Lateral Pressures on Retaining Walls Due to Backfill Surface Loads

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For many decades the traditional method of evaluating the lateral pressure on a retaining wall due to a load applied at the surface of the soil backfill has been to substitute a uniformly distributed load for the actual load, and then calculate the pressure by either the Rankine or the Coulomb classical theory. This method of approach to the problem has several shortcomings and disadvantages. First, there is no logical or scientific basis for determining the magnitude of the uniformly distributed load in relation to the actual load. Judgement and intuition are the only guides for this substitution. Second, the lateral pressure on the wall resulting from the substitution is of uniform intensity throughout the entire height of the structure, whereas the intensity of pressure due to the actual load may vary considerably throughout the height of the wall.

The Iowa Engineering Experiment Station conducted experimental research during the decade from 1931 to 1941 to determine the lateral pressure on a wall due to concentrated loads applied at the backfill surface and to uniformly distributed line or strip loads parallel to the wall. These studies indicated that the surface loads produced lateral pressures which were closely related to the pressures calculated by the Boussinesq theory of stress distribution in a semi-infinite elastic medium and provided a basis for further study of the influence of loads applied at the backfill surface.

More recently, under the sponsorship of the Iowa Highway Research Board and the Iowa Highway Commission, further studies have been conducted in which lateral pressures due to uniformly distributed loads over finite areas on the soil backfill have been measured. This paper contains a resume of the earlier research and a detailed presentation of data obtained in the recent studies, together with a correlation with the Boussinesq theory.

● THE quantitative determination of the magnitude and distribution of lateral pressures on retaining walls, caused by an earth backfill and by loads superimposed upon the surface of the backfill, is the first necessary step in the structural design of earth restraining structures of this type. The engineering profession has available an abundance of information, both scientific and empirical, relative to lateral pressures caused by an earth backfill. Acceptable and widely used techniques have been evolved throughout modern engineering history, based largely upon the scientific principles enunciated by Coulomb and Rankine and refined by experimental and analytical research by Baker, Feld, Terzaghi and many others.

On the other hand, lateral pressures due to loads superimposed on the surface of a backfill have received relatively little attention from researchers. Designers of retaining walls subjected to loads in this latter category are forced to rely, to a much greater extent, upon rule-of-thumb procedures and individual judgement and intuition. One widely used and more or less traditional approach to this problem is to substitute a uniformly distributed load on the surface of the backfill which is assumed to produce the same lateral pressure effect on the retaining wall as the actual load. Then this uniformly distributed load is converted to an equivalent additional height of fill above the top of the wall, and pressure on the wall due to the augmented fill height is calculated by conventional methods. This traditional procedure is illustrated in Figure 1.

There are a number of shortcomings and unsatisfactory features associated with this method of handling the problem. First, there is no scientific basis or guide to aid the designer in selecting a quantitative value of uniformly distributed load which will produce the same effect on the wall as the actual load. A decision on this point must be based solely upon judgement without the aid of well established criteria. Second, the lateral pressure on a wall resulting from this substitution of a uniformly distributed surface load is of uniform intensity throughout the entire height of the wall, regardless of the position or the shape and degree of concentration of the actual surface load. Research in recent years has indicated rather definitely that this pattern of pressure distribution does not coincide with fact.

In 1932 the Iowa Engineering Experiment Station began a series of experimental stud-

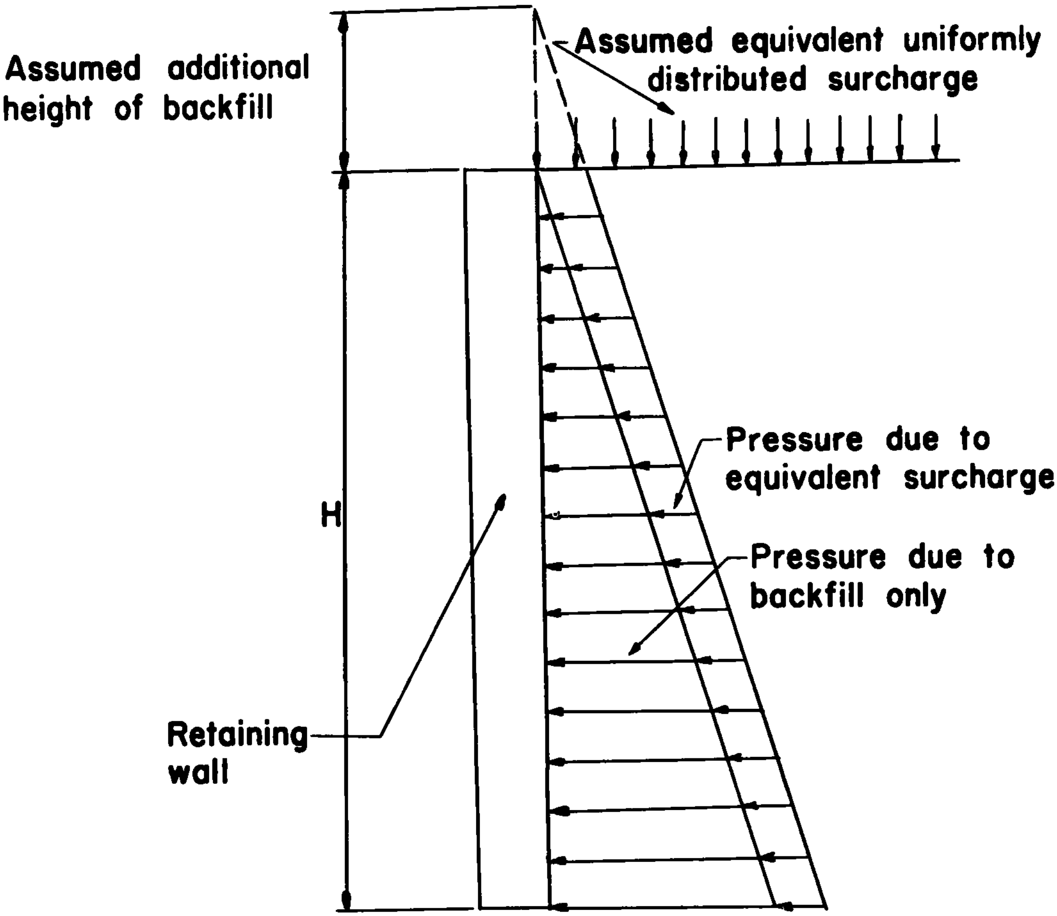

Figure 1. Traditional method of estimating lateral pressure due to surcharge load.

ies in which the magnitude and distribution of lateral pressures on a retaining wall caused by the application of a concentrated load on the surface of the backfill were measured. Later, this work was extended to include the pressures caused by a uniformly distributed line or strip load applied on the backfill surface and oriented parallel to the wall. The results of these studies were published in 1936 (3) and 1938 (4).

Still later, in 1939, a project was established in cooperation with the U. S. Bureau of Public Roads in which the lateral pressures on a retaining wall caused by a uniformly distributed load applied over a finite area on the surface of the backfill were to be measured. This project was scarcely started when shortages of labor and materials occasioned by the defense build-up prior to World War II began to be effective and little progress was made. Finally after the outbreak of the war, the project was suspended.

In 1951 the project was re-established in cooperation with the Iowa Highway Commission upon recommendation of the Iowa Highway Research Board. The purpose of this

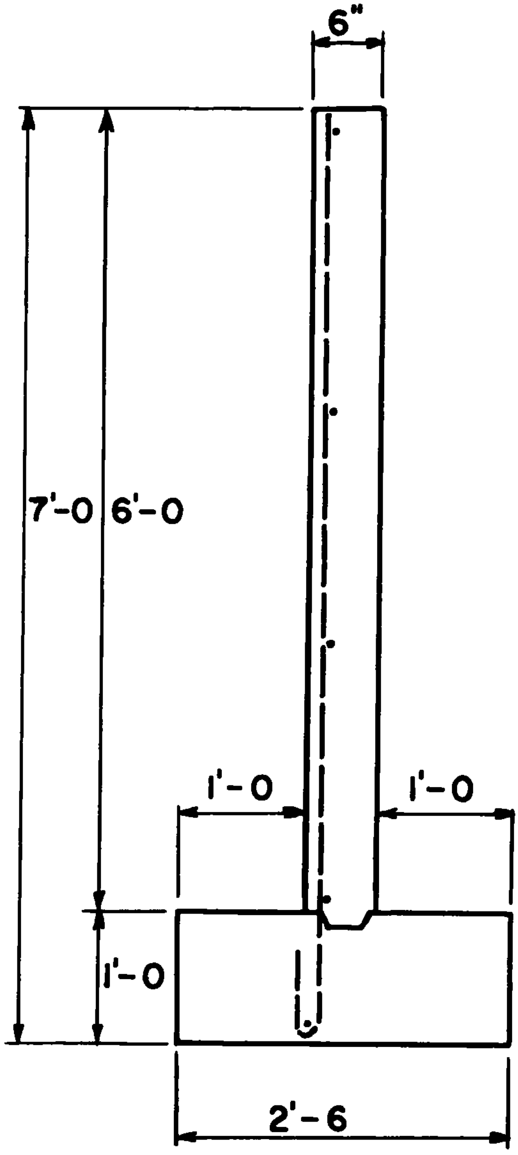

Figure 2. Cross section of experimental wall - 1932.

paper is to review the results of the measurements of lateral pressures caused by concentrated loads and uniformly distributed line loads on the backfill surface and to present in detail the data obtained in the more recent studies with uniformly distributed area loads.

All of these pressure measurements have been conducted on reinforced concrete retaining walls of cantilever design and T-shaped cross section. The experimental walls have been relatively rigid in character, that is, the yield of the wall has been relatively small in comparison with the deflection of the vartical plane in the backfill at the back face of the wall, if the soil mass had been continous without interruption by the restraining structure. The first experiments with concentrated loads and uniformly distributed line loads were conducted with retaining walls 6 feet high above the base, as shown in Figure 2.

The pressure measuring devices in the earlier experiments were of two types; stainless steel friction ribbons and Goldbeck pressure cells. They were installed flush with the vertical back face of the walls and were calibrated prior to placement of the soil backfill by means of an air pressure apparatus clamped on the wall successively over each pressure measuring unit.

The pressure caused by the soil backfill was first measured. Then concentrated loads of various magnitudes were placed on the backfill surface at various positions back of the wall and the total pressure measured. The difference between the total pressure and that due to the backfill alone was considered to be the pressure caused by the applied surface load.

The backfill material was a pit run gravelly sand consisting of about 40 percent gravel, 48 percent sand, 8 percent silt and 4 percent of 5 micron clay. The liquid limit was 17 and the plasticity index, 4. It was placed behind the experimental retaining walls by hand methods without special compaction. The concentrated loads applied to the surface of the backfill consisted of one rear wheel of a heavily loaded truck. The wheel was equipped with dual hard rubber tires and was considered to transmit a concentrated load to the backfill surface, although of course, there was a finite area of contact of about one square foot. This truck wheel load was positioned at various distances behind the back face in a vertical plane at right angles to the wall and passing through the vertical element in which the pressure measuring devices were installed. The applied wheel loads were of several different magnitudes in the several series of tests which were run, ranging from 6,800 lb to 10,650 lb.

The results of Series V of these early tests with concentrated loads are shown in Figures 3, 4 and 5. The wheel load in this series was 10,450 lb, but the data are shown in terms of unit lateral pressure per 1,000 lb of load. Although the data points are scat-

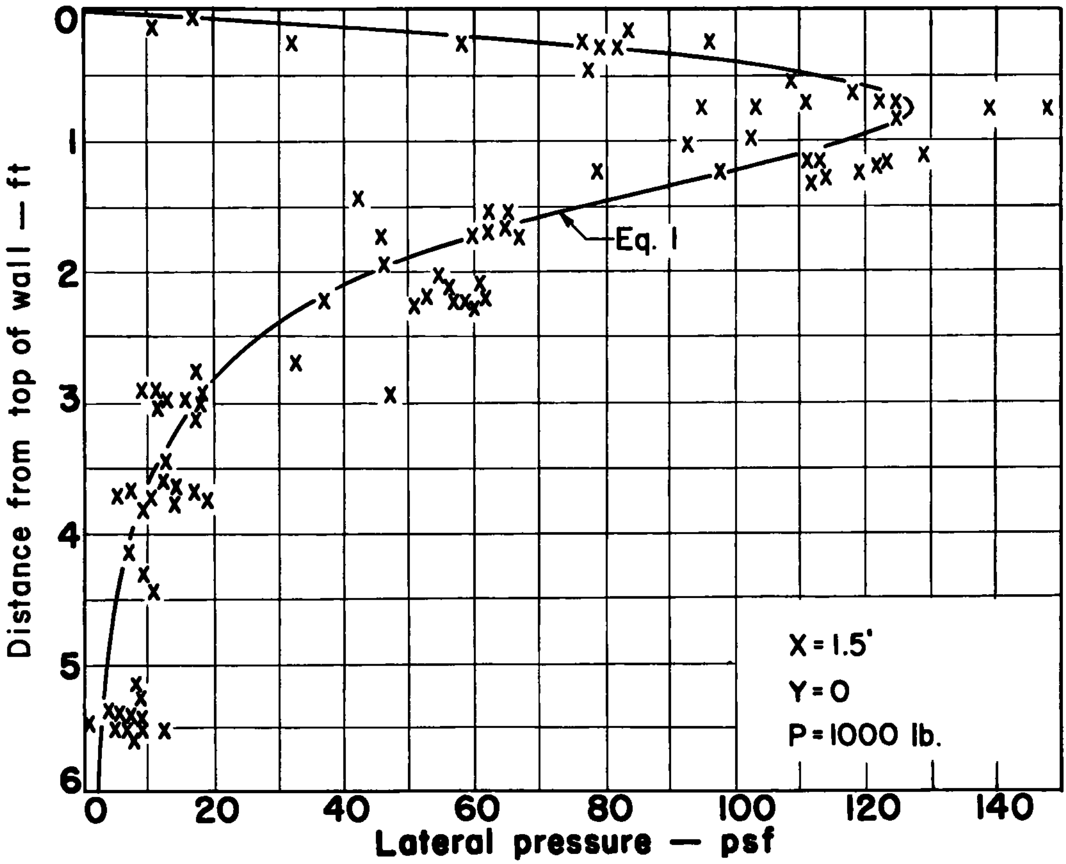

Figure 3. Lateral pressure due to concentrated load - 1934.

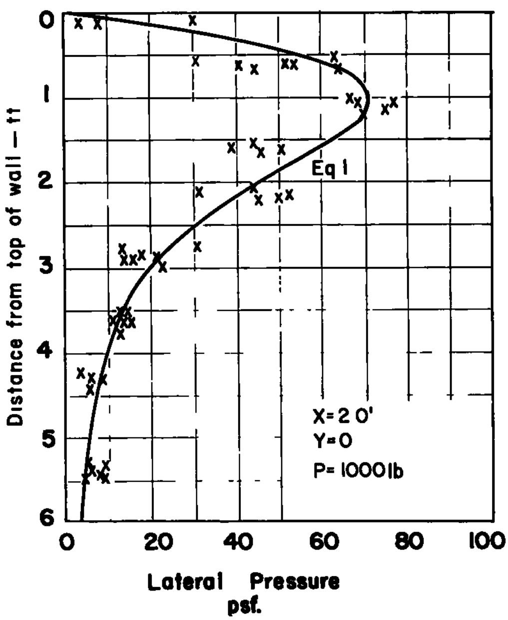

Figure 4. Lateral pressure due to concentrated load - 1934.

tered over a wide area, the general pattern of lateral pressure is unmistakably similar to that indicated by the Boussinesq equation for normal stress on a vertical plane in a semi-infinite elastic medium, due to a point load acting at the surface, with the exception that the magnitude of the measured pressures is roughly about double that indicated by the Boussinesq formula when Poisson's Ratio is assumed to be 0.5. Thus on the basis of these experiments we may write the equation

$$h_c = P\frac{x^2 z}{R^5} \qquad (1)$$

in which

h_c = horizontal unit pressure at any point on the wall due to a concentrated surface load;

P = concentrated load applied at surface of backfill;

x, y and z = coordinates of any point on the wall;

R = radial distance from load to any point $= \sqrt{x^2 + y^2 + z^2}$.

The results of these experiments were first presented at the International Conference on Soil Mechanics and Foundation Engineering at Harvard University in 1936. In a discussion of the paper, Dr. R. D. Mindlin (2) of Columbia University pointed out that it can be shown theoretically by the method of images that the pressure on a smooth, rigid wall is exactly double that indicated by the Boussinesq formula. The retaining walls used in these experiments were relatively rigid in character, but they were not smooth to the extent that no shearing stresses existed on the back face, which may partially account for the fact that a number of the experimental points indicate pressures greater than double the Boussinesq pressures. Nevertheless, this suggestion by Mindlin lends confidence to the pressure measurements.

If Equation 1 is integrated in the direction parallel to the wall, between the limits ∞ and $-\infty$ the following expression is obtained

$$h_1 = 1.33\, P_1 \frac{x^2 z}{R_1^4} \qquad (2)$$

in which

h_1 = horizontal unit pressure at any point on the wall due to a uniformly distributed parallel line load of infinite length;
P_1 = load per unit length;
R_1 = slant distance from line load to any point,
= $\sqrt{x^2 + z^2}$.

The validity of this integration was investigated experimentally by placing a narrow strip load on the backfill and measuring the lateral pressure on the retaining wall. The

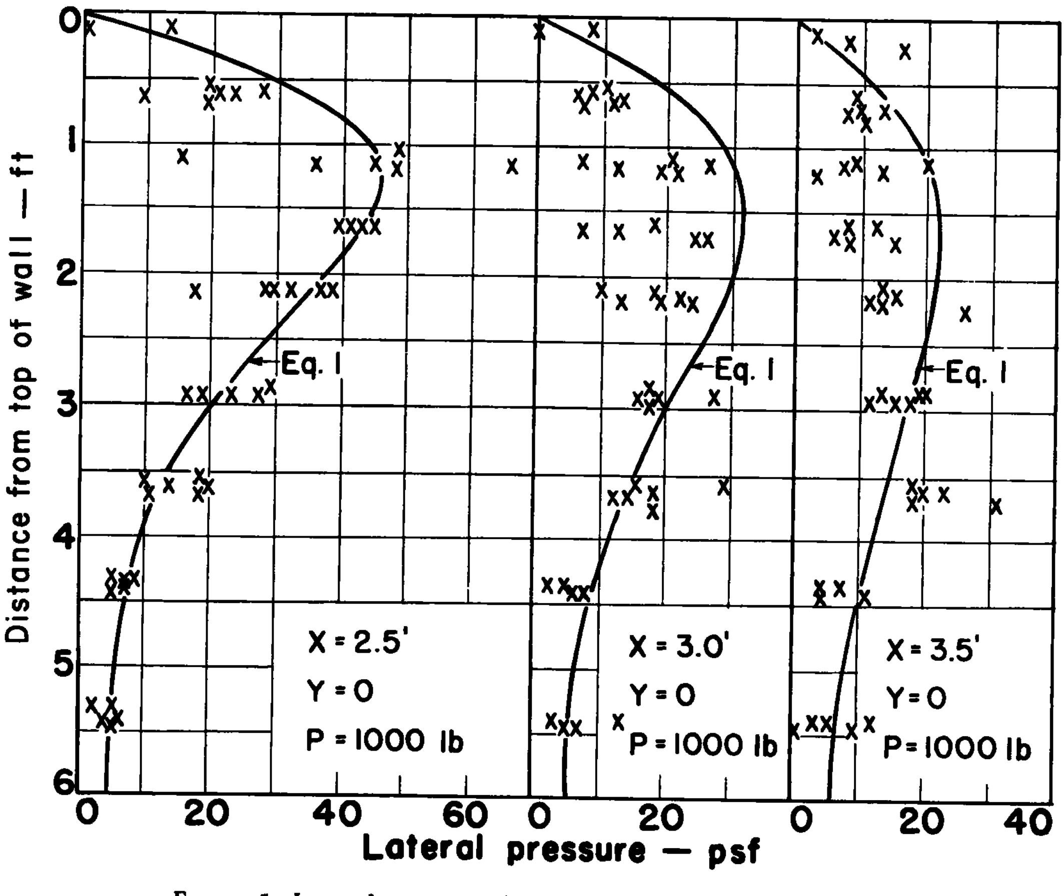

Figure 5. Lateral pressure due to concentrated load - 1934.

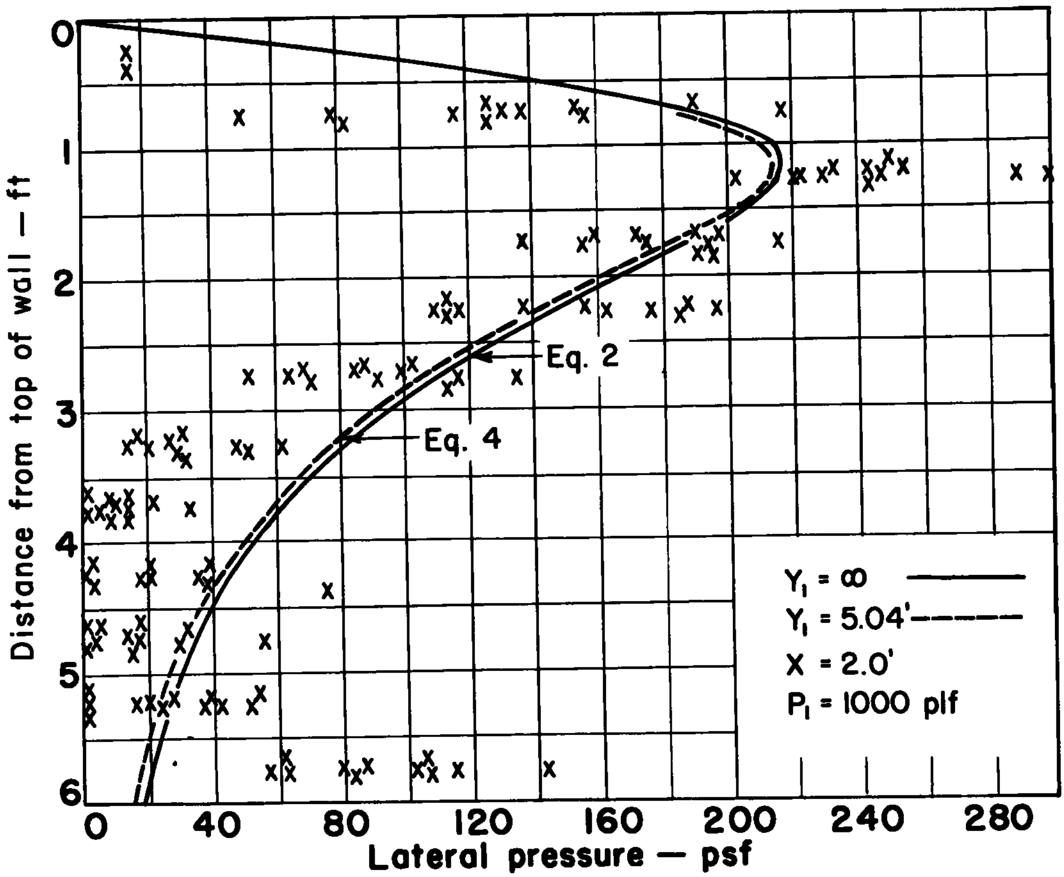

Figure 6. Lateral pressure due to uniformly distributed line load - 1934.

narrow strip load was applied by placing both rear wheels of a truck on a 6 x 8 in. timber 10 ft-1 in. long, which was laid with the 8 in. side down, parallel to the wall, and centered 2 ft back of the back face. The timber was centered directly opposite the pressure measuring devices and the rear wheels of the truck were placed symmetrically about the center of the timber. The total axle load of the truck was 19,080 lb and, assuming this load was uniformly distributed over the length of the timber, the load per unit length was 1,893 lb per ft.

The results of the line load pressure measurements are shown in Figure 6. Again the measured pressures indicate a definite correlation with those calculated by the modified Boussinesq Theory, although the usual wide scattering of data masks this relationship in any individual load application.

As previously stated, the actual length of the line load applied in the experiments was 10 ft-1 in., whereas Equation 2 represents the pressure due to a load of infinite length. If Equation 1 is integrated between finite limits of y_1 and $-y_2$, we obtain

$$h_1 = P\frac{x^2 z}{R_1^4}\left[\frac{R_1^2 y_1}{3(R_1^2 + y_1^2)^{1.5}} + \frac{2y_1}{3(R_1^2 + y_1^2)^{0.5}} - \frac{R_1^2 y_2}{3(R_1^2 + y_2^2)^{1.5}} - \frac{2y_2}{3(R_1^2 + y_2^2)^{0.5}}\right] \tag{3}$$

The maximum pressure on the wall will occur at points directly opposite the center of the finite load; that is, where y_1 and y_2 are numerically equal. For this condition we may substitute y_1 for $-y_2$ in Equation 3 which gives

$$h_1 = \frac{2}{3} P \frac{X^2 z}{R_1^4} \left[\frac{R_1^2 y_1}{(R_1^2 + y_1^2)^{1.5}} + \frac{2y_1}{(R_1^2 + y_1^2)^{0.5}} \right] \quad (4)$$

The dotted curve in Figure 6 shows pressures calculated by Equation 4, using $y_1 = 5.04$ ft, corresponding to the actual length of line load applied in the experiments. The difference between calculated pressures for the 10.08 ft load and a load of infinite length is negligible at this distance from the wall. The theoretical relationship between maximum pressures due to line loads of finite length (Equation 4) and infinite length (Equation 2) is shown in Figure 7.

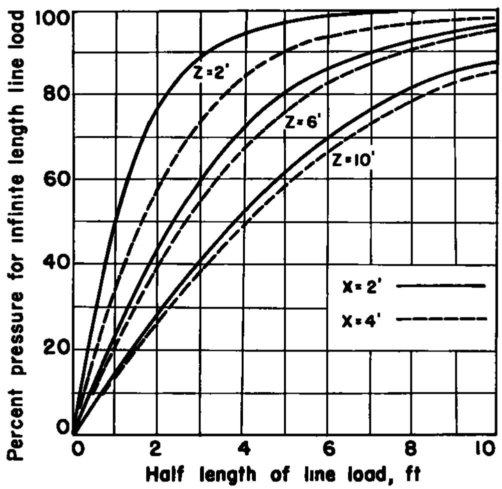

Figure 7.

1941 Experiments

The experimental work employing concentrated loads and uniformly distributed parallel line loads has demonstrated that the lateral pressures on a rigid retaining wall are closely related to those indicated by a simple modification of the Boussinesq formula. This experience led to the hypothesis that the lateral pressures due to a uniformly distributed area load may be estimated by integrating the line load formulas, Equation 2, 3 and 4, in the x-direction; that is, the direction normal to the wall.

The integration of Equation 2 has been completed and yields the following:

$$h_a = \frac{2}{3} Pa \left[\arc \tan \frac{x}{z} - \frac{xz}{(x^2 + z^2)} \right]_{x_0}^{x_1} \quad (5)$$

in which

- h_a = horizontal unit pressure at any point on the wall due to a uniformly distributed area load of finite width $(x_1 - x_0)$ and length greater than about 15 or 20 ft;
- Pa = load per unit area;
- x_0 = distance from back of wall to near side of load;
- x_1 = distance from back of wall to far side of load.

To obtain lateral pressures due to area loads less than about 15 or 20 ft in length, it will be necessary to integrate Equation 3 and 4 in the x-direction. These integrations have not been completed. Therefore, at present it is necessary to resort to mechanical summation procedures for these cases by dividing the applied load into a series of finite strip loads about 1 or 2 ft in width and utilizing Equation 3 or 4 to estimate the pressure caused by each strip load.

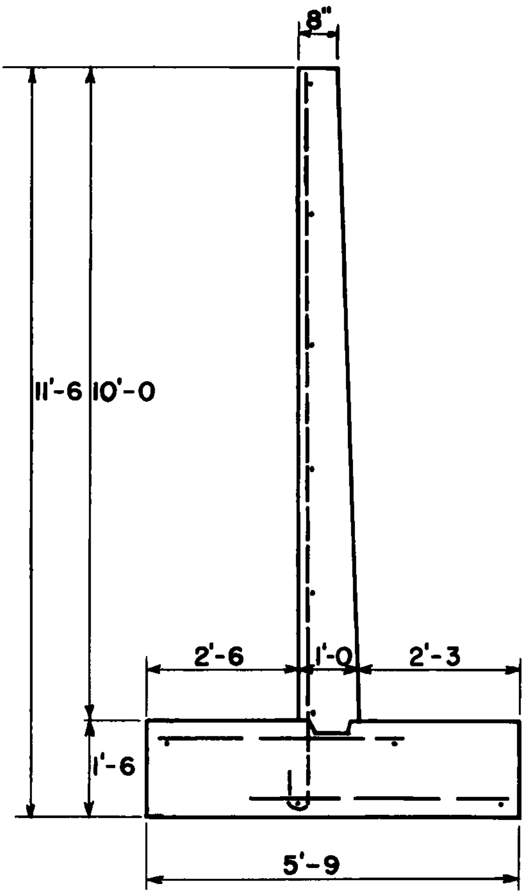

Figure 8. Cross section of experimental wall - 1940.

The 1941 experiments, which were coop-

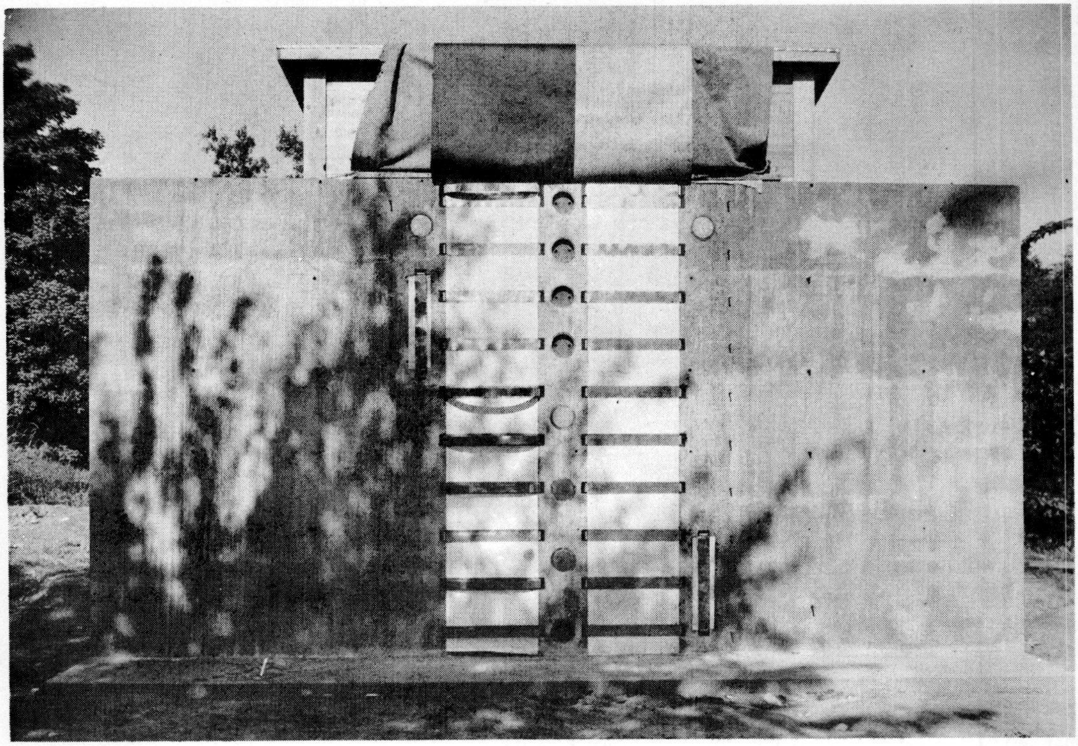

Figure 9. Experimental retaining wall - 1941.

erative with the Bureau of Public Roads, were designed to provide data bearing upon the validity of this hypothesis relative to the applicability of the modified Boussinesq equation to the case of an area load applied at the surface of a level backfill. A new experimental wall was constructed which was 10 ft high and 20 ft long, having the cross section indicated in Figure 8. This wall was fitted with pressure measuring devices in the vertical back face, consisting of a series of stainless steel friction ribbons and a series of Goldbeck pressure cells, as shown in the photograph in Figure 9.

The friction ribbons were 2 in. wide and installed with a length of 2 ft in the plane of the back face of the wall. At each end of this length the ribbons passed over a stainless steel roller and passed through the wall in such a manner that both ends of the ribbon were available for pulling from the front side of the wall. A winch was mounted in a shed at the front side for the purpose of applying pull to the ribbons.

The ribbons were mounted to slide between two sheets of stainless steel and the whole area covered with a sheet or rubber and then a sheet of tar paper to protect the ribbons from the backfill and moisture. They were calibrated individually by applying air pressure into a rubber bladder confined in an aluminum bottomless box. This box and bladder were centered directly over the ribbon to be calibrated and clamped to the wall. Pulls were applied to one end of the ribbon and the relationship between applied normal pressure and pull required to start sliding motion obtained.

The Goldbeck pressure cells were mounted in recesses in the wall with the measuring face flush with the back face. They were calibrated in essentially the same manner as the friction ribbons.

A vertical steel column was installed at a distance of 6 ft in front of the wall as a reference post for measurement of outward yield of the wall under the influence of backfill and surface loads. The column was set in a heavy concrete base entirely separate from the retaining wall structure. In order to make sure that the reference post itself did not move, a transit line was established between bench marks about 50 ft on each side of the column and well removed from the experimental wall. Frequent observations were made during the course of the loading operations, but no movement of the

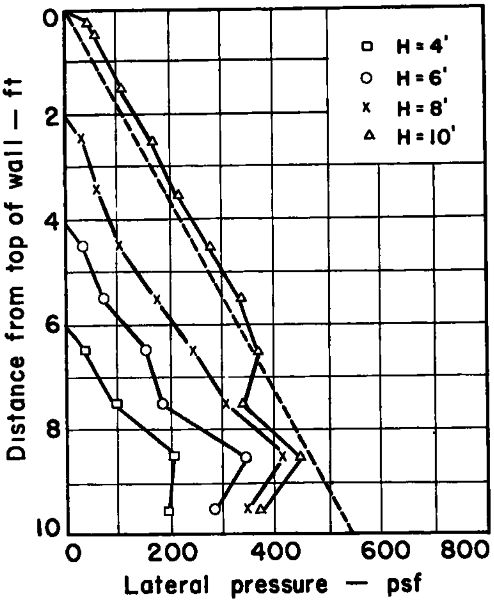

Figure 10. Lateral pressure, backfill only - 1940.

TABLE 1

Load Condition	Outward movement, in Top	Mid-height	Bottom
Backfill completed	06	02	02
First surcharge complete	60	36	20
First surcharge in place one month	91	54	34
First surcharge removed	73	45	29
Second surcharge complete	75	46	28
Second surcharge in place 2 weeks	77	46	.29
Second surcharge removed	75	.44	29
Third surcharge complete	74	45	28

reference post could be detected. The outward movement of the wall was measured by means of a micrometer caliper between the steel post and brass pins set near the top, center and bottom of the wall. These measurements are summarized in Table 1.

The first surcharge load caused relatively large outward movements, both rotation and translation, but subsequent loadings did not produce any movement of consequence. Also, when the experimental wall was again loaded during the current series of loadings, the wall movements were practically negligible. Apparently the first surcharge caused the wall to reach a state of equilibrium and no further movements occurred.

The backfill consisted of the same type of pit run gravelly sand as that used in the earlier experiments. It was placed behind the wall in the fall of 1940 by hand methods and not compacted except by its own weight. During the following winter the surface settled up to a maximum of 8 or 10 in. This settlement was made up the next spring by adding additional material up to the level of the top of the wall. During the winter the unit weight of the backfill was measured by sinking a shaft the full depth of the fill and weighing all the soil removed. The average unit weight was 111 pcf. The lateral pressures on the wall due to the backfill at various stages of its construction are shown in Figure 10.

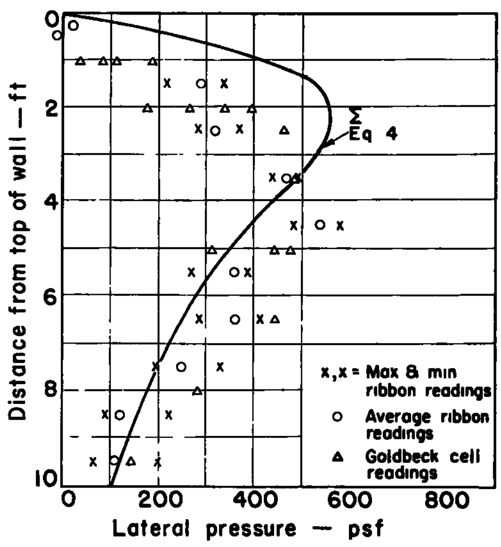

Figure 11. Lateral pressure due to area load - 1941.

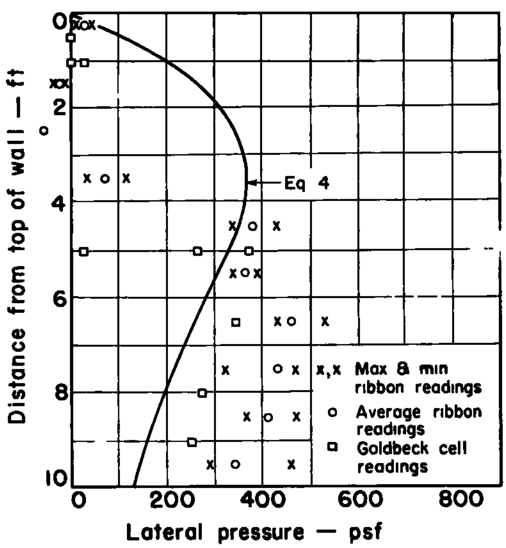

Figure 12. Lateral pressure due to area load - 1941. Load 4 feet from wall.

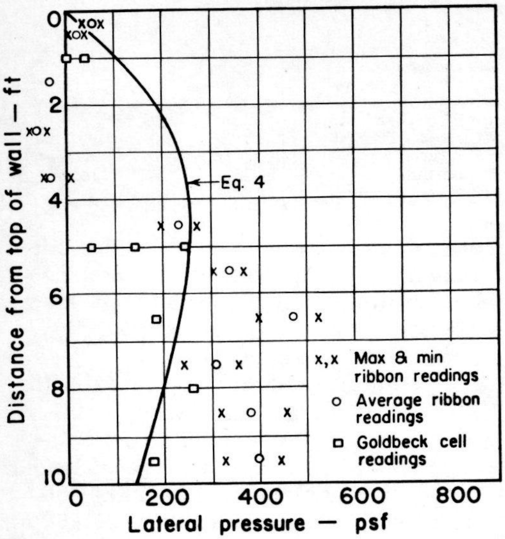

Figure 13. Lateral pressure due to area load - 1941. Load 6 feet from wall.

During the spring and summer of 1941 the backfill was loaded by piling sacks of gravel inside a wooden crib which was 6 ft wide normal to the wall and 16 ft long parallel to the wall. A series of three load applications was made, first with the load 2 ft back of the wall, then 4 ft and finally 6 ft. The magnitude of the superimposed load in each trial was 105,200 lb or 1,096 psf. The loading operation took about one to two weeks' time in each case and the maximum load was left in place from two weeks to one month. The backfill was not disturbed between the load applications. The results of these load applications are shown in Figures 11, 12 and 13.

Originally it was planned to recalibrate the measuring devices after removal of the backfill, but as stated earlier, the project was suspended at this time and the recalibration was not carried out. Hence the data obtained are not as reliable as they otherwise might have been. Also it is pointed out that only one load application is involved in each of these trials, whereas experience gained in the case of concentrated loads and line loads indicated that many repetitions of load are required to obtain a reasonably complete statistical picture of the magnitude and distribution of pressures due to loads applied at the backfill surface.

Current Experiments

The project was re-established in 1951 in cooperation with the Iowa Highway Commission. The previously constructed retaining wall was rehabilitated by pouring a 4 in. thick surfacing on the back face and by constructing 8 ft long wing walls at each end. Recesses were cast in the back face surfacing to receive the pressure measuring devices, which were soil pressure cells of the type developed by the Waterways Experiment Station of Vicksburg, Mississippi. A photograph of the experimental wall after rehabilitation is shown in Figure 14.

The pressure cells were $4\frac{1}{2}$ in. in diameter and 1 in. thick and were machined of a special grade of stainless steel to resist corrosion. They were set in the wall recesses in neat cement with the measuring face of the cell flush with the back face of the wall. The cell housing is hermetically sealed to prevent the entrance of moisture. A 4-wire electrical cable attached to the side of the cell passed through the wall and was available from the front side for connection with a strain indicator. Entrance of moisture along the wires is prevented by a special Kovar seal.

The cells consist of a metal disk, supported around its periphery. Pressure on the cell causes the disk to deflect a minute amount. The strain in the disk is measured by four SR-4 strain gages which constitute the four resistance arms of a complete Wheatstone's Bridge. The arrangement is such that strain in the disk causes an unbalance of the bridge which is a measure of the pressure causing the strain, and the relationship between pressure and bridge unbalance can be determined by calibration.

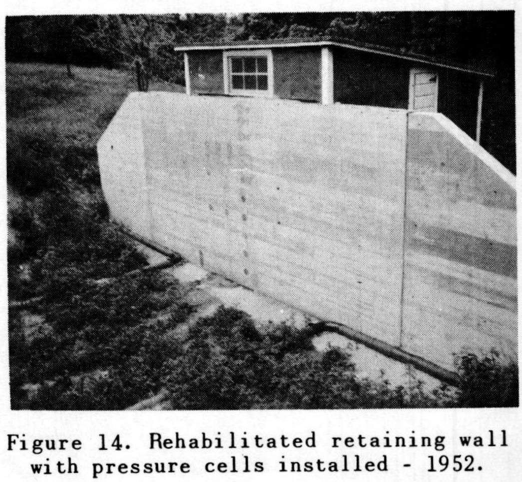

Figure 14. Rehabilitated retaining wall with pressure cells installed - 1952.

An SR-4 Type L portable strain indicator manufactured by the Baldwin-Lima-Hamilton Corporation was used to measure the unbalance of the bridge. It was housed in a constant temperature box at 95 deg F to minimize the effect of temperature changes on the indicator. It was checked from time to time with a Baldwin constant resistance box. Power imput to the indicator was furnished through a Baldwin transformer early in the experiments, but this was abandoned after a short time because of poor line voltage. Batteries were substituted as a source of power during the balance of the study. Individual cells were connected to the indicator by means of a Baldwin twenty pole selector.

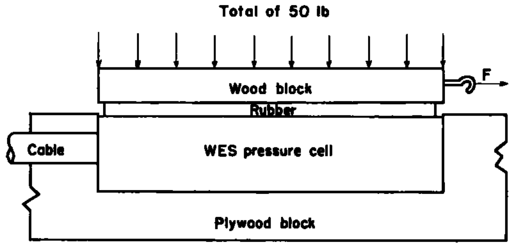

Figure 15. Apparatus for applying a shearing force on the face of a pressure cell.

Thermometers were inserted into the holes through which the cables passed through the wall, to a point 4 in. in front of the cells. It was noted that temperature variations changed the unbalance of the bridge, but no correlation between temperature change and bridge unbalance could be established.

Calibration curves for the pressure cells were furnished by the supplier. However, results obtained with the first backfill placed behind the wall led to the conclusion that conditions prevailing in the factory calibration and the actual installation were not the same, and an extensive in-place calibration program was carried out. This was done by clamping a 9-in. diameter hemispherical vessel over a cell and introducing air pressure into a rubber bladder which impinged directly on the cell. Calibration curves obtained in this manner were reproducible and appeared to be satisfactory. The cells were recalibrated after removal of each of the backfills placed behind the wall, and little change in calibration was noted.

At this stage of the investigation a question arose relative to the effect of shearing forces on the measuring face of the pressure cell on the indicated normal pressure. In order to study this question, a cell was removed from the wall and mounted in a wood block in the laboratory with the face of the cell flush with the surface of the block, in much the same way as the cells were mounted in the retaining wall. A piece of thin rubber was placed over the cell to develop frictional resistance to tangential force. Then a circular piece of plywood the same diameter as the cell was placed on the rubber directly over the cell. A diagram of this arrangement is shown in Figure 15. A 50 lb weight was placed on the plywood disk which actuated the pressure cell at about 3 psi. Next, a shearing force was applied by pulling the plywood disk at right angles to the radial axis of the cell; that is, parallel to the measuring face. Tangential forces up to more than one-half the normal force were applied, but they did not change the unbalance of the bridge. However, when the tangential force was applied at a slight angle with the face of the cell, the influence of a normal component was readily detected on the SR-4 indicator. From these trials, it was concluded that the cells measured normal components of pressure only, uninfluenced by shearing forces acting on the back face of the wall.

Up to the time of this report, four backfills have been placed behind the experimental wall. The first three consisted of a sandy loam glacial till, which contained 6 percent gravel, 57 percent sand, 25 percent silt and 12 percent 5-micron clay. The liquid limit was 18 and the plasticity index 4.

Backfill number 4 was a pit run gravel which contained 56 percent gravel, 36 percent sand, 5 percent silt and 2 percent 5-micron clay. The liquid limit was 21 and the plasticity index was 1. The dates of placement and removal of the backfills are shown in Table 2.

TABLE 2

Backfill No	Date placed	Date removed	Unit weight pcf
1	June, 1953	Aug , 1953	115 3
2	Oct , 1953	May, 1954	-
3	July, 1954	Oct , 1954	117 6
4	Dec , 1954	Apr , 1955	115 5

TABLE 3

Backfill No	Surcharge No	Unit Load psf	Distance wall to load, x_0, ft
1	1-A	938	3
2	2-A	938	3
3	3-A	938	3
	3-B	1,448	3
	3-C	1,448	1.5
4	4-A	1,448	2
	4-B	1,448	2
	4-C	1,448	3

All of the backfills were placed by essentially hand methods. A small dragline was used to move the material from a nearby stockpile to the general area behind the wall. It was then hand shoveled up to the wall and brought up in horizontal layers. Care was exercised to see that no stones or lumps of soil were placed in the vicinity of the pressure cells. In the case of backfill No. 3, a vertical layer of clean river sand about 6 in. thick was placed next to the retaining wall as the backfill was built. The soil was not compacted behind the wall in any of the experiments.

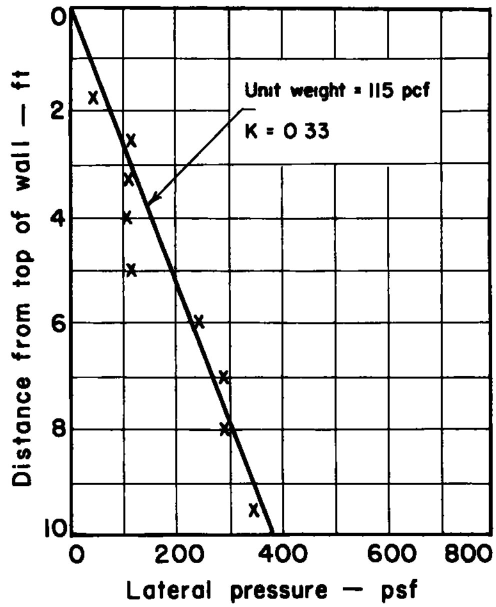

Figure 16. Lateral soil pressures caused by backfill only. Backfill number one before surcharging.

Surcharge loads consisted of a wooden crib 6 ft wide and 10 ft long, filled with 50 lb bags of pea gravel. The bottom of the crib was made of loose 2 in. by 12 in. planks 2 ft long laid end to end with joints staggered in adjacent rows. The purpose of this arrangement was to enable the gravel bags to conform to the surface of the backfill at all times. The bags were piled in orderly arrangement to attain a uniform distribution of pressure over the 6 ft by 10 ft area. The crib and gravel bags were kept covered with a heavy tarpaulin at all times to prevent rainfall from changing the load.

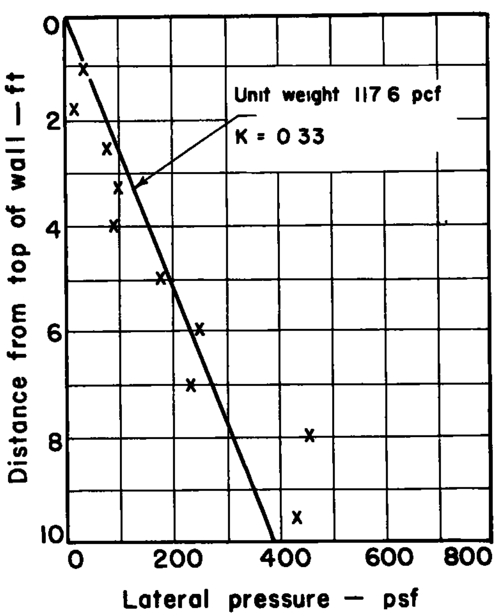

Figure 17. Lateral soil pressures caused by backfill only. Backfill number three before surcharging.

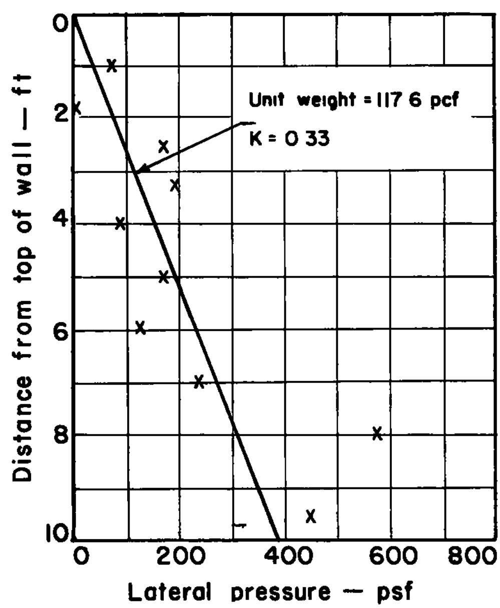

Figure 18. Lateral soil pressures caused by backfill only. Backfill number three after removal of first surcharge.

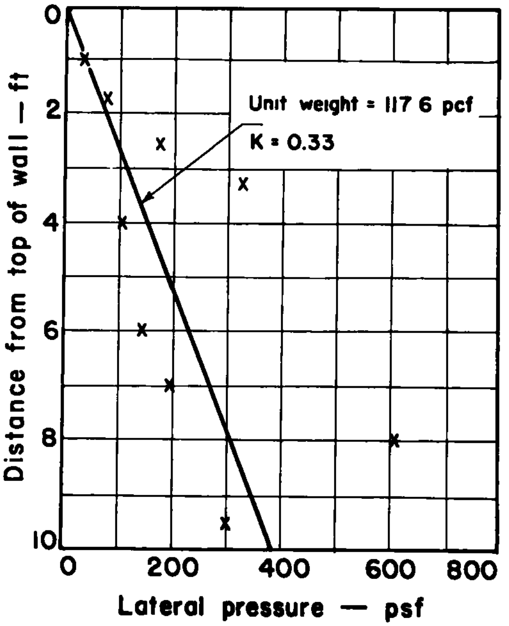

Figure 19. Lateral soil pressures caused by backfill only. Backfill number three after removal of second surcharge.

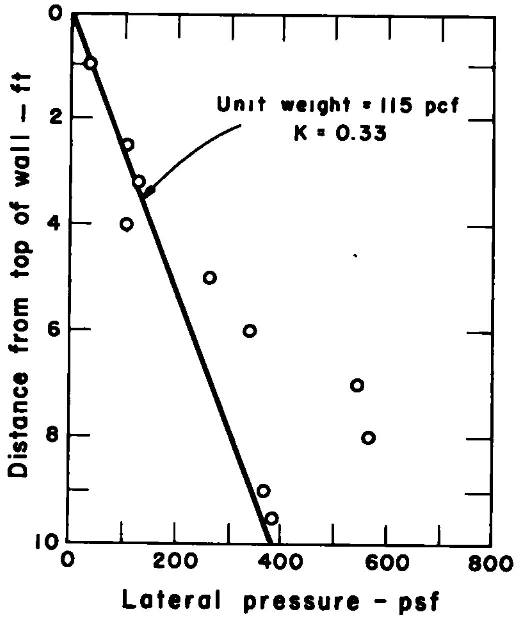

Figure 20. Lateral soil pressures caused by backfill only. Backfill number four before surcharging.

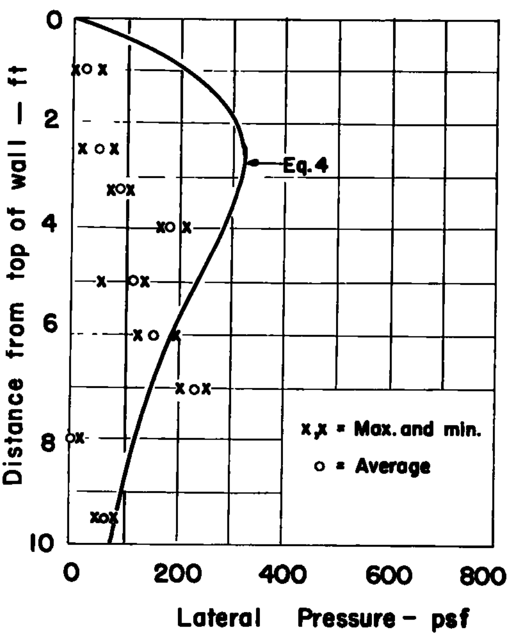

Figure 21. Lateral pressures caused by surcharge only, backfill number one. Surcharge number one, 938 psf at 3 feet clear distance from wall.

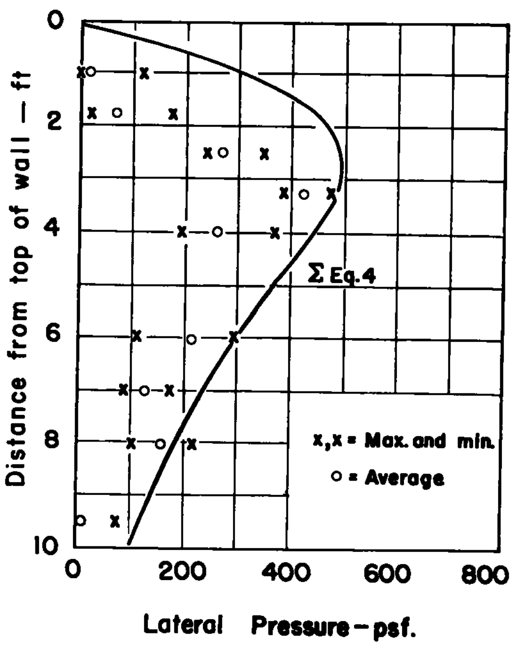

Figure 22. Lateral pressures caused by surcharge only, backfill number four. Surcharge number two, 1,448 psf at 2 feet clear distance from wall.

A total of eight surcharge loads have been placed; one each on backfills 1 and 2, and three each on backfills 3 and 4. The center of the surcharge area was placed opposite the center of the wall in each case. The magnitude and position of each surcharge are shown in Table 3.

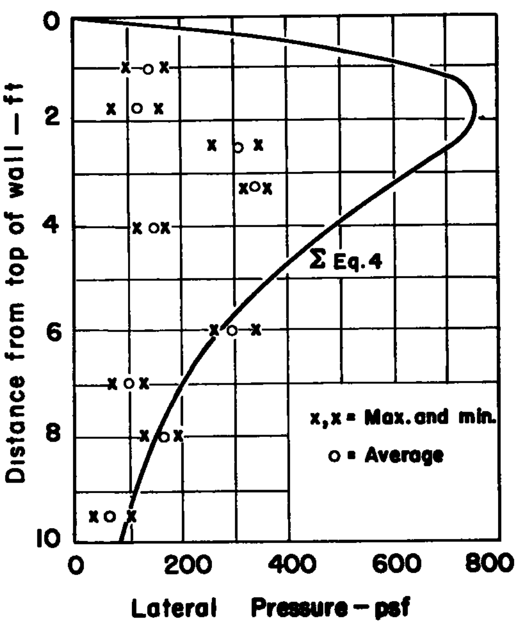

Figure 23. Lateral pressures caused by surcharge only, backfill number three. Surcharge number two, 1,448 psf at 3 feet clear distance from wall.

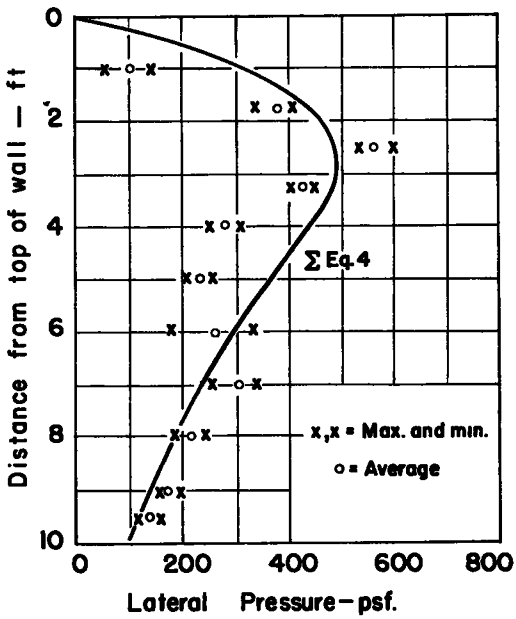

Figure 24. Lateral pressures caused by surcharge only, backfill number three. Surcharge number three, 1,448 psf at 1 foot 6 inches clear distance from wall.

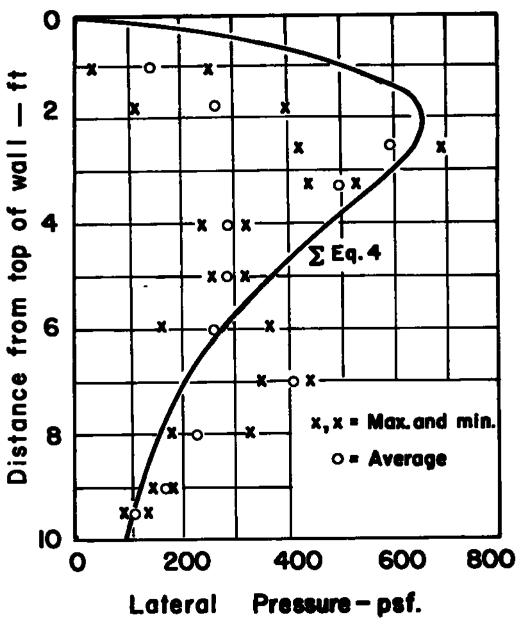

Figure 25. Lateral pressures caused by surcharge only, backfill number four. Surcharge number three, 1,448 psf at 3 feet clear distance from wall.

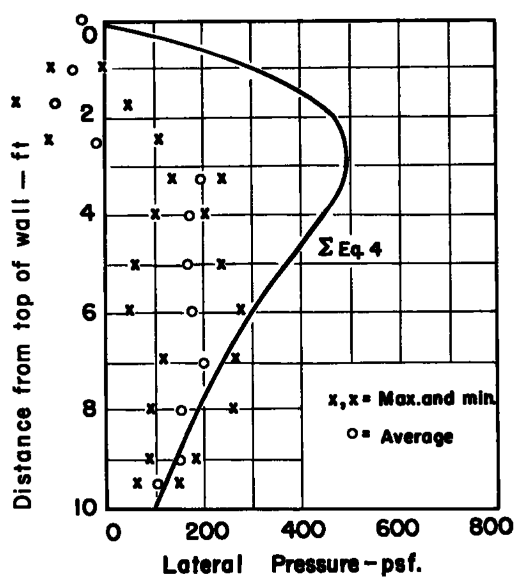

Figure 26. Lateral pressures caused by surcharge only, backfill number four. Surcharge number one, 1,448 psf at 3 feet clear distance from wall.

The procedure employed in interpreting the data has been to measure the pressures due to backfill only. Then a surcharge was applied and the total pressure observed. The difference between the total pressure and that due to backfill only was deemed to be the increment of pressure caused by the surcharge load. This procedure is logical, but has been fraught with difficulties and uncertainties because of wide fluctuations in the pressure cell readings with no apparent change in loading conditions. Temperature changes, rainfall, periods of dry weather all seemed to effect the cell readings, but no logical or consistent relationship between these phenomena and the cell readings could be identified.

In those cases where more than one surcharge was placed on the same backfill, the pressure on the wall due to backfill alone was frequently greater after removal of a surcharge than it was prior to loading. In other words, there were residual pressures against the wall after removal of the first surcharge. The initial backfill pressure readings prior to application of any surcharge has been subtracted from the total pressure readings in order to obtain the net increment of pressure due to surcharge alone.

The results of the current series of pressure measurements are summarized in Figures 16 to 26. Pressures due to backfill alone are shown in Figures 16 to 20 and pressure increments due to surcharge are shown in Figures 21 to 26.

The data points representing the measured pressures are widely scattered and fall far short of accurate coincidence with the curves representing the modified Boussinesq formula for lateral pressures due to surcharge loads. Nevertheless, the general statistical trend of the measured pressures, both as to magnitude and distribution, appears to be compatible with the theory and the authors believe that the modified formulas, Equations 1 to 5, are appropriate for estimating lateral pressures on retaining walls caused by concentrated loads, line loads, and area loads respectively.

In the early phases of this research program, it was assumed that the scattering of lateral pressure data was primarily due to shortcomings of the pressure measuring devices or the technique of their use. After long and extensive experience with a rather wide variety of pressure cells, the authors are convinced that a substantial part of the dispersion of data is not necessarily due to lack of precision of the measuring devices, but rather, is inherent in the problem itself. A soil backfill, even though reasonably homogeneous as a soil, is far removed from a homogeneous material as that term is used in the science of mechanics. Therefore, it is probably futile to expect that stresses transmitted through the soil to a retaining wall should consistently conform to a well defined theoretical pattern. It seems very probable that local variations in density and other properties of the soil will cause deflection and discontinuity of stress lines which may account for a substantial part of the dispersion which has been observed. This statement is not to imply that there is no need for further improvement in pressure cells and the technique of their use. Rather it is to say that the nature of the problem of measuring pressures on retaining walls is such that wide dispersion of measured data is a characteristic with which the researcher must contend.

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Discussion

EDWARD S. BARBER, Civil Engineer, Arlington, Virginia — The excellent data of this paper substantiate the use of theory of linear elasticity for calculating lateral pressures on walls, due to live loads. The charts presented herewith facilitate such calculations.

Figures A, B, and C give lateral pressures in a semi-infinite mass and must be doubled to give pressures on a rigid wall. The formulas presented in the paper are higher by the ratio of $\pi \div 3$. Figure A gives pressures from an infinite strip load parallel to the wall and of variable pressure perpendicular to the wall. Figure B gives

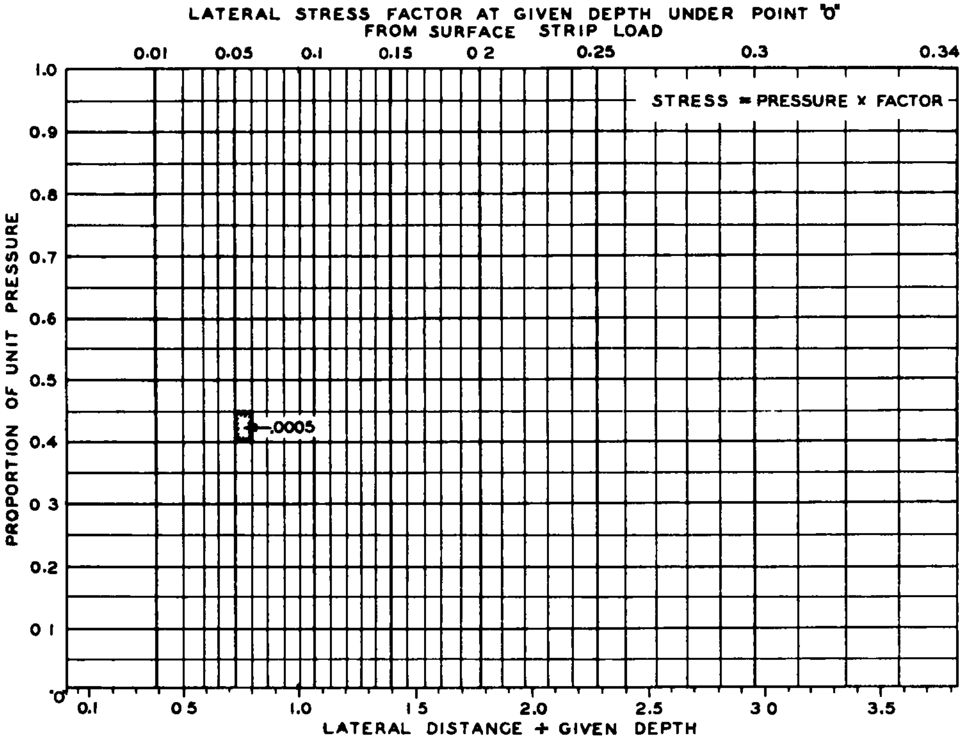

Figure A. Chart for computing lateral stress at any point from surface strip load.

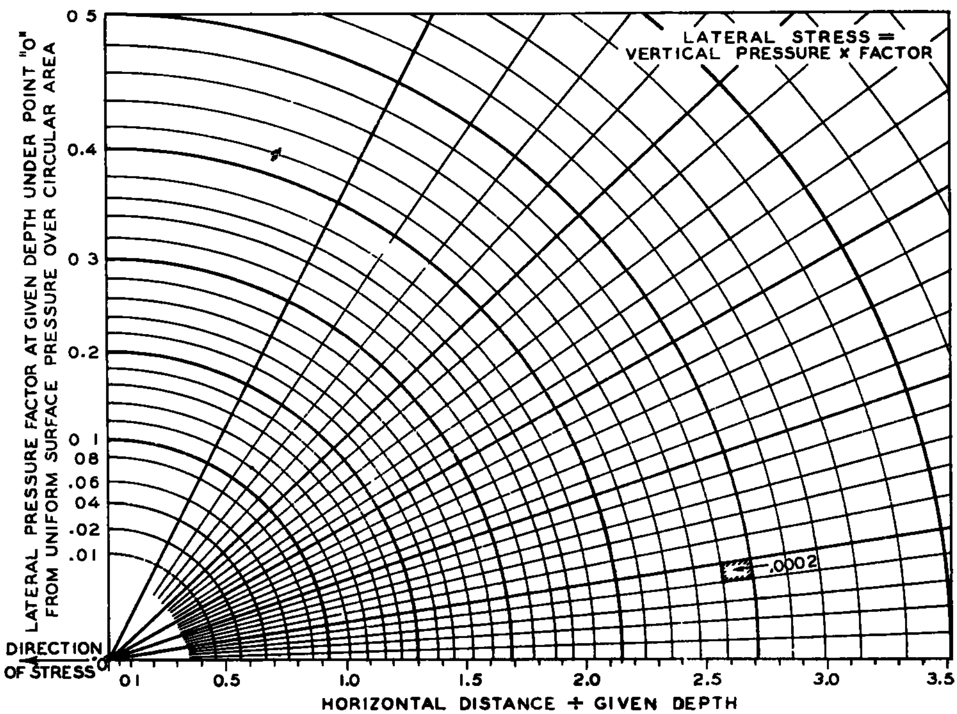

Figure B. Chart for computing lateral pressure at any point from finite surface load - Poisson's ratio = 0.5.

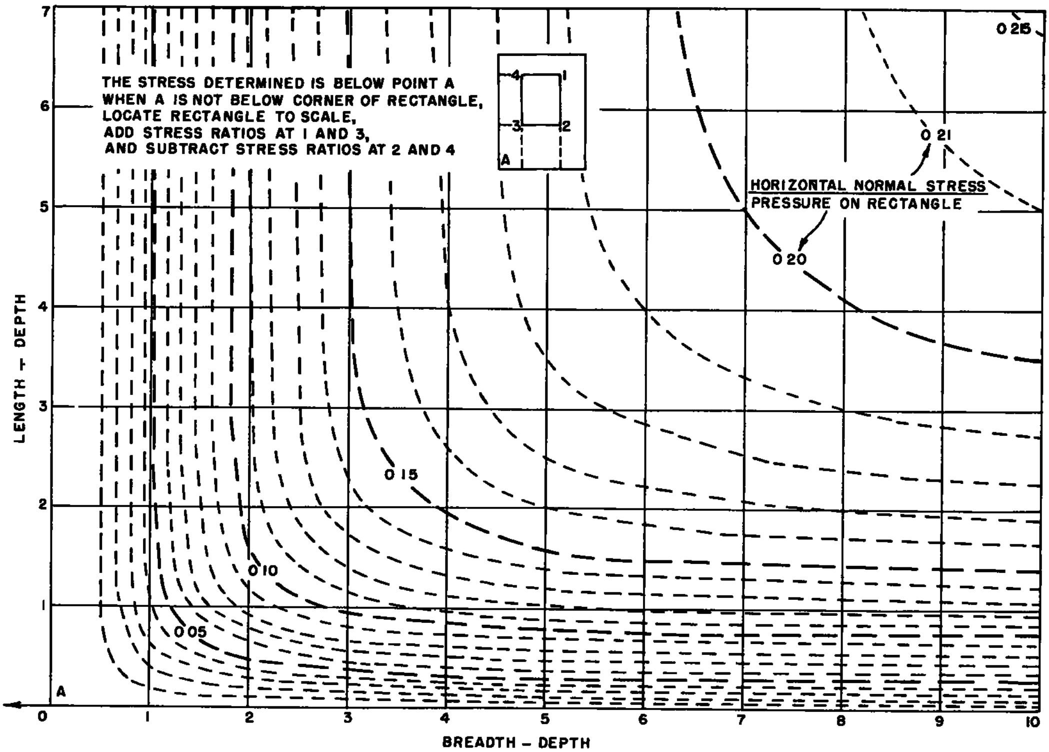

Figure C. Graph of horizontal normal stress under corner of rectangle loaded with unit pressure.

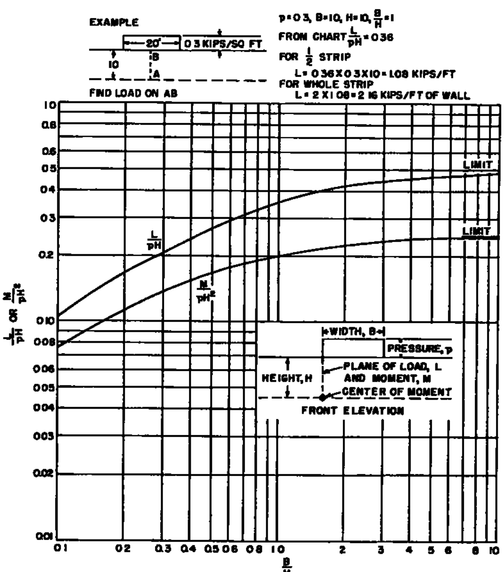

Figure D. Lateral load and moment on smooth boundary due to parallel uniform strip of infinite length.

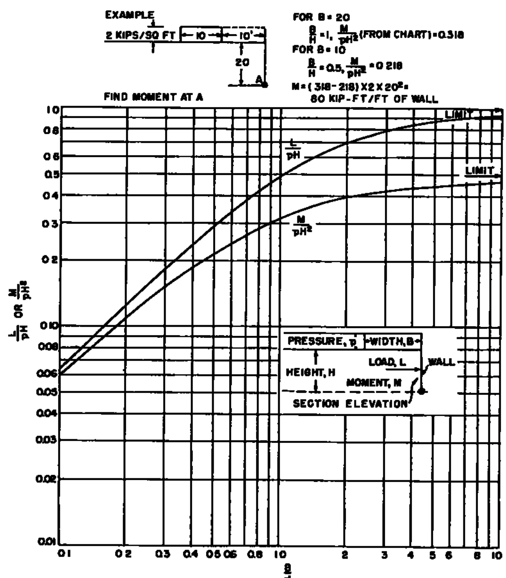

Figure E. Lateral load and moment on smooth rigid boundary due to perpendicular uniform strip load of infinite length.

lateral pressures from a uniform pressure over an area of any shape. The influence factor is 0.0002 x the number of influence areas covered by a plan of the loaded area plotted according to the scale given on the abscissa. Figure C gives the lateral pressure directly for uniform stress over a rectangular area with one side parallel to the wall.

Figures D and E give total stresses from strip loads on a vertical strip of unit width on a rigid wall and the moment of this total stress. The stress in a semi-infinite mass has already been doubled. In Figure D the strip load is parallel to the wall, while in Figure E the strip load is perpendicular to the wall, as for a highway going over an abutment.