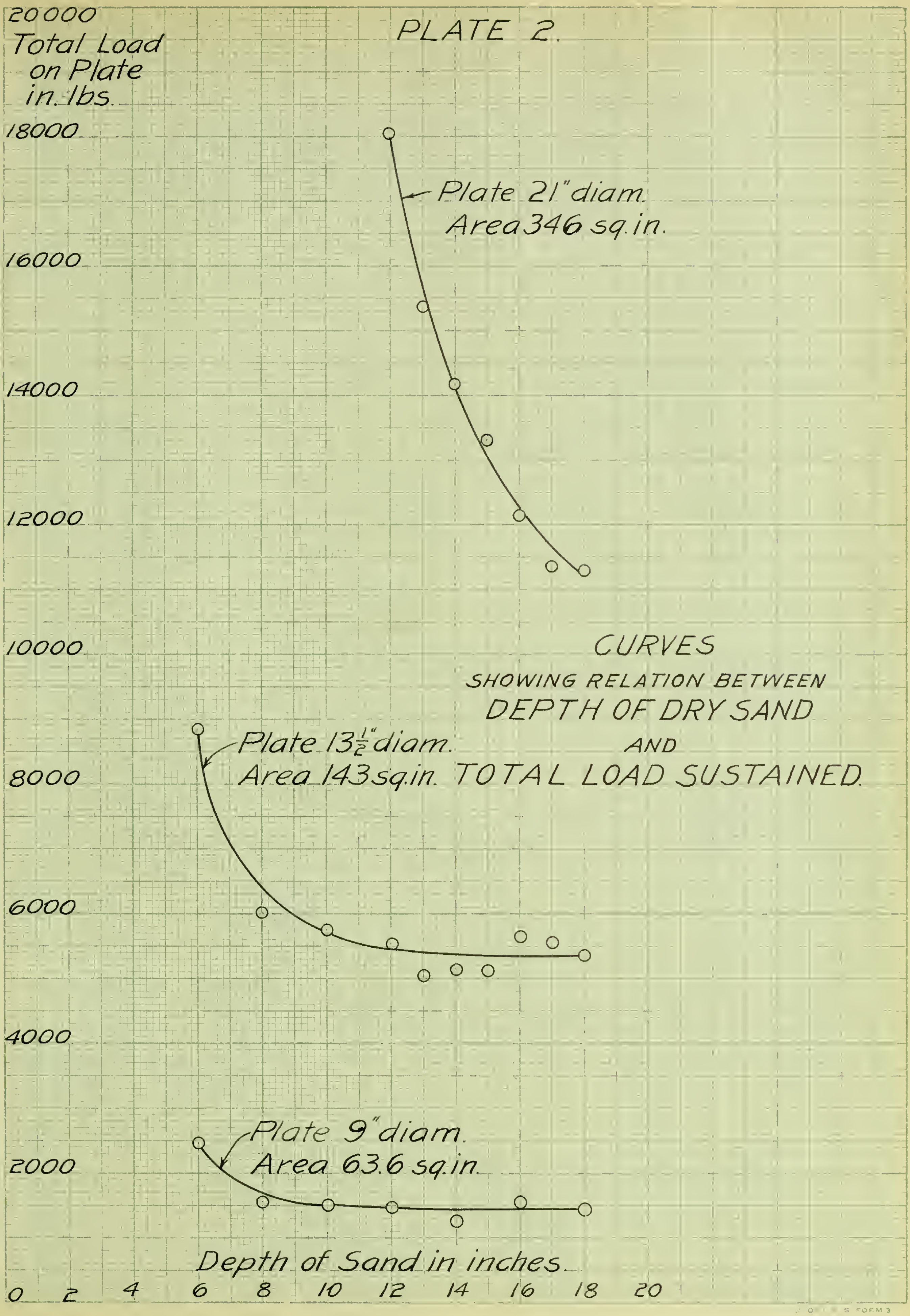


PLATE I.
Load in lbs.
40000
36000
32000
28000
24000
20000
16000
12000
8000
4000
Load on
Load off
CALIBRATION CURVE
OF
DYNAMOMETER
FOR
MEASURING LOADS.
Deflections in thousandths of an inch
40
80
120
160
200

PLATE 2.



20000
Total Load on Plate in. lbs.
18000
16000
14000
12000
10000
8000
6000
4000
2000
Plate 21" diam.
Area 346 sq. in.
CURVES
SHOWING RELATION BETWEEN
DEPTH OF DRY SAND
AND
TOTAL LOAD SUSTAINED.
Plate $13\frac{1}{2}$" diam.
Area 143 sq. in.
Plate 9" diam.
Area 63.6 sq. in.
Depth of Sand in inches.
0 2 4 6 8 10 12 14 16 18 20

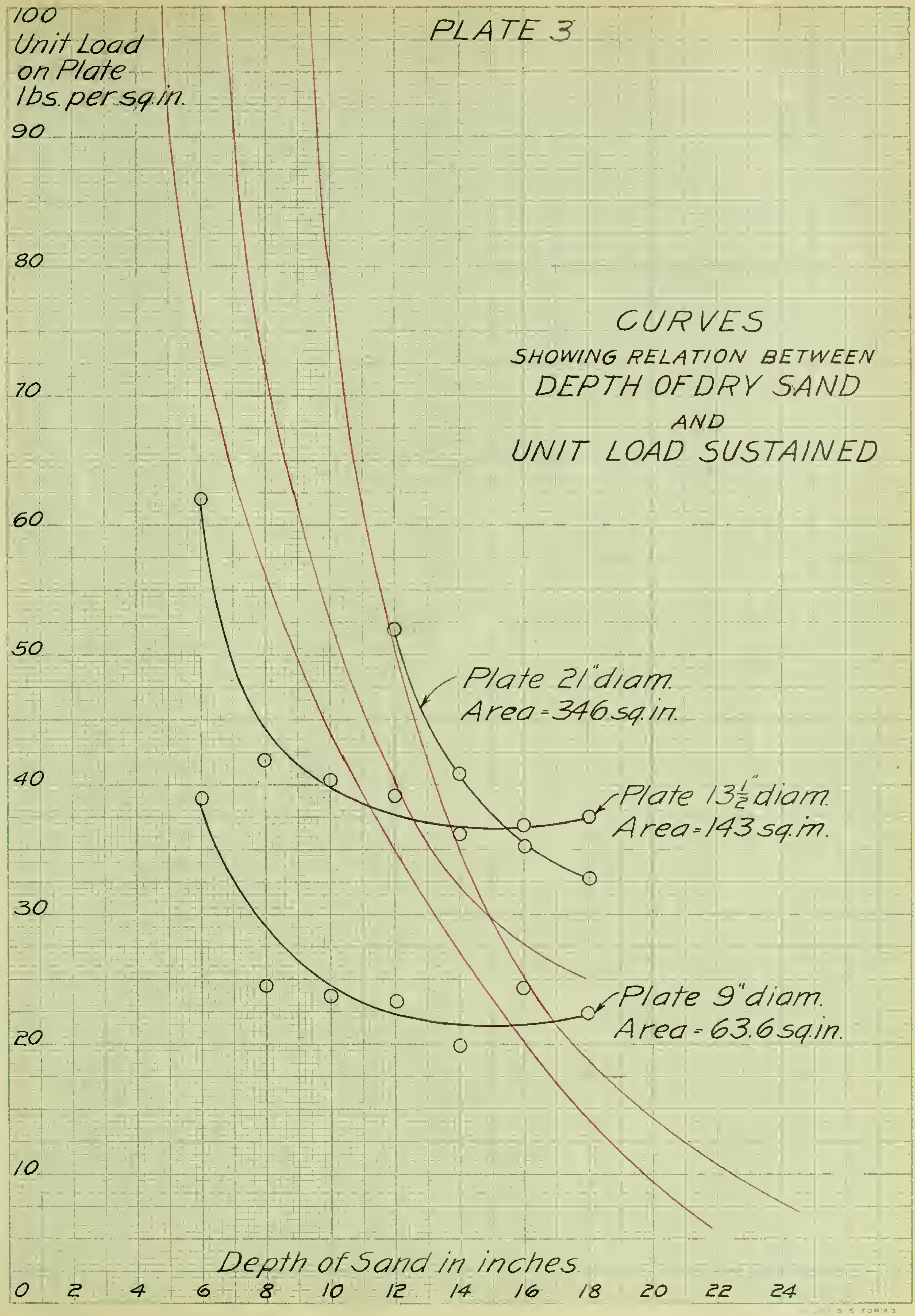


PLATE 3
100
Unit Load on Plate lbs. per sq. in.
90
80
70
60
50
40
30
20
10
CURVES
SHOWING RELATION BETWEEN
DEPTH OF DRY SAND
AND
UNIT LOAD SUSTAINED
Plate 21" diam.
Area = 346 sq. in.
Plate 13½" diam.
Area = 143 sq. in.
Plate 9" diam.
Area = 63.6 sq. in.
Depth of Sand in inches
0
2
4
6
8
10
12
14
16
18
20
22
24

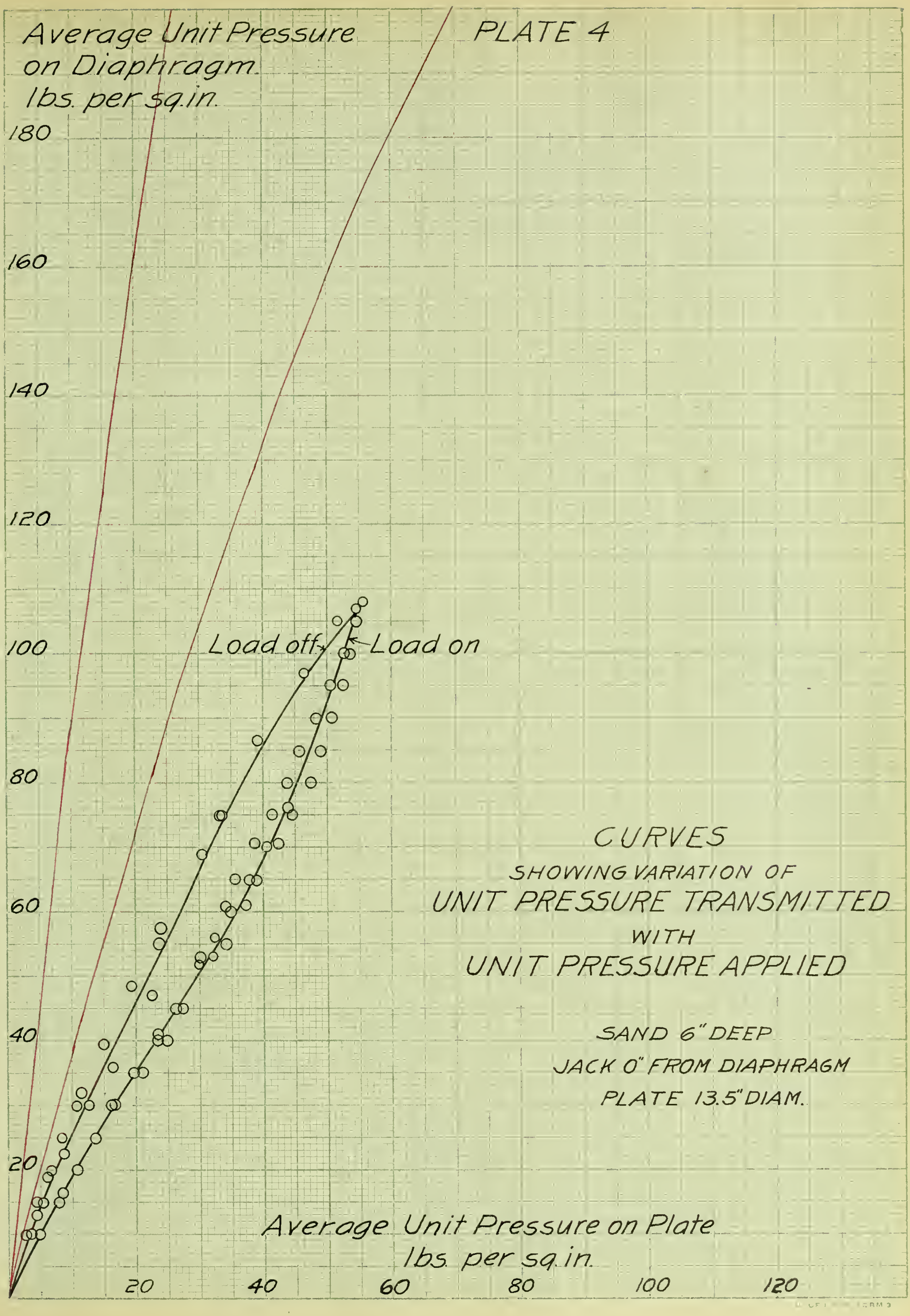

Average Unit Pressure
on Diaphragm
lbs. per sq.in.
PLATE 4
180
160
140
120
100
80
60
40
20
Load off
Load on
CURVES
SHOWING VARIATION OF
UNIT PRESSURE TRANSMITTED
WITH
UNIT PRESSURE APPLIED
SAND 6" DEEP
JACK 0" FROM DIAPHRAGM
PLATE 13.5" DIAM.
Average Unit Pressure on Plate
lbs. per sq.in.
20
40
60
80
100
120

PLATE 5

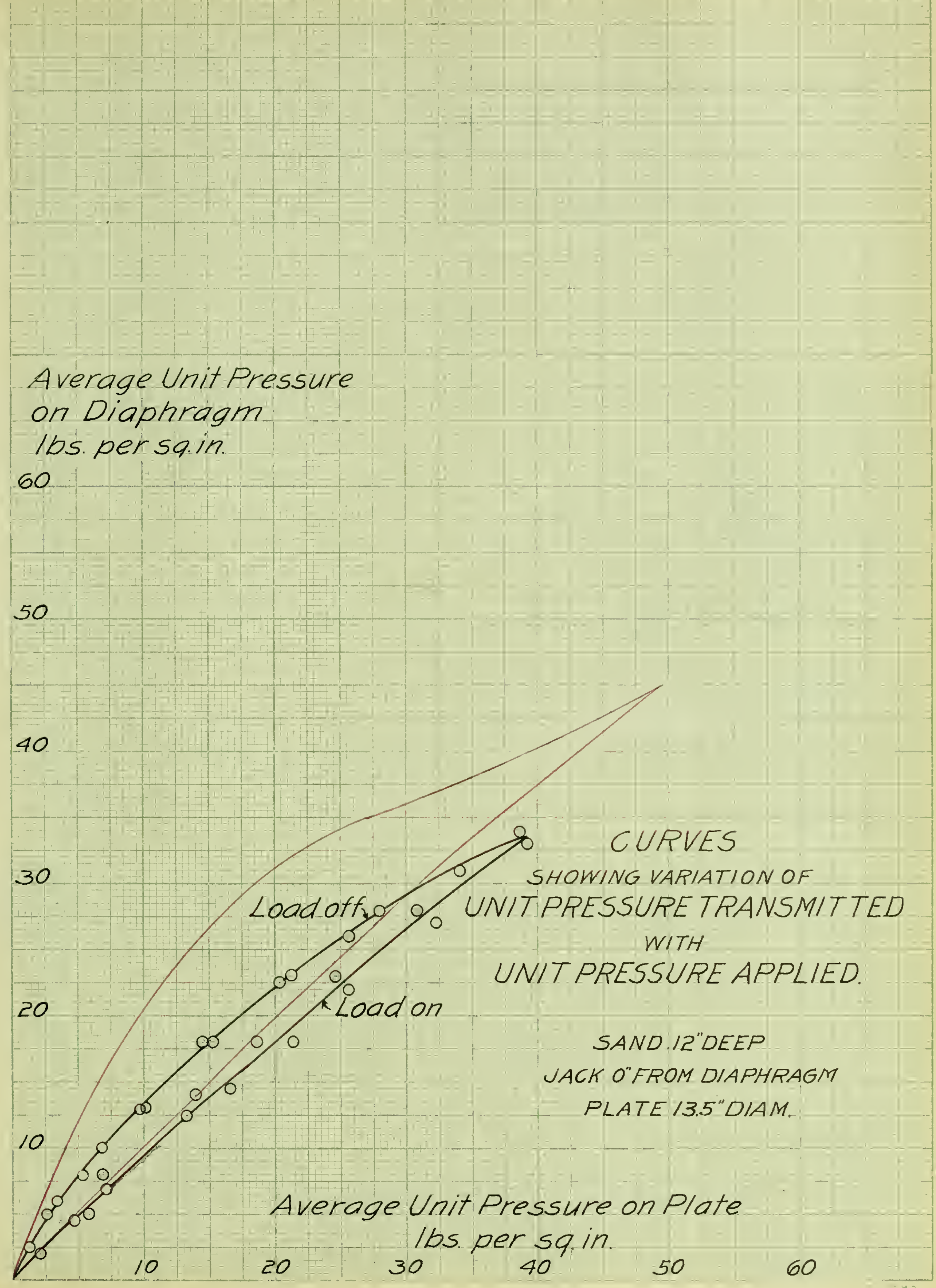
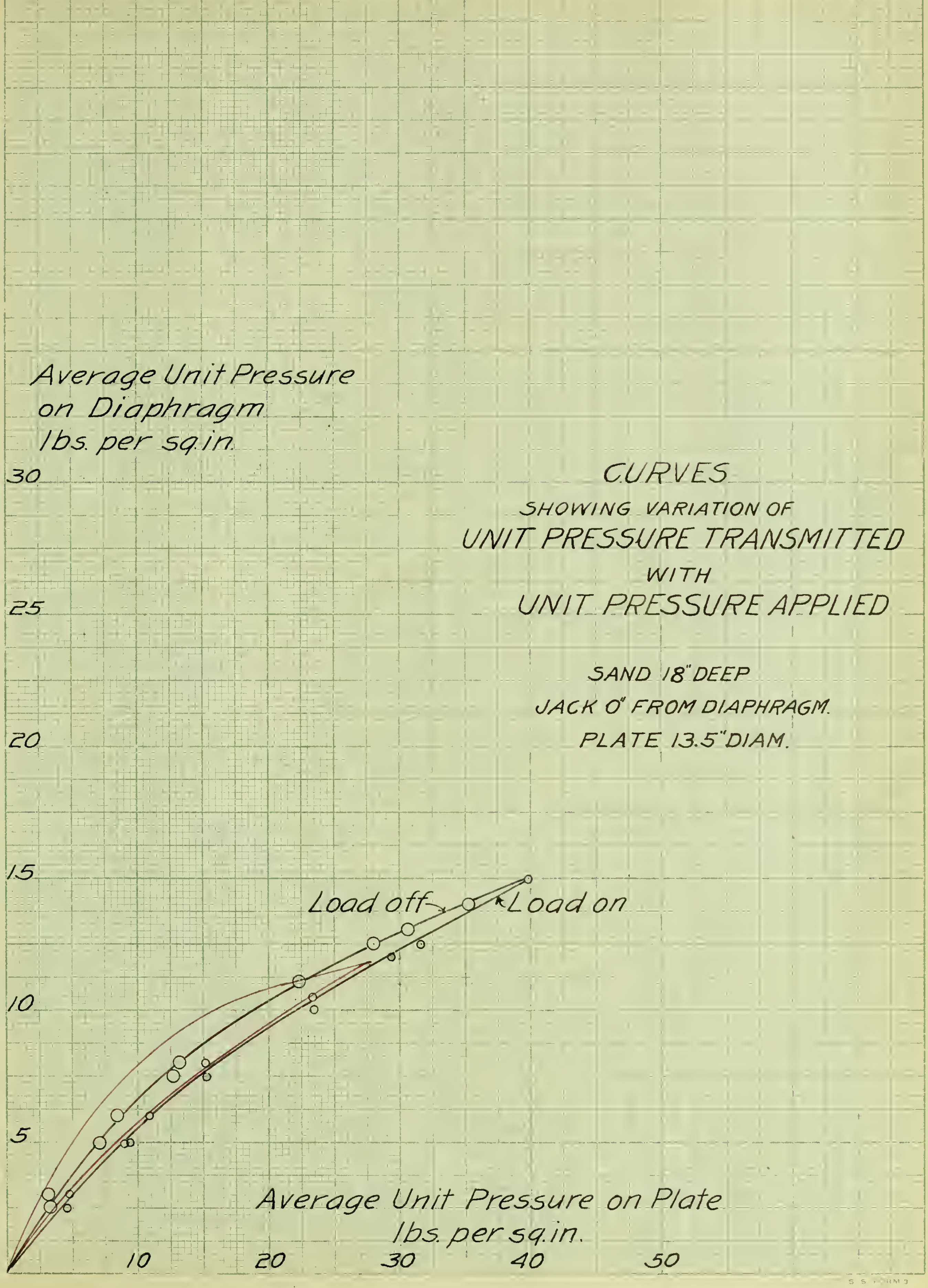

Average Unit Pressure
on Diaphragm
lbs. per sq. in.
60
50
40
30
20
10
Load off
Load on
CURVES
SHOWING VARIATION OF
UNIT PRESSURE TRANSMITTED
WITH
UNIT PRESSURE APPLIED.
SAND 12" DEEP
JACK 0" FROM DIAPHRAGM
PLATE 13.5" DIAM.
Average Unit Pressure on Plate
lbs. per sq. in.
10
20
30
40
50
60

PLATE 6


Average Unit Pressure
on Diaphragm
lbs. per sq. in.
30
25
20
15
10
5
CURVES
SHOWING VARIATION OF
UNIT PRESSURE TRANSMITTED
WITH
UNIT PRESSURE APPLIED
SAND 18" DEEP
JACK 0" FROM DIAPHRAGM.
PLATE 13.5" DIAM.
Load off
Load on
Average Unit Pressure on Plate
lbs. per sq. in.
10
20
30
40
50

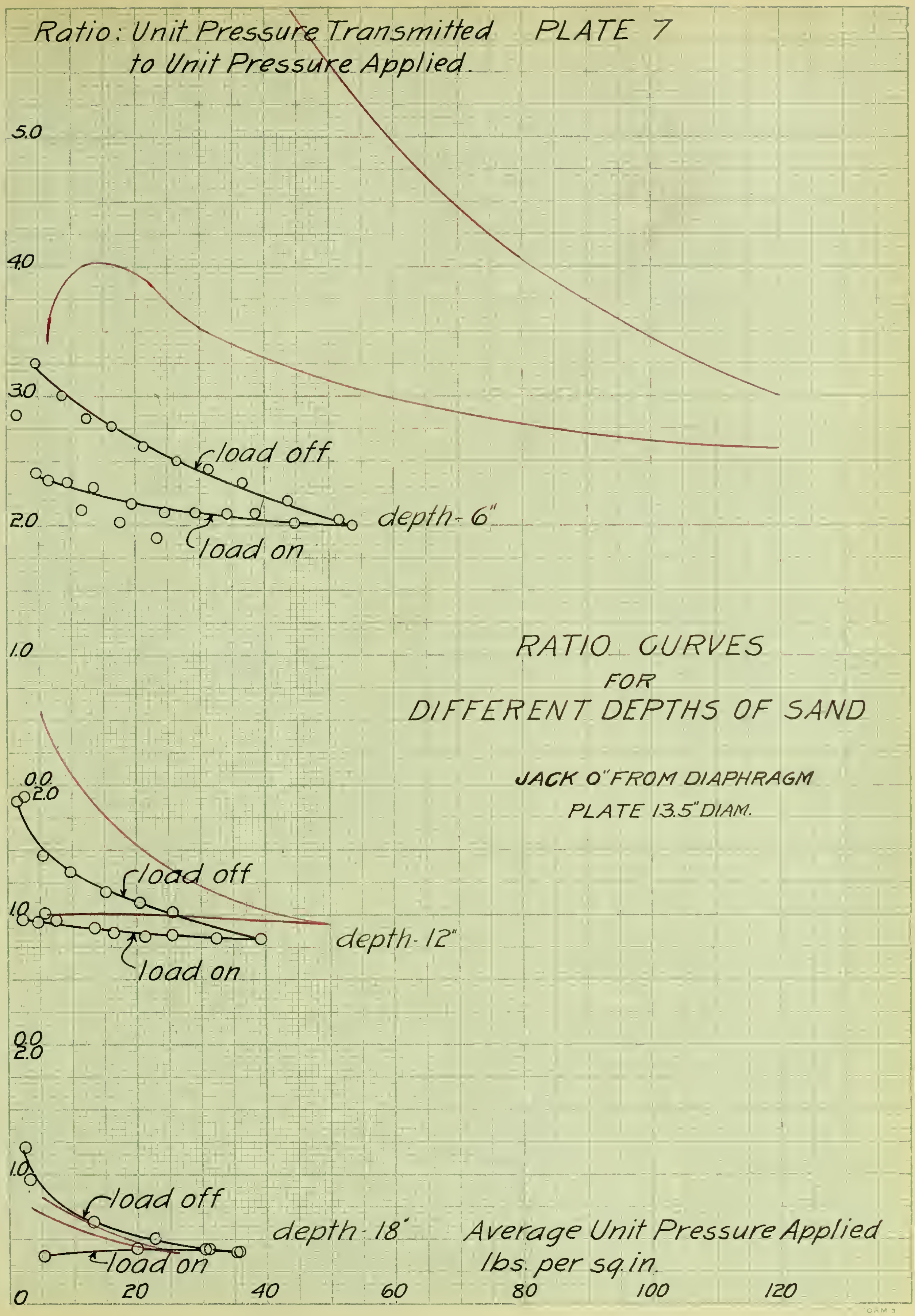
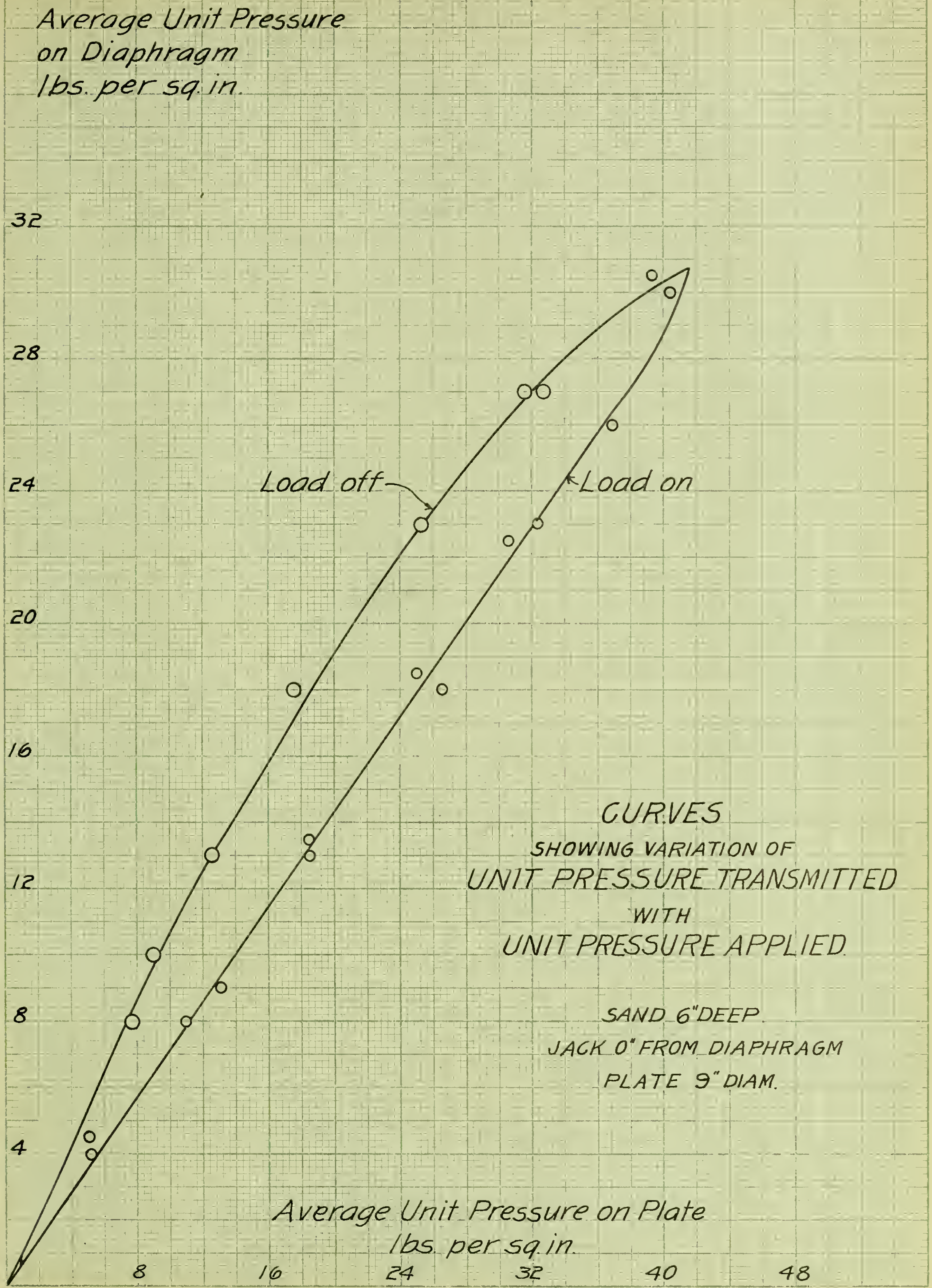

Ratio: Unit Pressure Transmitted to Unit Pressure Applied.
PLATE 7
5.0
4.0
3.0
2.0
1.0
load off
load on
depth - 6"
RATIO CURVES FOR DIFFERENT DEPTHS OF SAND
JACK 0" FROM DIAPHRAGM
PLATE 13.5" DIAM.
0.0
2.0
1.0
depth - 12"
0.0
2.0
1.0
depth - 18"
Average Unit Pressure Applied lbs. per sq. in.
0
20
40
60
80
100
120

PLATE 8


Average Unit Pressure
on Diaphragm
lbs. per sq. in.
32
28
24
20
16
12
8
4
Load off
Load on
CURVES
SHOWING VARIATION OF
UNIT PRESSURE TRANSMITTED
WITH
UNIT PRESSURE APPLIED
SAND 6" DEEP.
JACK 0" FROM DIAPHRAGM
PLATE 9" DIAM.
Average Unit Pressure on Plate
lbs. per sq. in.
8
16
24
32
40
48

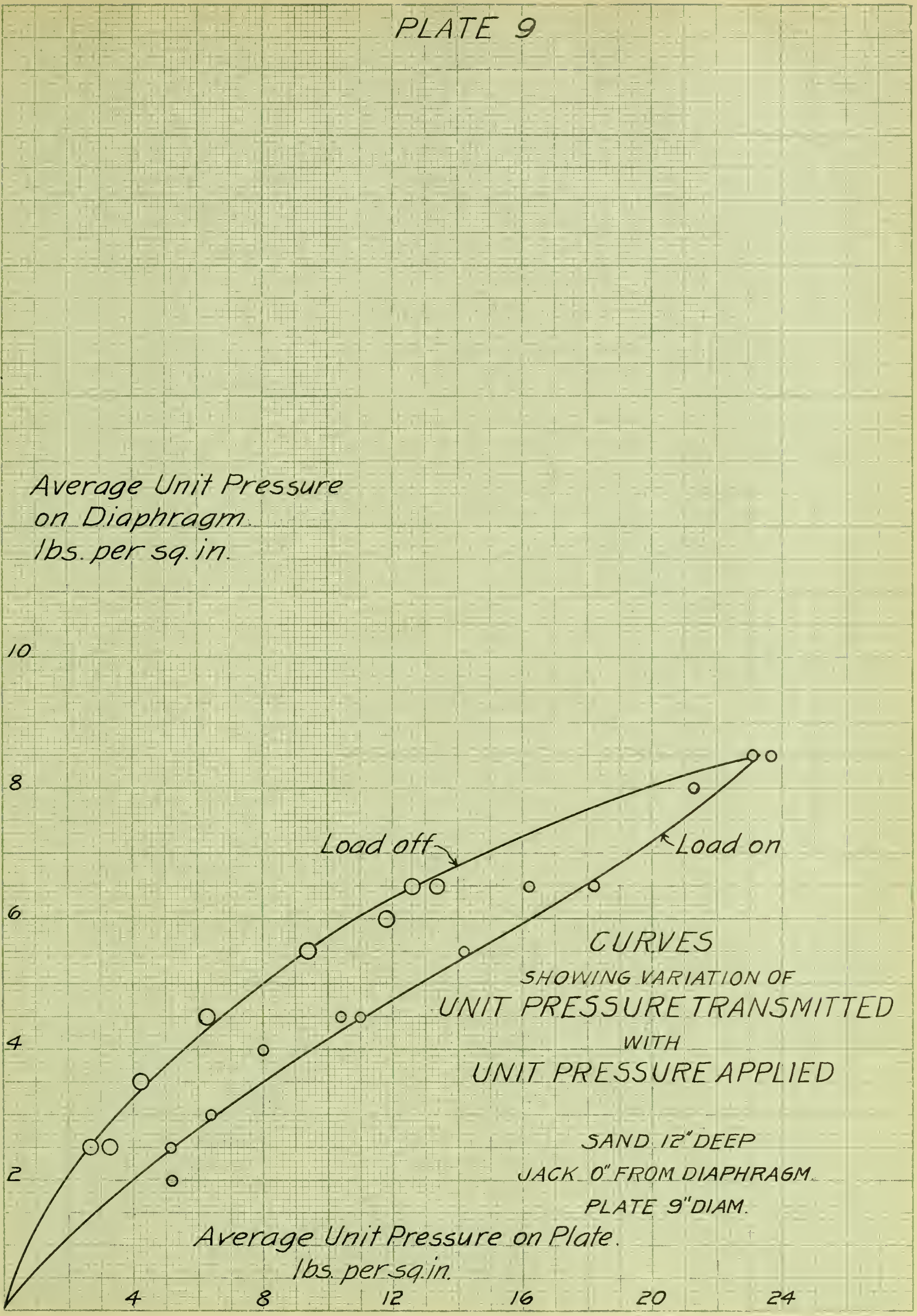


PLATE 9
Average Unit Pressure on Diaphragm. lbs. per sq. in.
10
8
6
4
2
Load off
Load on
CURVES
SHOWING VARIATION OF
UNIT PRESSURE TRANSMITTED
WITH
UNIT PRESSURE APPLIED
SAND 12" DEEP
JACK 0" FROM DIAPHRAGM.
PLATE 9" DIAM.
Average Unit Pressure on Plate. lbs. per sq. in.
4
8
12
16
20
24

PLATE 10

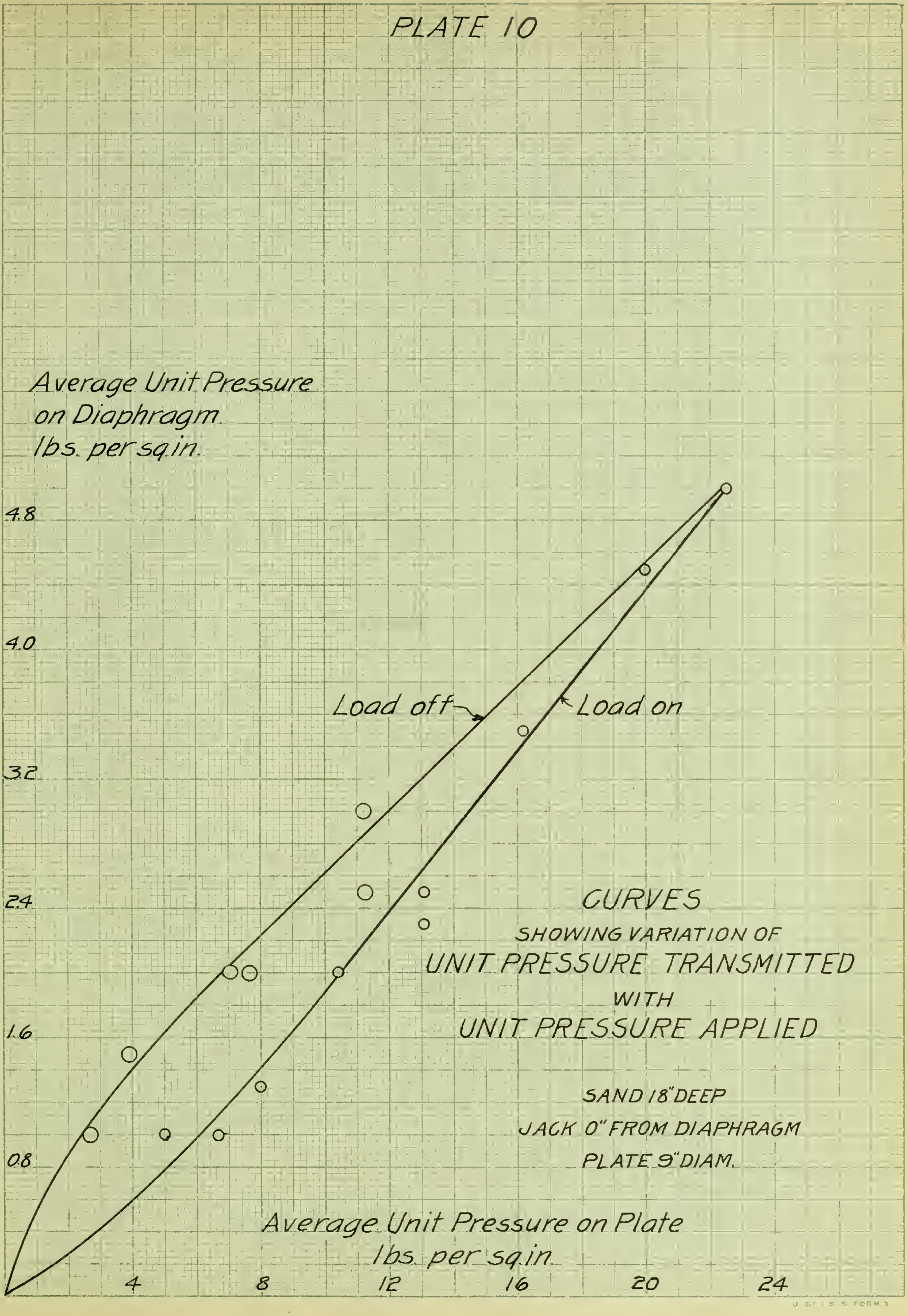
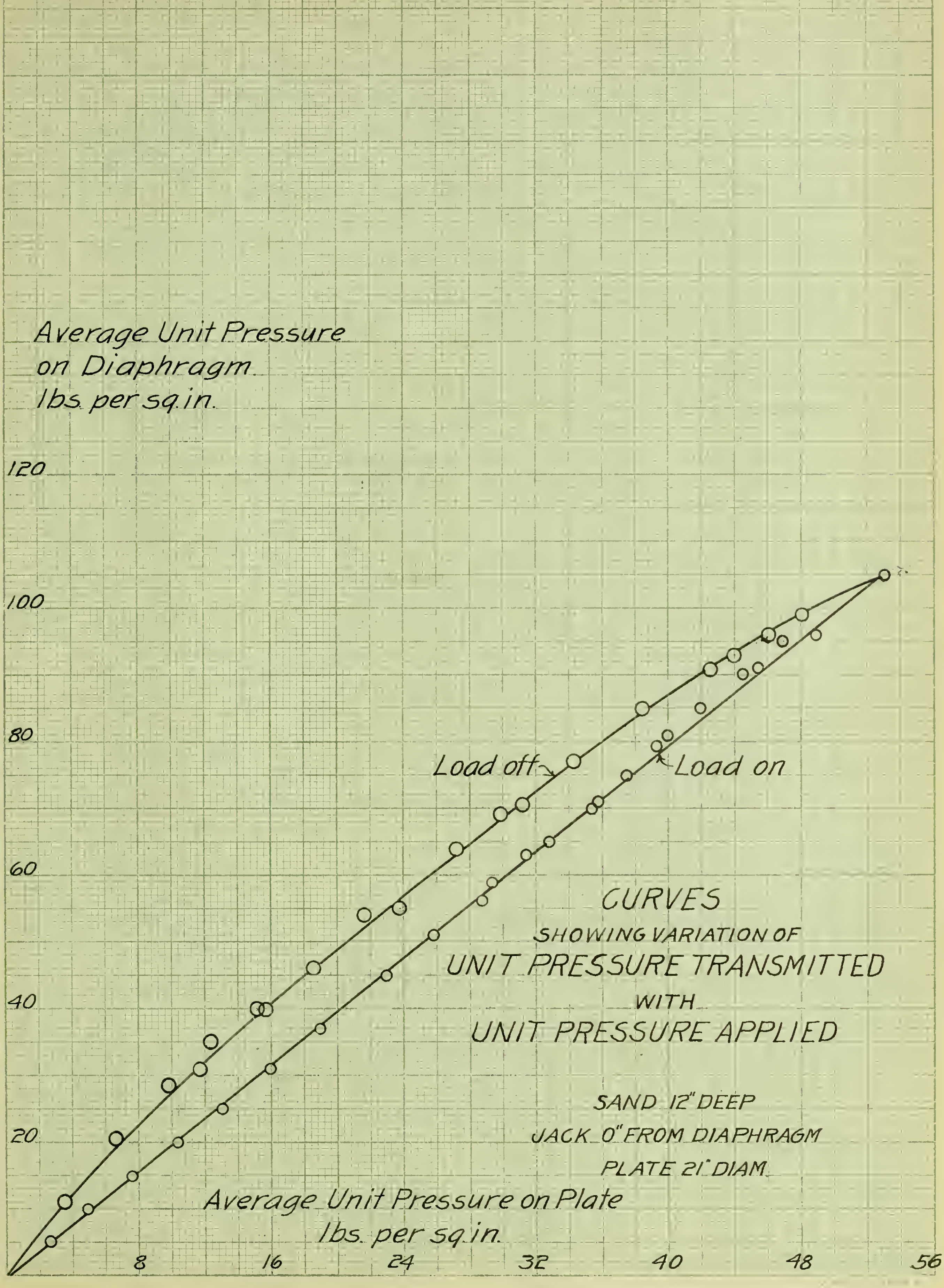

Average Unit Pressure
on Diaphragm
lbs. per sq. in.
4.8
4.0
3.2
2.4
1.6
0.8
Load off
Load on
CURVES
SHOWING VARIATION OF
UNIT PRESSURE TRANSMITTED
WITH
UNIT PRESSURE APPLIED
SAND 18" DEEP
JACK 0" FROM DIAPHRAGM
PLATE 9" DIAM.
Average Unit Pressure on Plate
lbs. per sq. in.
4
8
12
16
20
24

PLATE II


Average Unit Pressure
on Diaphragm
lbs. per sq. in.
120
100
80
60
40
20
Load off
Load on
CURVES
SHOWING VARIATION OF
UNIT PRESSURE TRANSMITTED
WITH
UNIT PRESSURE APPLIED
SAND 12" DEEP
JACK 0" FROM DIAPHRAGM
PLATE 21" DIAM.
Average Unit Pressure on Plate
lbs. per sq. in.
8
16
24
32
40
48
56

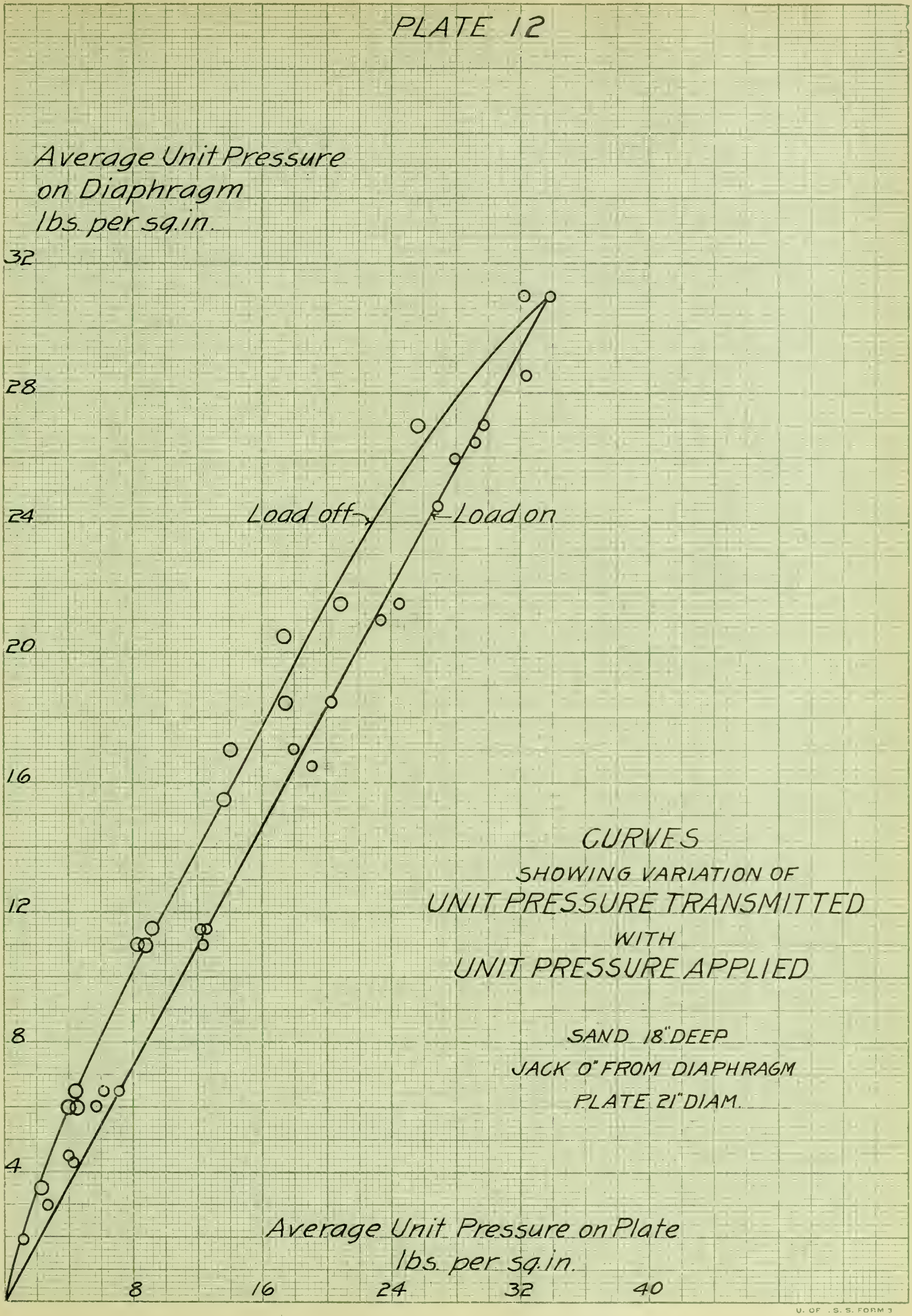
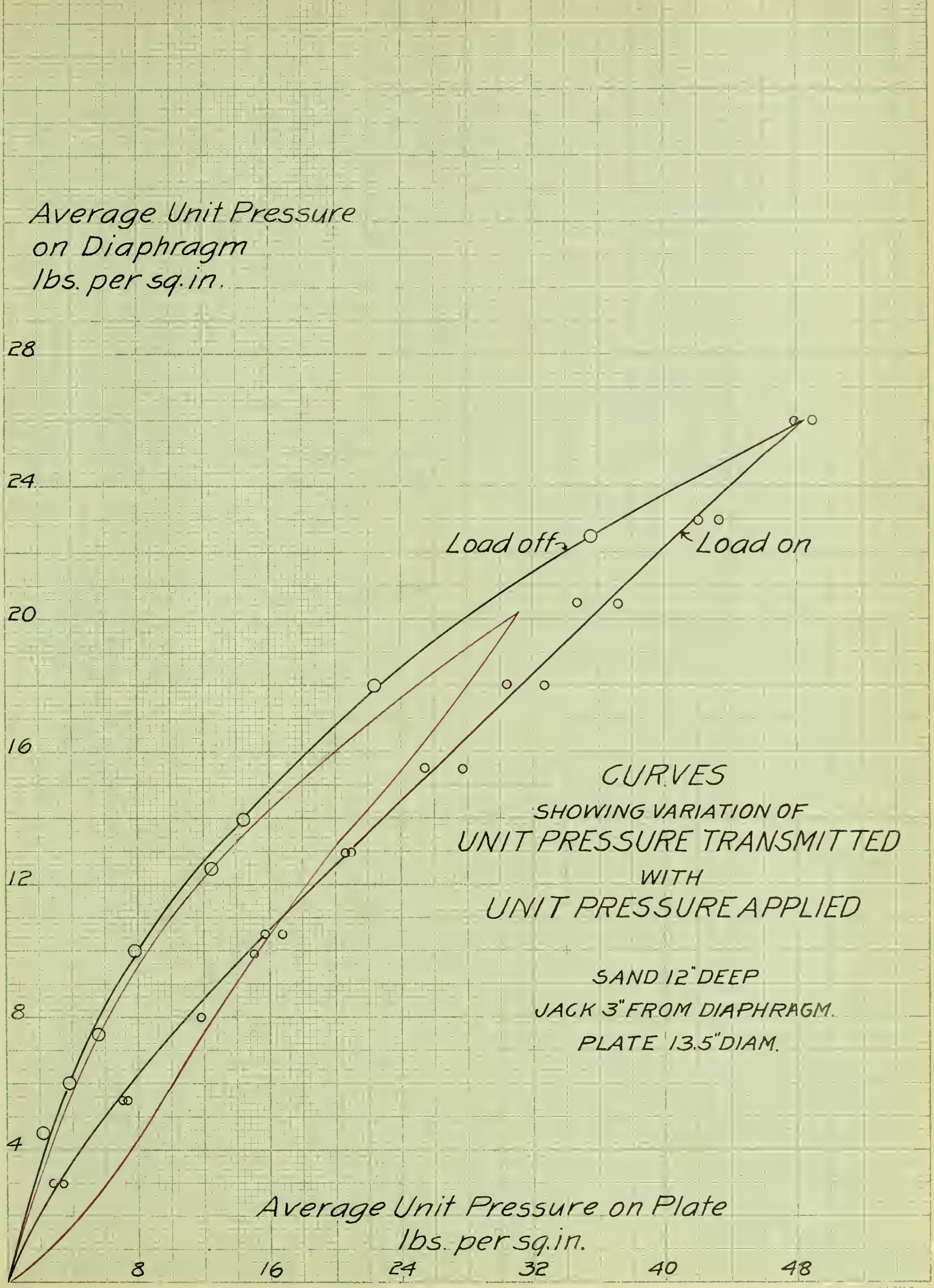


PLATE 12
Average Unit Pressure on Diaphragm lbs. per sq. in.
32
28
24
20
16
12
8
4
Load off
Load on
CURVES
SHOWING VARIATION OF
UNIT PRESSURE TRANSMITTED
WITH
UNIT PRESSURE APPLIED
SAND 18" DEEP
JACK 0" FROM DIAPHRAGM
PLATE 21" DIAM.
Average Unit Pressure on Plate
lbs. per sq. in.
8
16
24
32
40

PLATE 13


Average Unit Pressure
on Diaphragm
lbs. per sq. in.
28
24
20
16
12
8
4
Load off
Load on
CURVES
SHOWING VARIATION OF
UNIT PRESSURE TRANSMITTED
WITH
UNIT PRESSURE APPLIED
SAND 12" DEEP
JACK 3" FROM DIAPHRAGM.
PLATE 13.5" DIAM.
Average Unit Pressure on Plate
lbs. per sq. in.
8
16
24
32
40
48

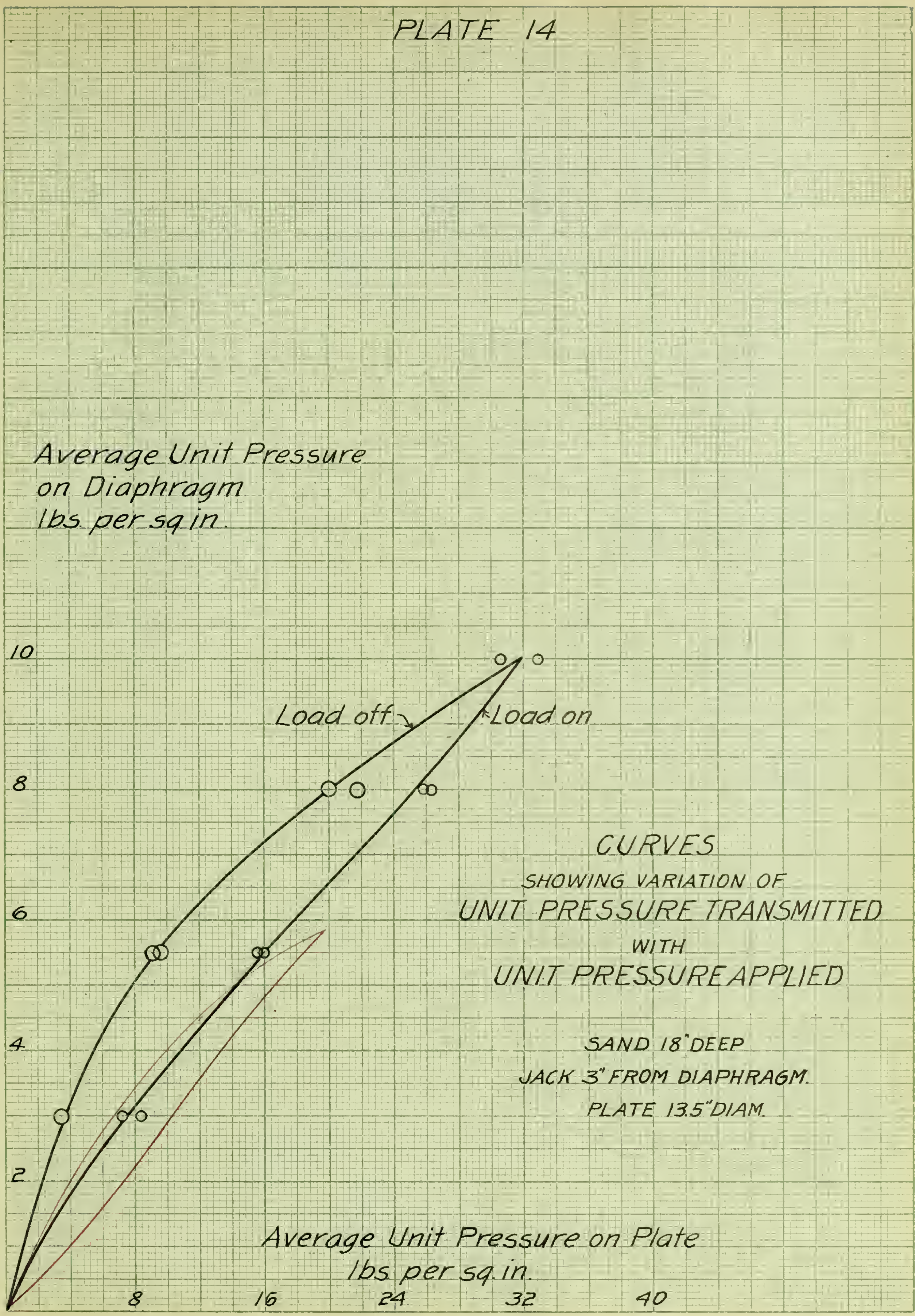
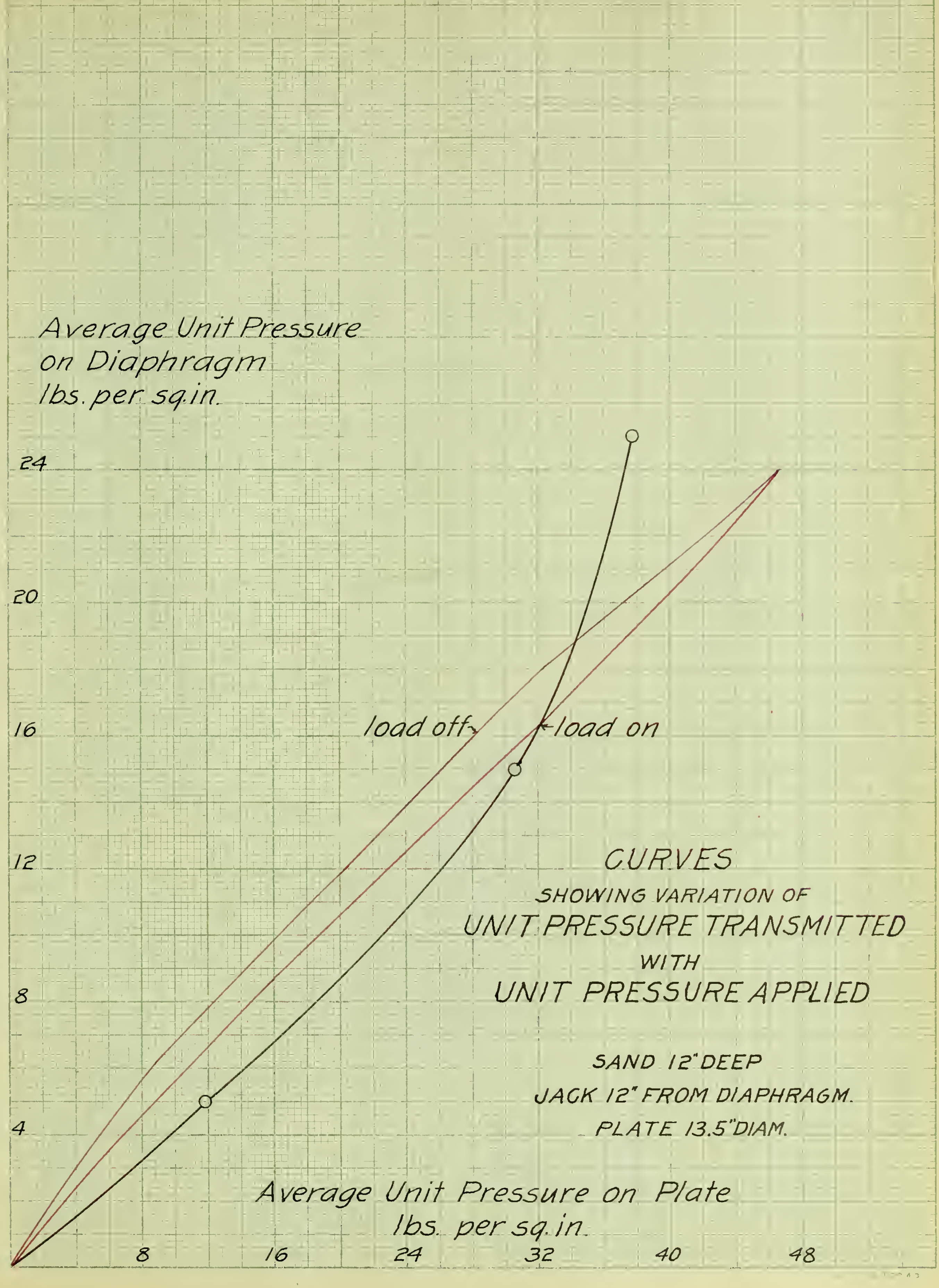


PLATE 14
Average Unit Pressure on Diaphragm lbs. per sq. in.
10
8
6
4
2
Load off
Load on
CURVES
SHOWING VARIATION OF
UNIT PRESSURE TRANSMITTED
WITH
UNIT PRESSURE APPLIED
SAND 18" DEEP
JACK 3" FROM DIAPHRAGM.
PLATE 13.5" DIAM.
Average Unit Pressure on Plate lbs. per sq. in.
8
16
24
32
40

PLATE 15


Average Unit Pressure
on Diaphragm
lbs. per sq. in.
24
20
16
12
8
4
load off
load on
CURVES
SHOWING VARIATION OF
UNIT PRESSURE TRANSMITTED
WITH
UNIT PRESSURE APPLIED
SAND 12" DEEP
JACK 12" FROM DIAPHRAGM.
PLATE 13.5" DIAM.
Average Unit Pressure on Plate
lbs. per sq. in.
8
16
24
32
40
48

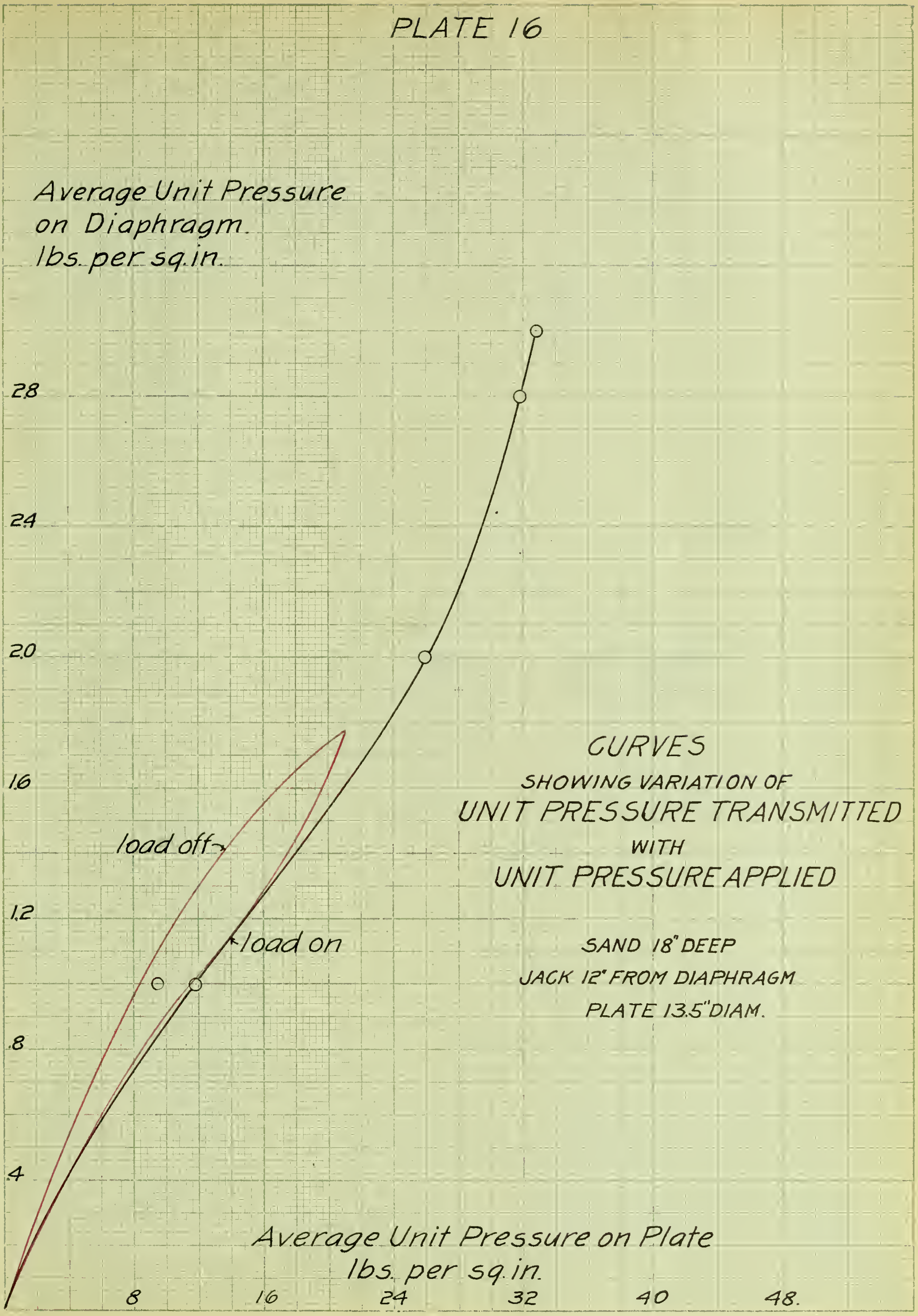
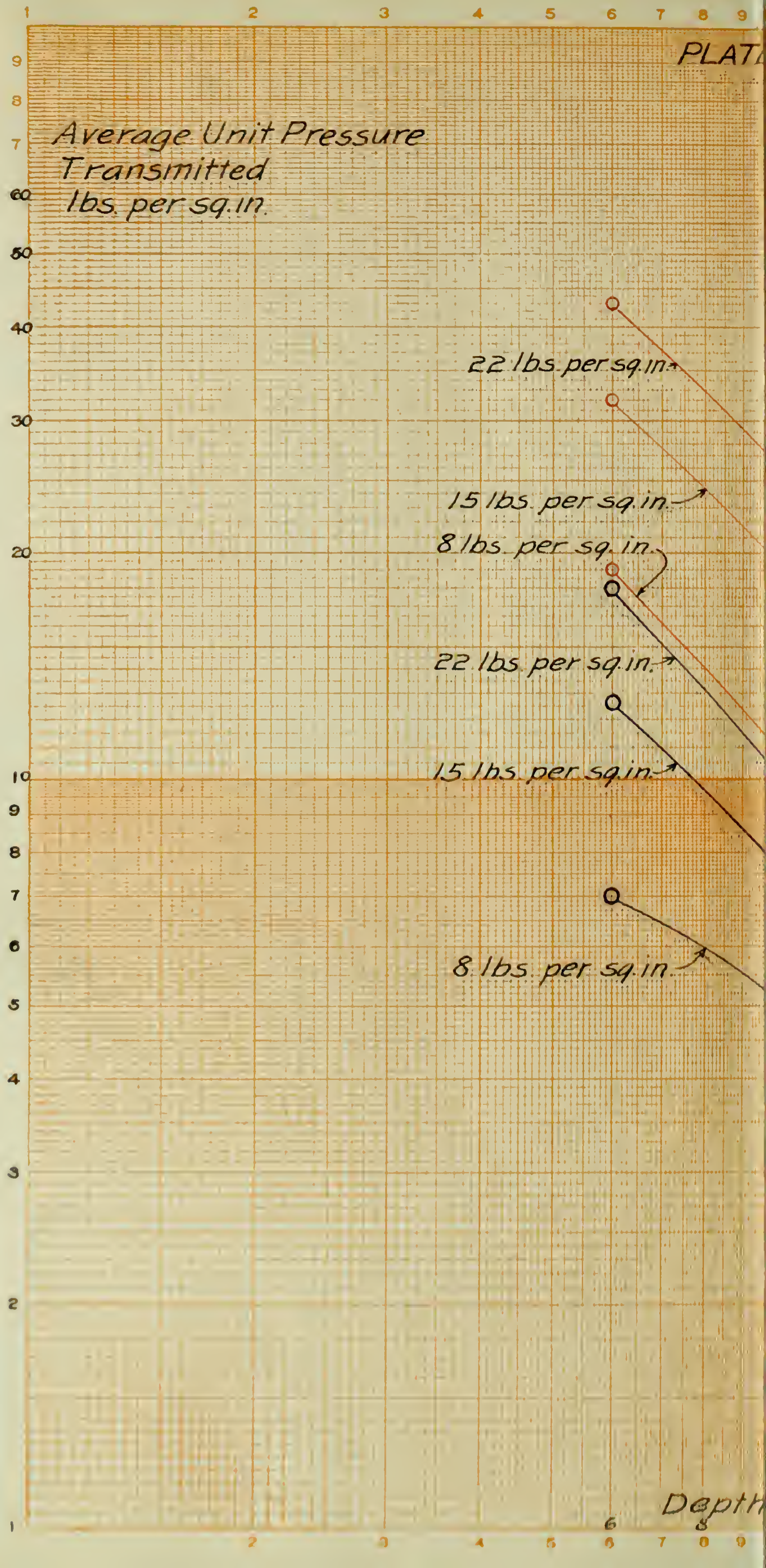


PLATE 16
Average Unit Pressure
on Diaphragm.
lbs. per sq. in.
28
24
20
16
1.2
.8
.4
CURVES
SHOWING VARIATION OF
UNIT PRESSURE TRANSMITTED
WITH
UNIT PRESSURE APPLIED
load off
load on
SAND 18" DEEP
JACK 12" FROM DIAPHRAGM
PLATE 13.5" DIAM.
Average Unit Pressure on Plate
lbs. per sq. in.
8
16
24
32
40
48.


PLAT
Average Unit Pressure
Transmitted
lbs. per sq. in.
22 lbs. per sq. in.
15 lbs. per sq. in.
8 lbs. per sq. in.
22 lbs. per sq. in.
15 lbs. per sq. in.
8 lbs. per sq. in.
Depth

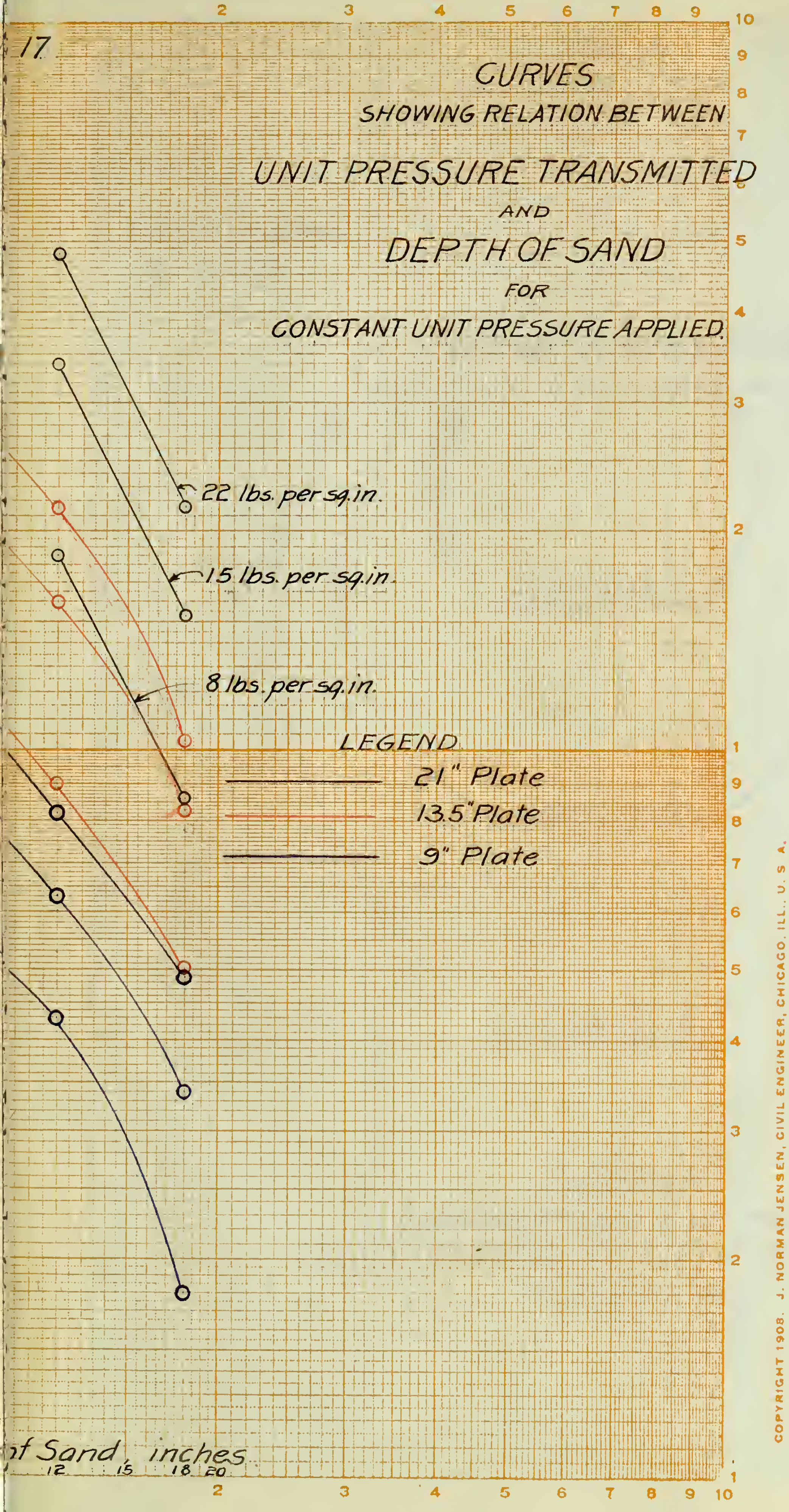

17
CURVES
SHOWING RELATION BETWEEN
UNIT PRESSURE TRANSMITTED
AND
DEPTH OF SAND
FOR
CONSTANT UNIT PRESSURE APPLIED.
22 lbs. per sq. in.
15 lbs. per sq. in.
8 lbs. per sq. in.
LEGEND
21" Plate
13.5" Plate
9" Plate
of Sand, inches
12
15
18
20
COPYRIGHT 1908. J. NORMAN JENSEN, CIVIL ENGINEER, CHICAGO, ILL., U. S. A.

PLATE 18.

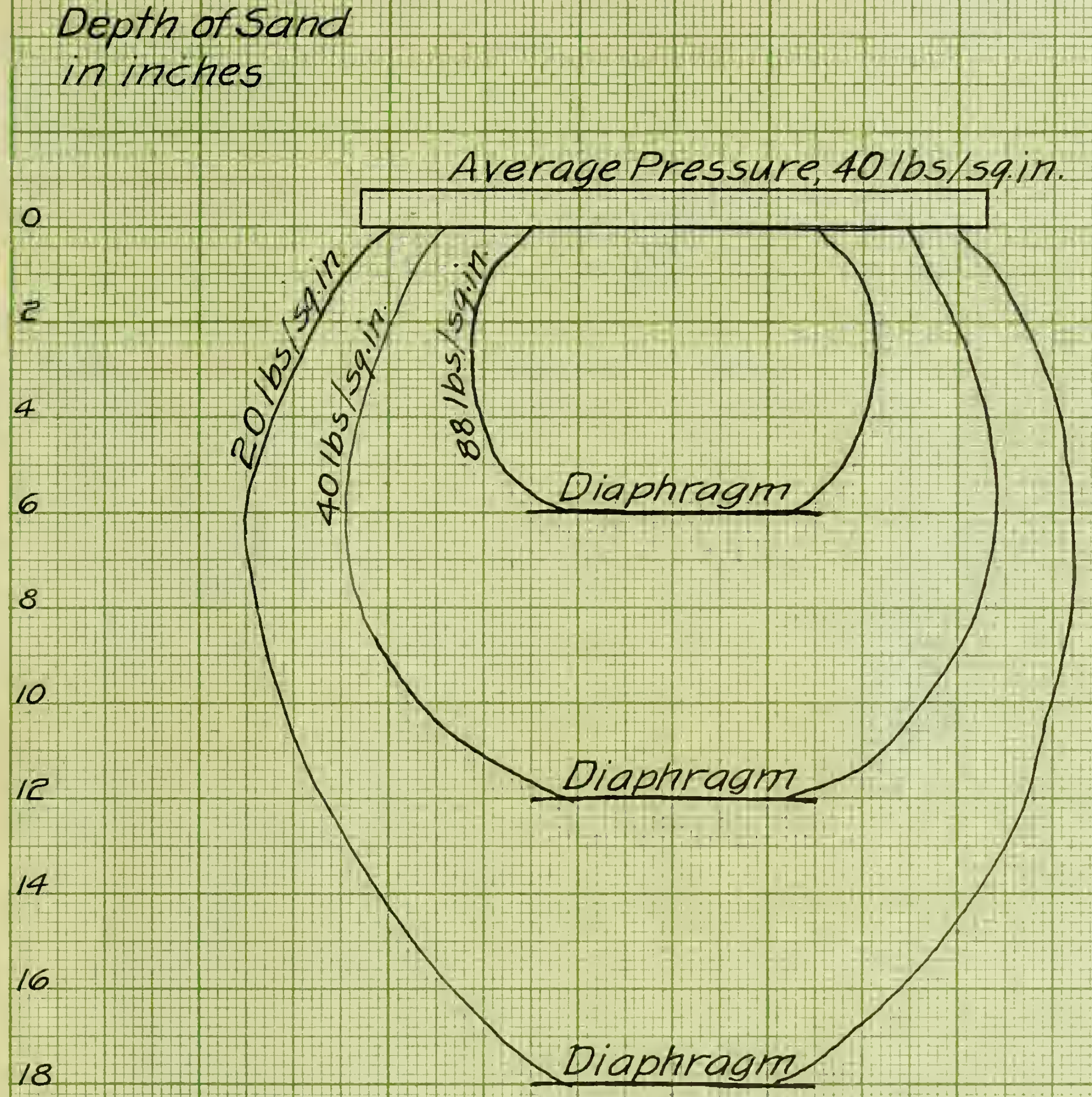
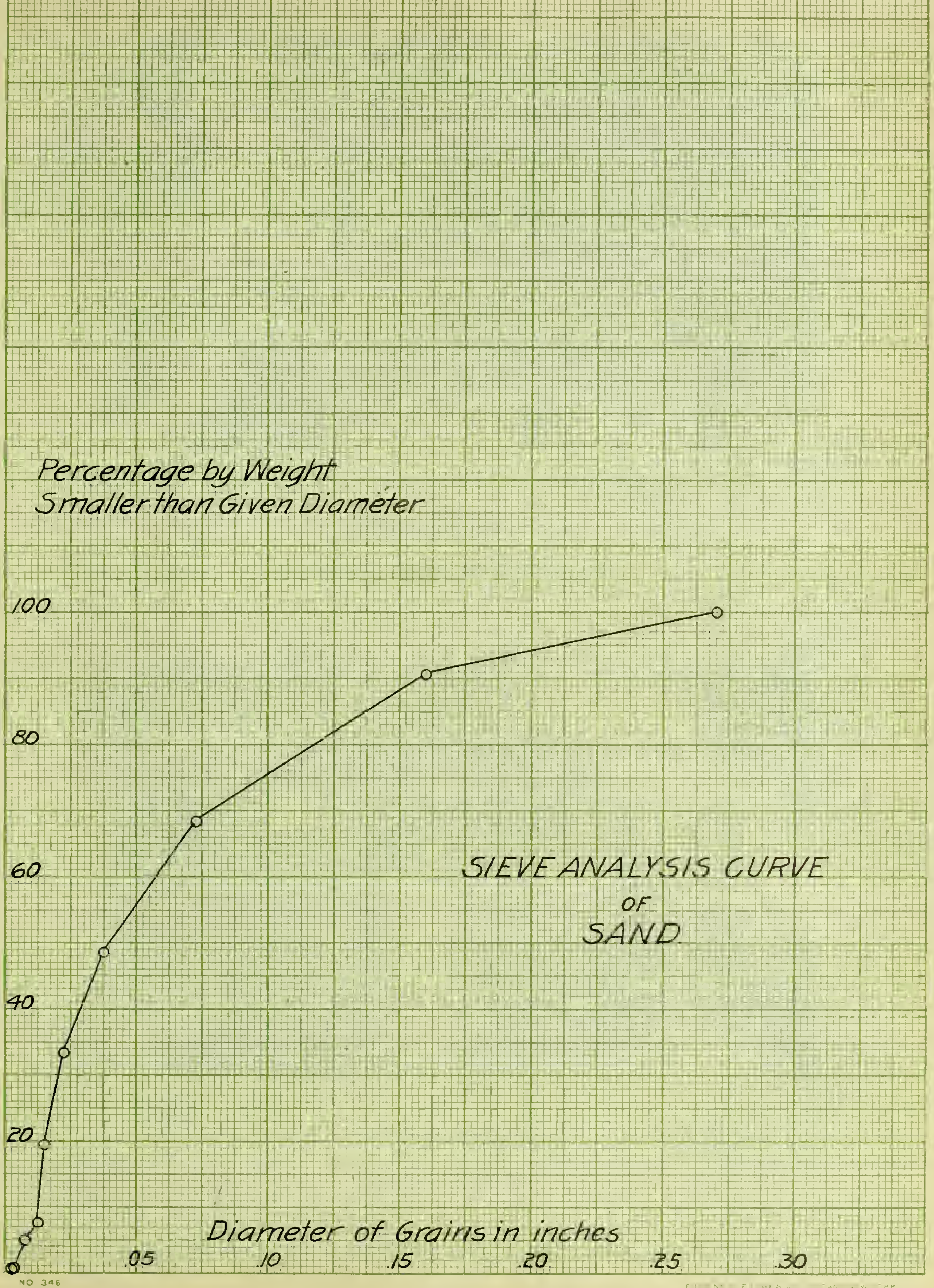
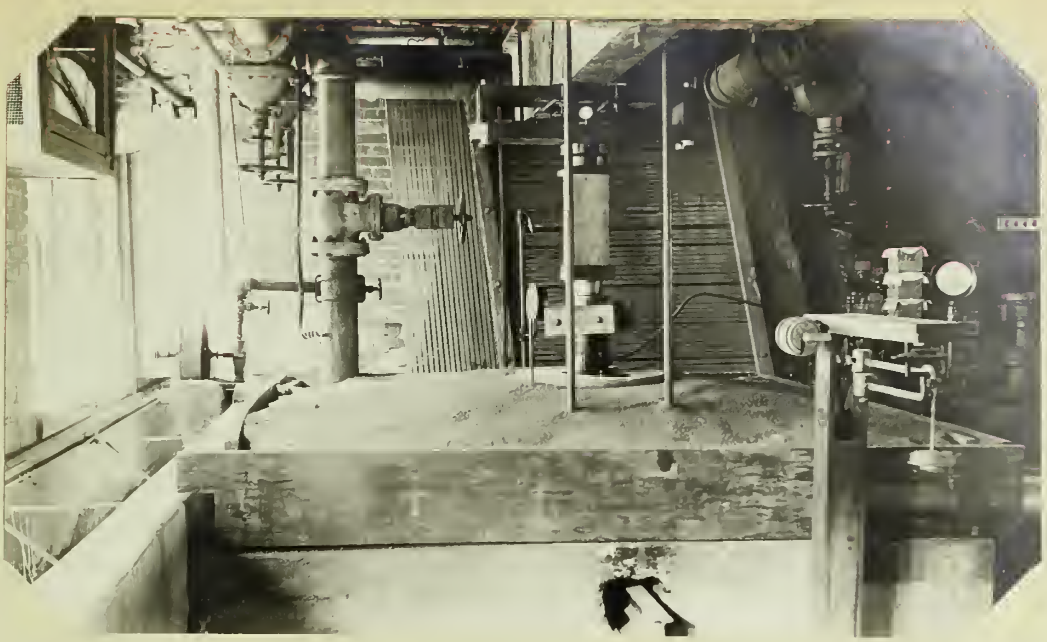


DIAGRAM
SHOWING POSSIBLE DISTRIBUTION OF
LINES OF EQUAL VERTICAL UNIT PRESSURE
PLATE 13.5" DIAM.

NO 346

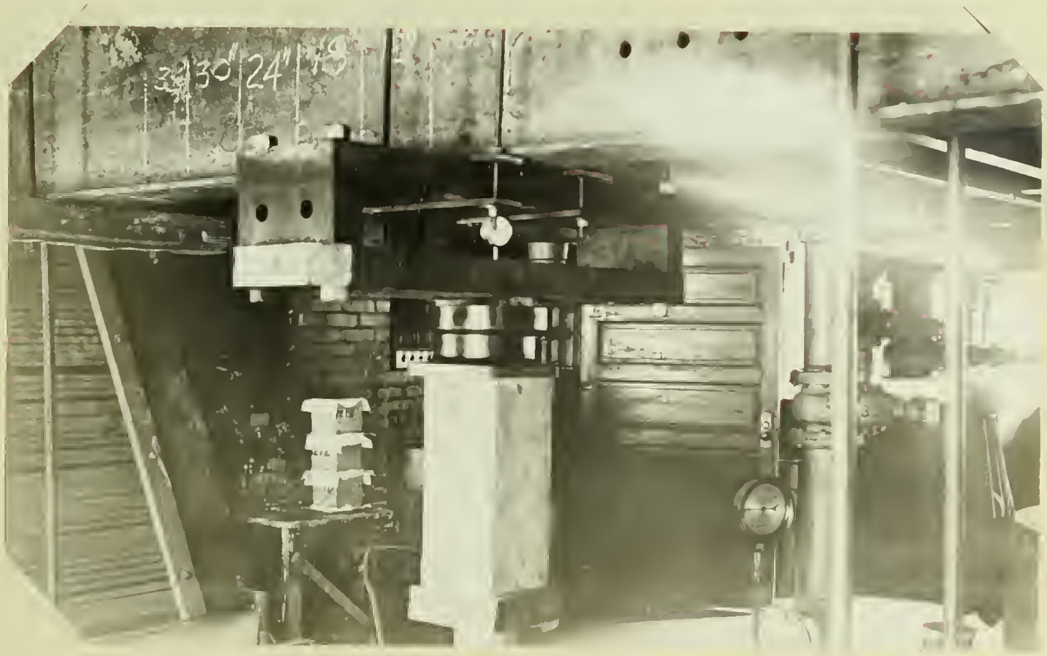
PLATE 19


Percentage by Weight
Smaller than Given Diameter
100
80
60
40
20
SIEVE ANALYSIS CURVE
OF
SAND
Diameter of Grains in inches
.05
.10
.15
.20
.25
.30



Photograph No. 1.

General View of Apparatus.

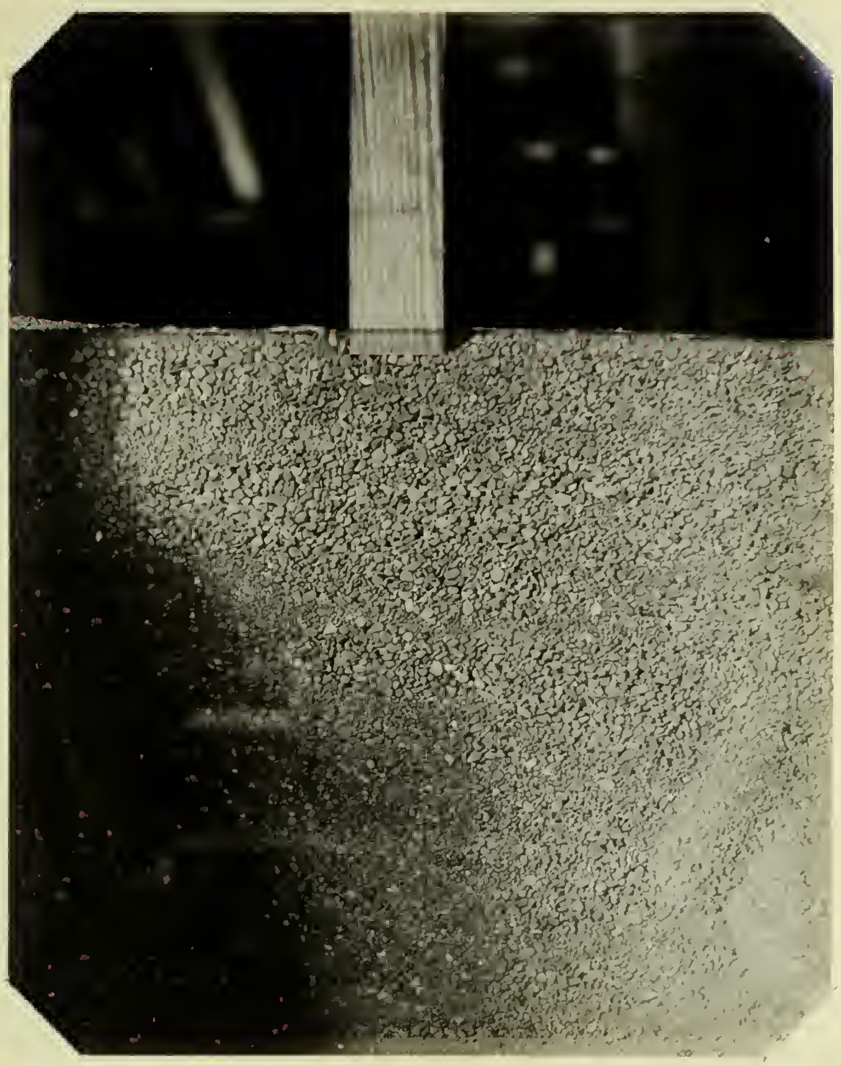


Photograph No. 2.

Steel Spring.

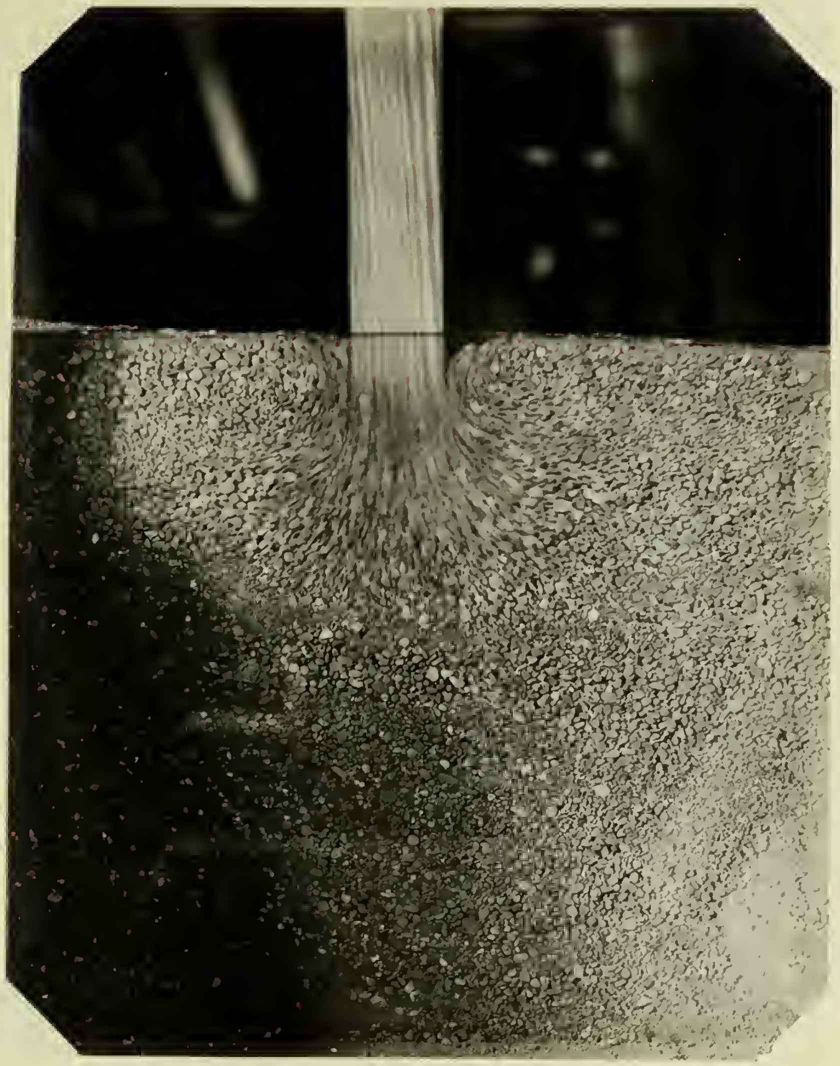
Photograph No. 3.

Apparatus Used to Secure Photographs 4 to 15.



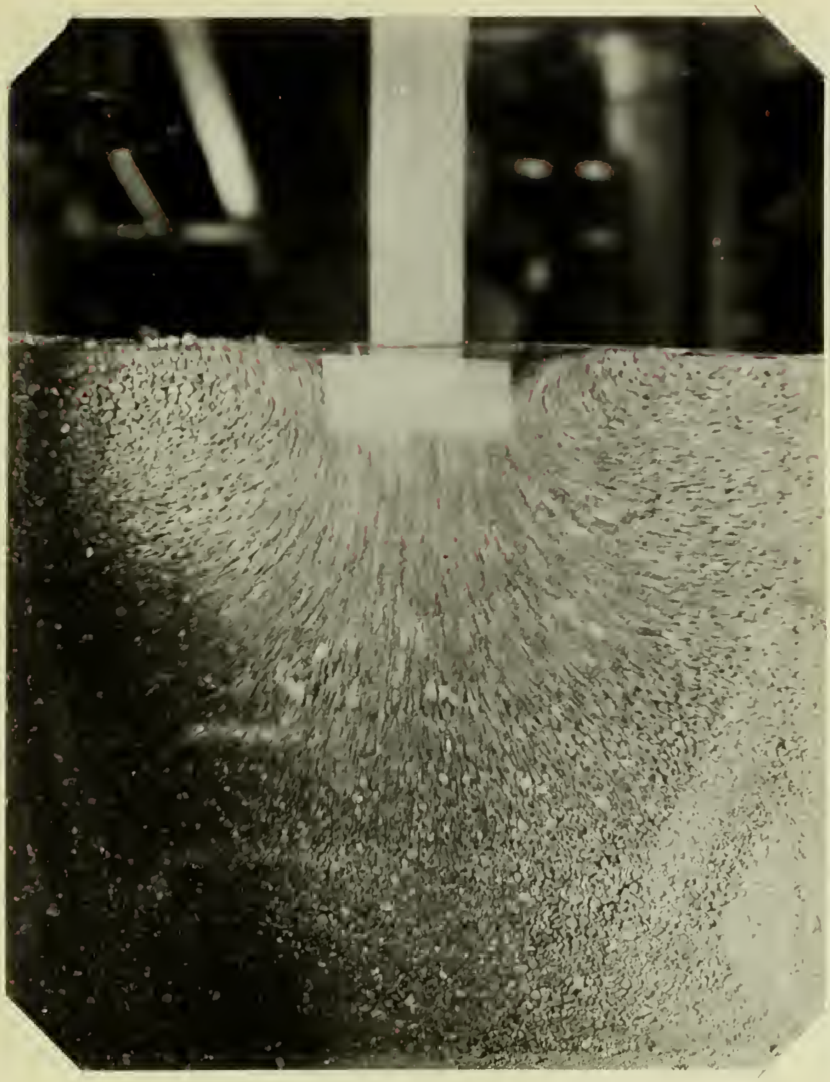
Photograph No. 4.

Original Condition of Sand with no Load.



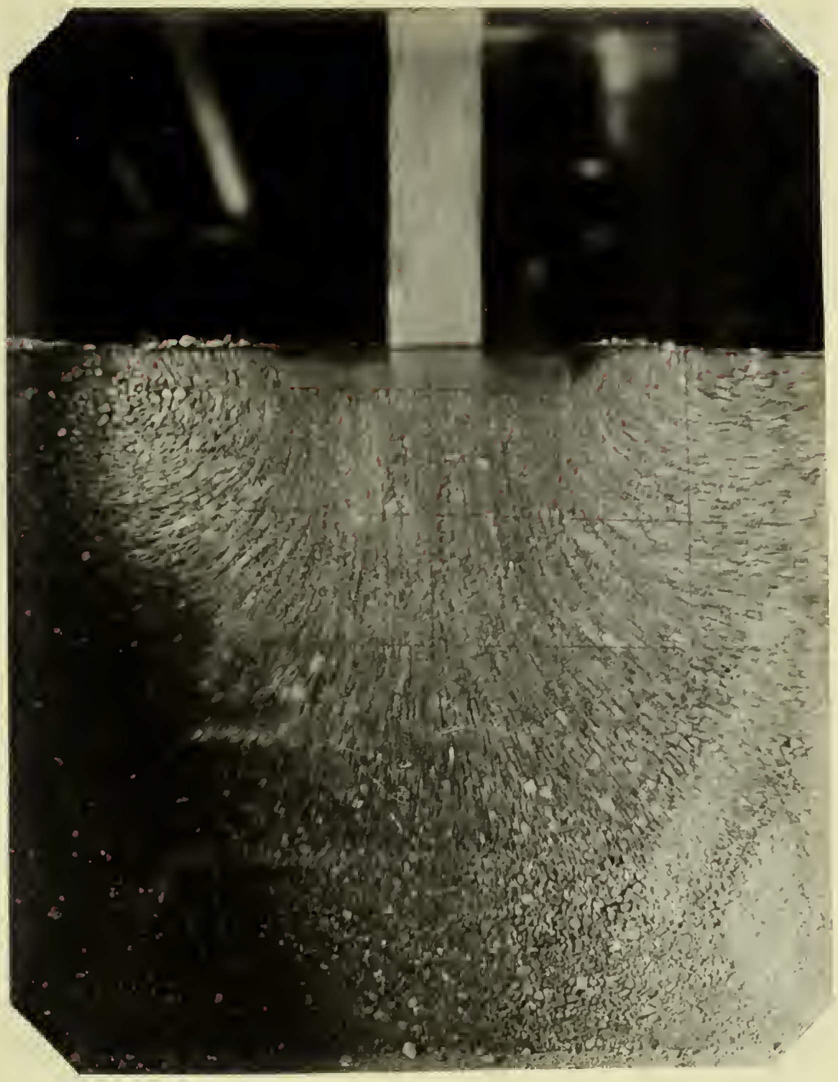
Photograph No. 5.

Pressure Applied to One Block 2" Wide.



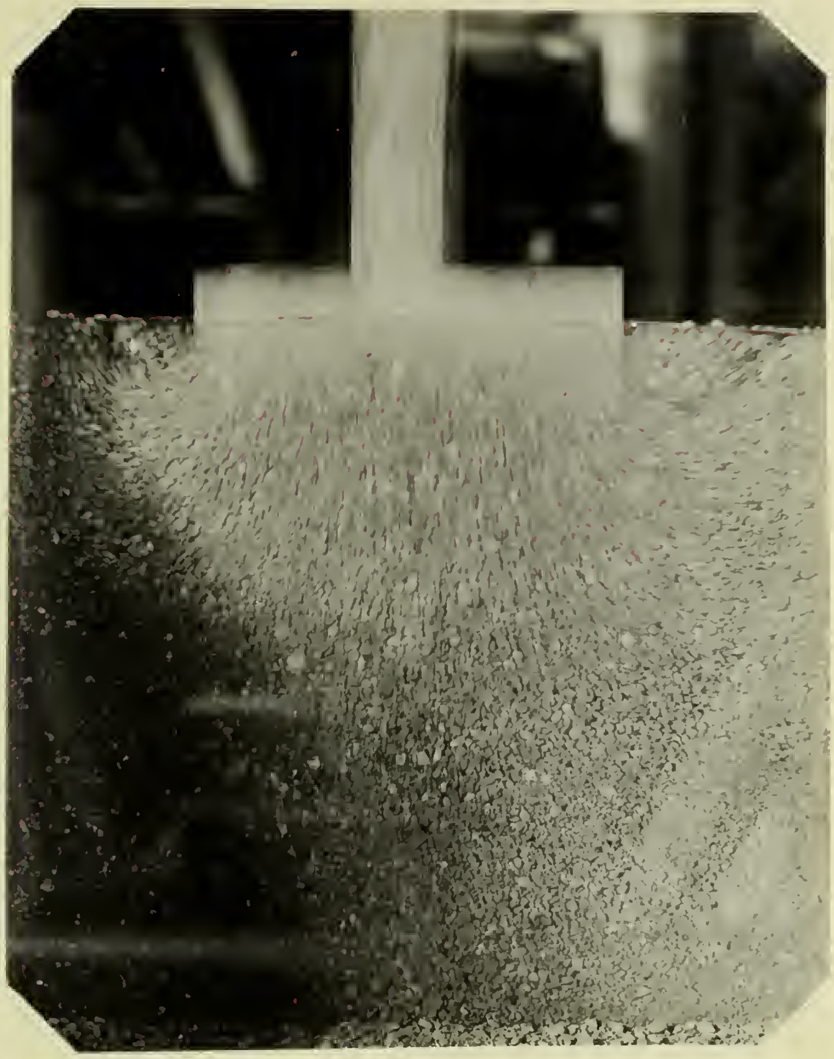
Photograph No. 6.

Pressure Applied to One Block 4" Wide.



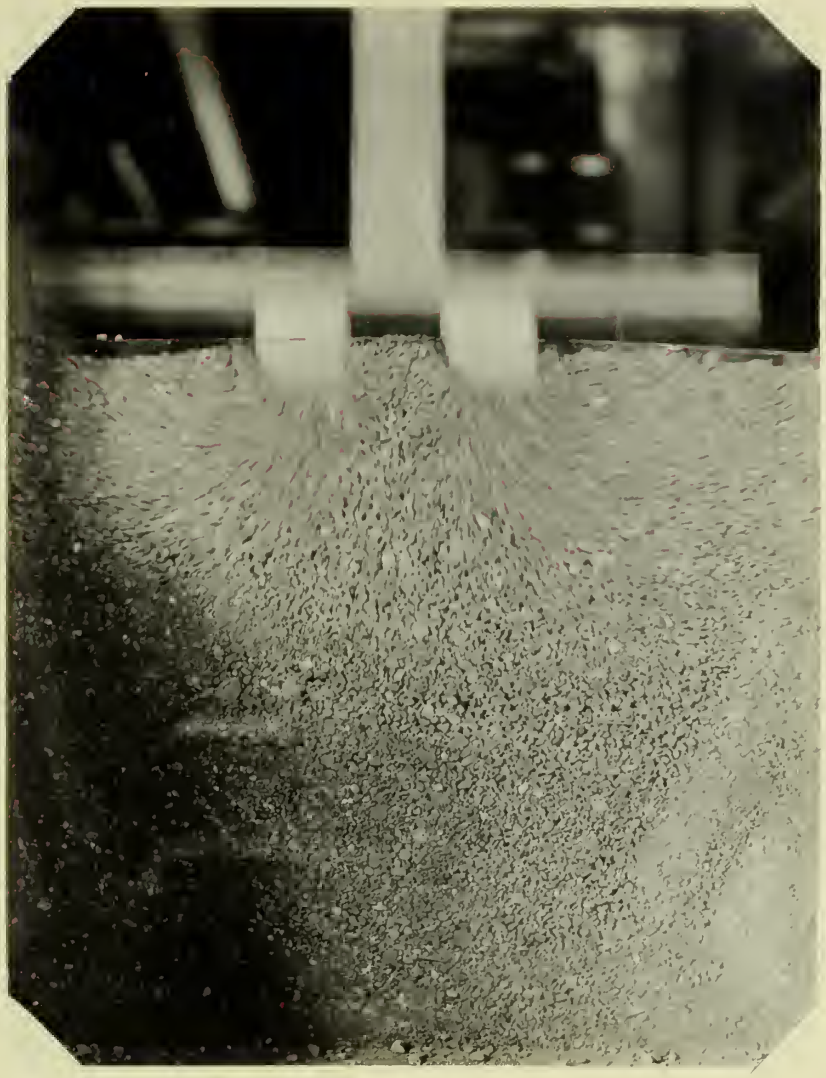
Photograph No. 7.

Pressure Applied to One Block 6" Wide.



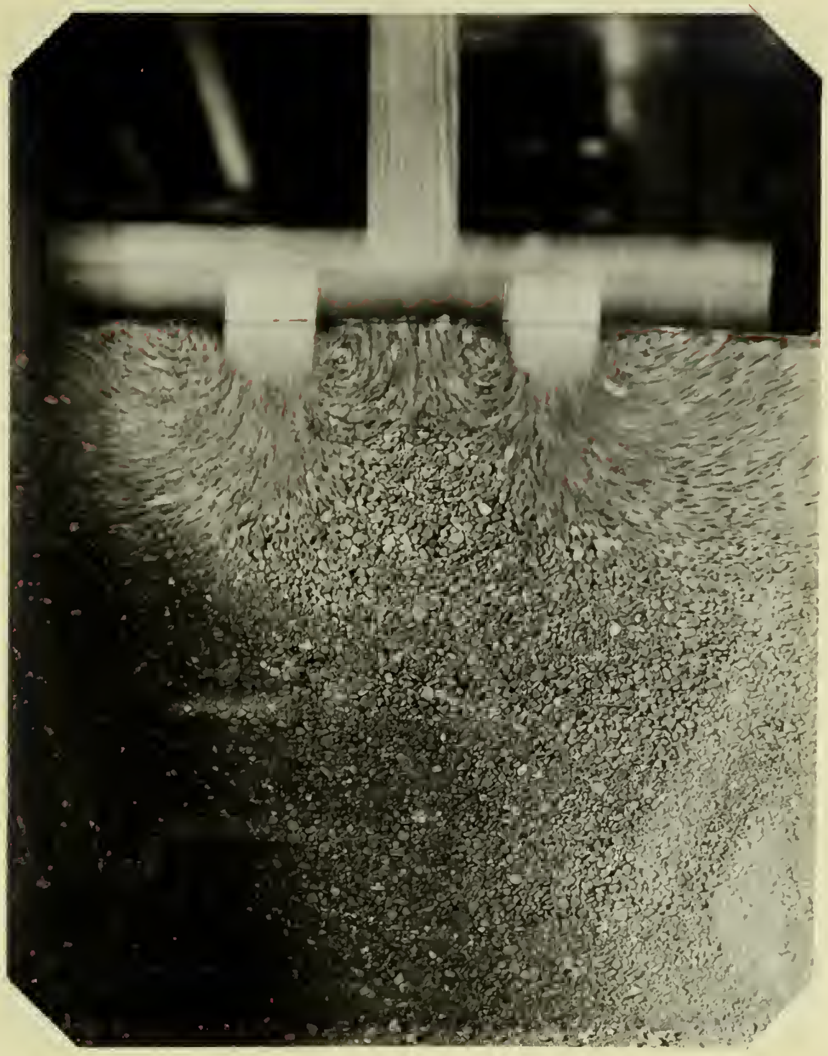
Photograph No. 8.

Pressure Applied to One Block 9" Wide.



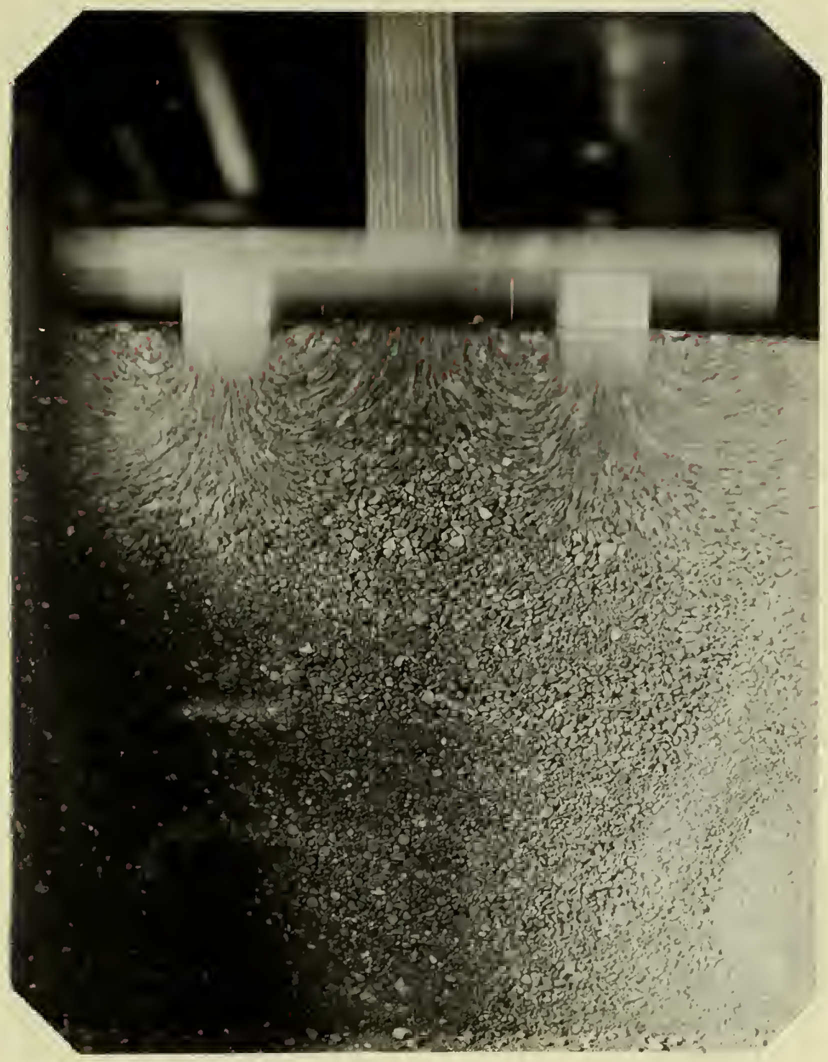
Photograph No. 9.

Pressure Applied to Two 2" Blocks, 4" Centers.



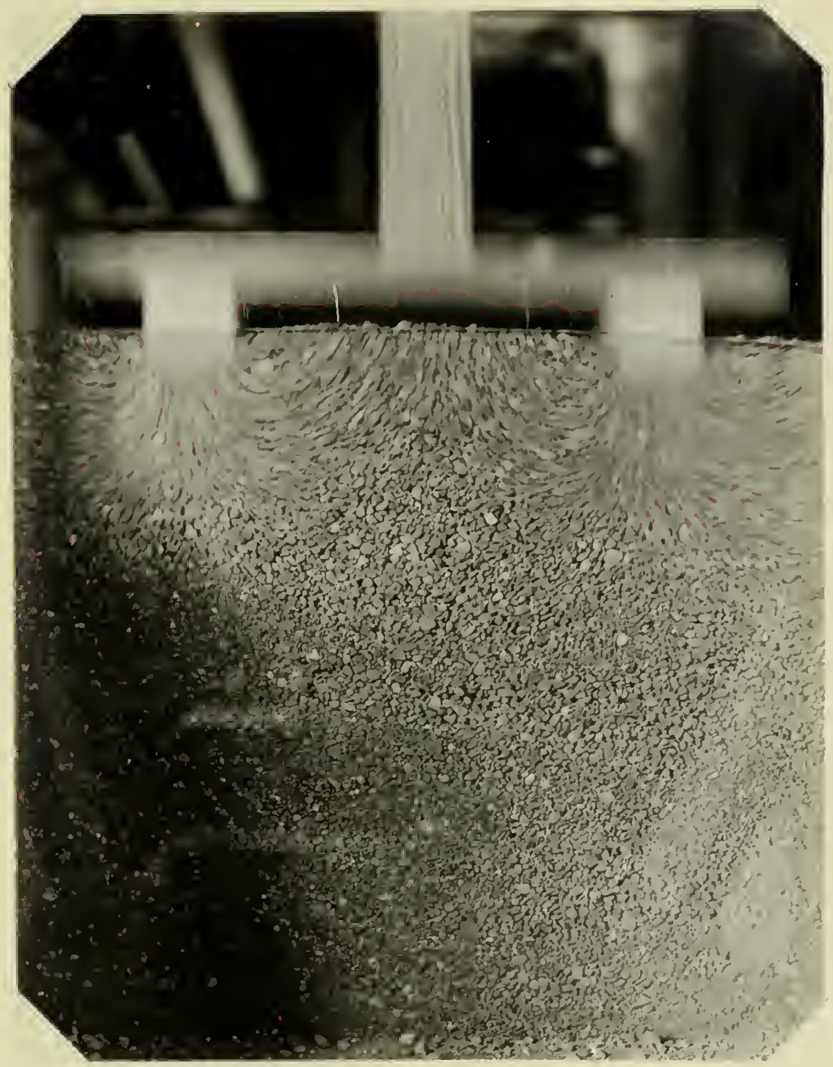
Photograph No. 10.

Pressure Applied to Two 2" Blocks, 6" Centers.



Photograph No. 11.

Pressure Applied to Two 2" Blocks, 8" Centers.

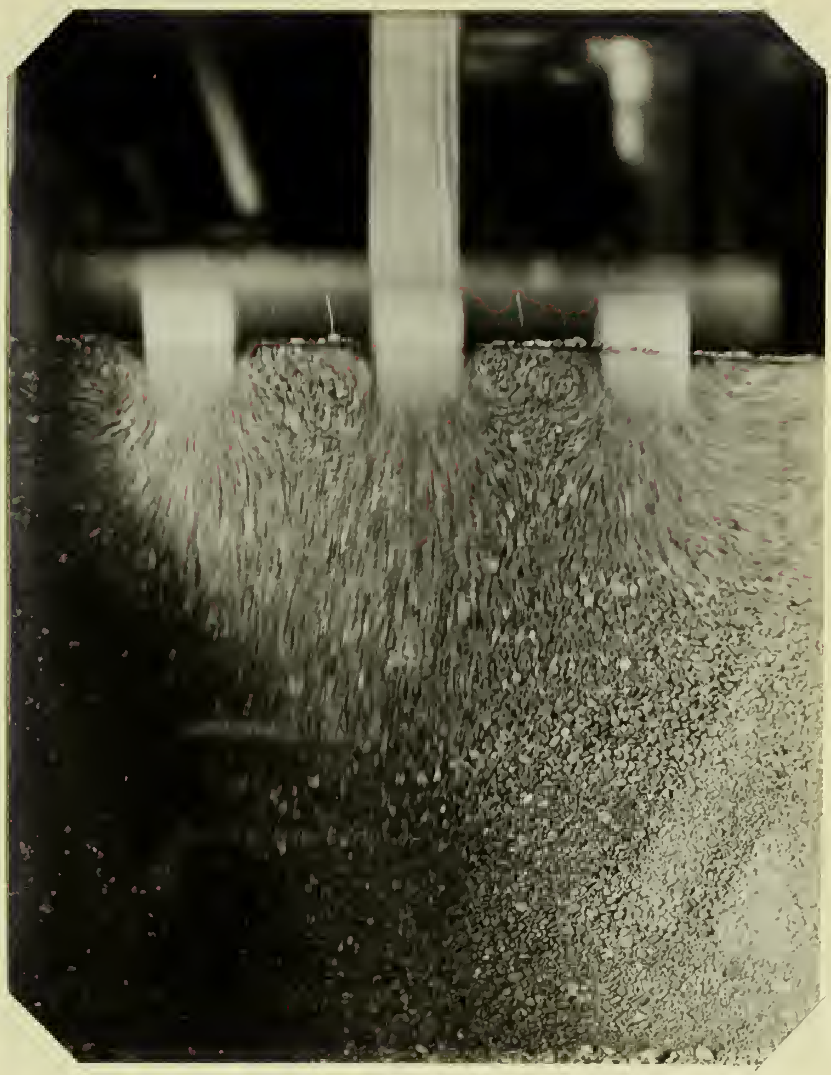


Photograph No. 12.

Pressure Applied to Two 2" Blocks, 10" Centers.

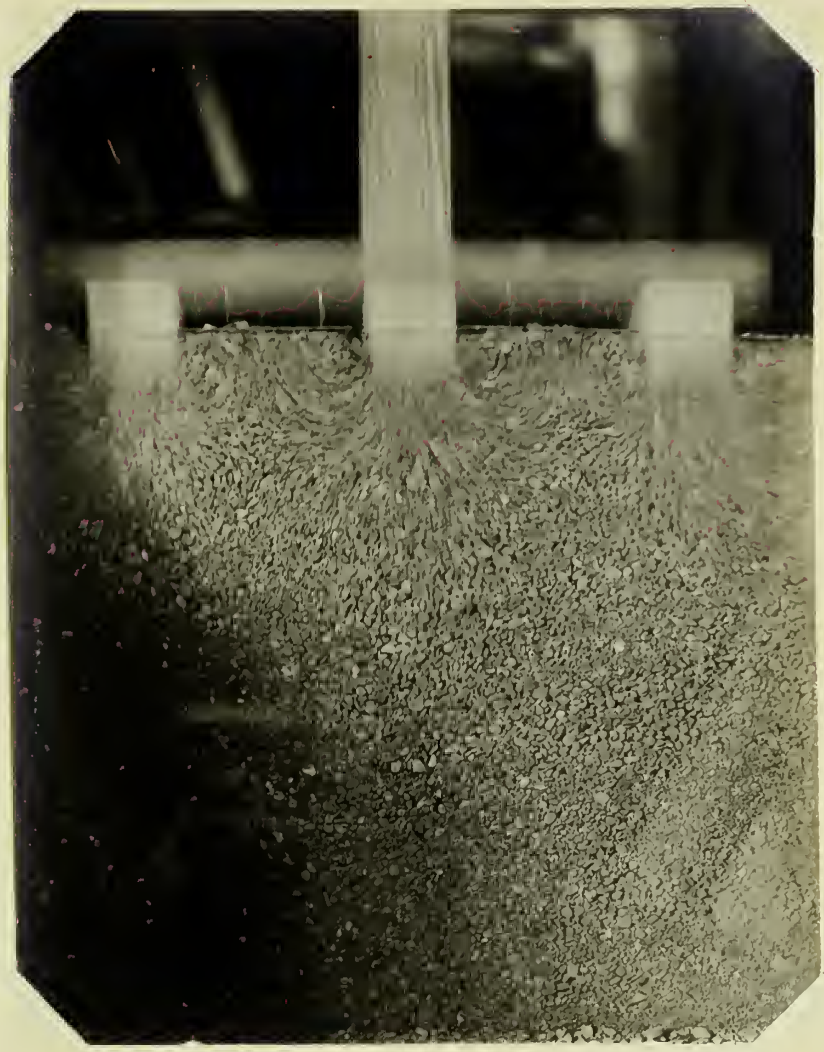
Photograph No. 13.

Pressure Applied to Three 2" Blocks, 4" Centers.



Photograph No. 14.

Pressure Applied to Three 2" Blocks, 6" Centers.



Photograph No. 15.

Pressure Applied to Three 2" Blocks, 8" Centers.

TABLE 1.

COMPARISON OF VALUES OF UNIT TRANSMITTED PRESSURE p'.

As computed from the formula $p' = .182A \frac{p}{d^{1.34}}$,

and as taken from experimental curves.

Diameter of Plate in.	p lbs. per sq. in.	d in.	p' lbs. per sq.in. Calc.	Exp.	Variation Per cent
9.0	6	6	6.25	5.0	+25
"	"	12	2.39	3.5	-31
"	"	18	1.44	1.4	0
"	12	6	12.4	9.6	+ 29
"	"	12	4.79	7.0	- 32
"	"	18	2.90	2.6	+11
"	18	6	18.7	15.0	+25
"	"	12	7.2	6.3	+14
"	"	18	4.35	4.0	+ 9
"	40	6	41.6	30.0	+38
				Mean	21.4
13.5	6	6	14.1	14.6	- 1
"	"	12	5.4	7.5	- 28
"	"	18	3.2	4.0	- 20
"	12	6	28.1	26.0	+ 8
"	"	12	10.8	14.5	- 25
"	"	18	6.5	7.0	- 7
"	18	6	42.2	37.0	+ 14
"	"	12	16.2	18.5	- 12
"	"	18	9.8	9.3	+ 5
"	40	6	94.0	77.0	+ 22
"	"	12	36.0	34.5	+ 4
"	"	18	20.9	15.0	+ 27
				Mean	14.5
21.0	6	12	13.0	14.0	- 7
"	"	18	7.8	6.8	+15
"	12	12	26.1	27.5	- 5
"	"	18	15.8	12.4	+27
"	18	12	39.0	40.0	- 2
"	"	18	23.7	17.6	+ 34
"	40	12	87.0	84.0	+ 4
				Mean	13.5
				Mean of all	16.7

TABLE 2.

DETERMINATION OF THE COEFFICIENT OF FRICTION OF SAND.

Percentage of Moisture, 1.25%.

N lbs.	F lbs.	Average F lbs.	f
47	28 26 27 26 26	26.60	.566
72	40 43 43 44 40	42.00	.583
97	54 55 59 57 56	56.20	.579
122	64 71 72 68 70	69.00	.566
147	75 76 87 79 84	80.20	.546
		Grand Average	.568

TABLE 3.

DETERMINATION OF THE COEFFICIENT OF FRICTION OF SAND.

Percentage of Moisture, 1.95%.

N lbs.	F lbs.	Average F lbs.	f
45	29 28 27 27	27.75	.622
70	44 41 45 40	42.50	.610
95	56 56 57 54	55.75	.589
120	71 70 69 68	69.50	.581
145	86 85 83 79	83.25	.576
	Grand Average		.596

TABLE 4.

DETERMINATION OF THE COEFFICIENT OF FRICTION OF SAND.

Percentage of Moisture, 3.67%.

N lbs.	F lbs.	Average F lbs.	f
45	32 31 29 29	30.25	.671
70	44 43 43 42	43.00	.614
95	57 56 56 56	56.25	.592
120	75 71 69 74	72.25	.601
145	90 86 83 86	86.25	.594
Grand Average			.614

TABLE 5.

DETERMINATION OF THE COEFFICIENT OF FRICTION OF SAND.

Percentage of Moisture, 5.38%.

N lbs.	F lbs.	Average F lbs.	f
45	32 31 29 28	30.00	.663
70	45 44 43 44	44.00	.626
95	57 56 55 57	56.25	.591
120	72 72 69 73	71.50	.594
145	85 88 85 89	86.75	.597
	Grand Average		.614

TABLE 6.

DETERMINATION OF THE COEFFICIENT OF FRICTION OF SAND.

Percentage of Moisture, 9.59%.

N lbs.	F lbs.	Average F lbs.	f
49	36 33 33 32	33.50	.685
74	48 47 47 46	47.00	.636
99	61 59 59 57	59.00	.597
124	76 74 74 69	73.25	.591
149	91 89 92 83	88.75	.596
		Grand Average	.621

TABLE 7.

DETERMINATION OF THE COEFFICIENT OF FRICTION OF SAND.

Percentage of Moisture, 12.21%.

N lbs.	F lbs.	Average F lbs.	f
52	33 34 39 37	35.75	.681
77	50 47 51 51	49.75	.642
102	64 60 62 60	61.50	.600
127	80 74 74 74	75.50	.592
152	88 88 88 88	88.00	.578
Grand Average			.619

TABLE 8.

SIEVE ANALYSIS TABLE OF SAND.

Number of Sieve	Diameter of Sieve Opening inches	Weight Caught on Sieve grams	Total Weight Coarser than Given Diameter grams	Total of Sand Passing Sieve of Given Diameter	
				grams	Per cent
3	.27	0	0	2446	100.0
5	.16	225	225	2221	90.8
10	.073	555	780	1666	68.1
18	.037	473	1253	1193	48.8
30	.022	379	1632	814	33.3
40	.015	329	1961	485	19.85
50	.012	299	2260	186	7.61
74	.0078	87	2347	99	4.95
150	.0033	77	2424	22	0.90
200	.0027	6	2430	16	0.65
Pan		16	2446	0	0.00