THE MEASUREMENT OF EARTH PRESSURE ON RETAINING WALLS

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The numerous theories for the determination of the lateral pressure of earth on retaining walls which have been developed[1] rather clearly indicated the lack of an adequate foundation of facts upon which rational theory must be based

It is not the purpose of this paper to discuss the theory of earth pressures, but rather to describe a particular method of measuring pressures which has been used with some success, both in this country and in many foreign countries The method referred to employs the soil pressure cell which, in the course of time, has become known as the Goldbeck cell

HISTORY OF THE DEVELOPMENT OF THE SOIL PRESSURE CELL

In 1913 the late Logan Waller Page, then Director of the Office of Public Roads and Rural Engineering brought to the writer's attention the desirability of studying the distribution of pressures through earth fills due to concentrated loads This problem was made the subject of immediate study by the writer, then Engineer of Tests, and by Mr E B Smith, Assistant Engineer of Tests, in the Testing Division of the Office of Public Roads and Rural Engineering then under the immediate supervision of Mr Prevost Hubbard We were familiar with the work of E P Goodrich who employed a weighing disk in contact with the earth He weighed the earth pressure by mechanical means and employed electrical contact to determine when to take the pressure reading Based on this same principle, Mr Smith designed a weighing disk resting on a system of weighing levers and likewise employing electrical contact This method offered possibilities, but at the same time its use was limited because of the necessity for weighing the load mechanically

It occurred to the writer that if the principle of the Emery cell which had been employed so successfully in the Emery testing machine could be used together with air pressure for equilibrating the soil pressure and electrical contact for determining when to weigh the load, a soil pressure measuring device could thus be built which could be used in inaccessible places A number of rather crude soil pressure cells were made up and discarded but finally through the continued effort of the writer, Mr Smith and others in the Testing Division, a soil pressure cell was devised which gave promise of being satisfactory

PRINCIPLE OF OPERATION OF SOIL PRESSURE CELL

Any device, to measure successfully the internal pressure of earth, must be so designed that its operation will not change the earth pressure Obviously, if the weighing area of the soil pressure measuring device is moved against the earth, greater pressure will be exerted upon the weighing area than existed originally and vice versa, lesser pressure will be exerted if the weighing area is moved away from the earth It is evident, therefore, that the ideal soil pressure measuring device would be one in which the pressure might be weighed with no motion whatever of the weighing area during the weighing operation This is extremely difficult to accomplish and it is not entirely accomplished in the so-called Goldbeck cell It, however, is very nearly accomplished and the

[1] Jacob Feld, "History of the Development of Lateral Earth Pressure Theories," *Proceedings* Brooklyn Engineers' Club, Jan 1928

accuracy of the device depends, in large measure upon the extremely small motion of the weighing disk which is required to break electrical contact during the measurement of pressure

To understand fully the operation of the soil pressure cell as used in measuring pressures, it will be well to refer to a cross-section of the cell (See Fig 1) This should be studied in combination with Figure 2 which shows the control and indicating apparatus for determining soil pressure Referring to Figure 1, it will be seen that the soil pressure cell is in cylindrical form and is about as big as a saucer A brass diaphragm, only 0 002 in thick and having about the same flexibility as a sheet of writing paper is clamped between the disks A and B and is held down to the base C by means of the holding ring D There is thus formed an air-tight sack The lower disk, B, rests upon a bronze disk E having a very flat polished spherical top There is thus a point of contact between the centers of disks B and E Disk E is cemented to the base by means of bakilite cement which serves also as an electrical insulator

The annular space formed between the upper weighing disk A and the holding down ring, D, must be protected from the possibility of becoming clogged with earth and therefore the entire upper face of the cell is covered with a thin brass diaphragm such as used within the instrument and finally to protect this diaphragm from becoming punctured, it is coated with cheese cloth cemented with blown oil asphalt Blown

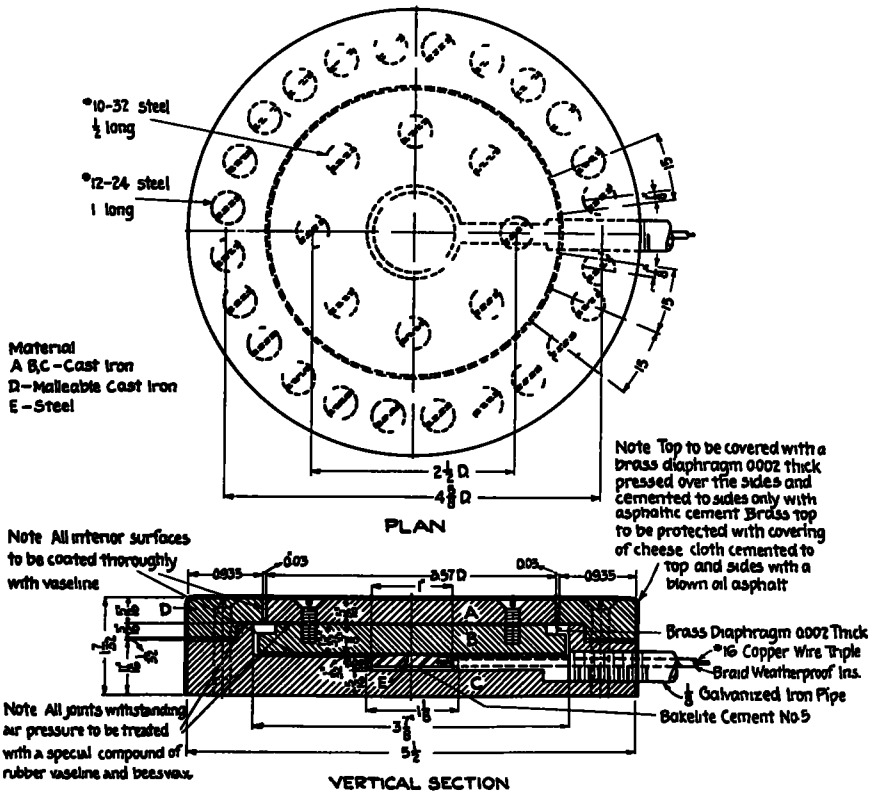

Figure 1 Diaphragm Cell for Determining Soil Pressure

oil asphalt was chosen because of its very low susceptibility to changes in viscosity due to temperature changes.

It is necessary to place the soil pressure cell in position before the earth fill is made and it is so placed that the weighing disk A comes in contact with the earth whose pressure is desired. If earth pressures in different positions against a retaining wall are desired, the soil pressure cells would have to be attached to the wall in those positions. From each cell an air pipe is led and within that pipe there is run an insulated electrical conductor leading to the central disk E.

It is obvious that the total earth pressure on the weighing face of disk A is supported as a concentrated load at the point of contact between disk E and disk B. The air pipe is led to a convenient position and is attached through proper connections to a small tank containing compressed air and having a sensitive pressure measuring gage in circuit. The electrical conductor is also led to a convenient position and is attached to a dry cell in circuit with an ammeter or a small electric light. The air pipe itself is the return conductor and a closed circuit is formed which will allow electrical current to flow as long as there is contact between disks B and E.

To obtain the soil pressure acting on disk A, air is allowed to escape very slowly from the compressed air tank into the soil pressure cell and the ammeter, or electric light in the electrical circuit is watched very intently. At the instant the ammeter, or electric light, shows that the circuit is broken, the air pressure is read and at that same instant is again relieved so that the light again glows and a reading is obtained during the re-making as well as during the breaking of contact. The air pressure read at these instants indicates the soil pressure which is acting on the disk at those same instants. The earth pressure, which prior to taking reading was equilibrated by a concentrated reaction between disks D and E, is, at the moment of breaking contact, equilibrated by a uniformly distributed air pressure which is exactly equal to the soil pressure.

As has been previously pointed out, any disturbance of the soil due to motion of the weighing instrument disturbs the pressure and gives results which are not entirely accurate. This point was fully realized in the development of the soil pressure cell and one of the first investigations made was to determine the degree of inaccuracy of the instrument. It will be appreciated that under the action of the soil pressure acting upon disk A and the concentrated load reaction at the bottom of that disk, there must be slight elastic bending downward of the disk. This bending theoretically is reduced to zero at the time of breaking of electrical contact because instead of a concentrated load at the bottom of the disk, there is then a uniformly distributed load. However, this bending is probably almost negligible. There is an additional elastic deformation which must be taken into account, namely, the elastic deformation of the entire instrument, most of which probably takes place at the point of contact between the spherical seat and the flat surface of disk D. These elastic motions add to the motion of the disk required to break electrical contact. In addition to the elastic recovery effect, there must be very slight motion required to create a gap sufficient to actually break electrical contact. It thus becomes pertinent to inquire: What increase in the unit load is required to produce deformations in the soil equivalent to those necessary to break electrical contact in the soil pressure cell?

In Table 1 are shown the results of tests made to obtain simultaneous readings of unit load and indentation of a

bearing block into the soil. In these experiments dry quartz sand was placed in a 6-in. cylinder, 6 in. deep and a circular bearing block of the same diameter as that used in the weighing face of the soil pressure cell was placed on top of the sand and loads were applied by the use of a testing machine. Movements of the bearing block were measured by a 0.0001 Ames dial. It will be noted that when the sand was tamped in the cylinder, greater increases in load were required for given motions than for the sand loosely placed in the cylinder. Accordingly, when the soil is stiff and rigid, the amount of motion required to break electrical contact in the soil pressure cell corresponds to a greater error in reading than would be the case in a softer material, but, even so, the percentage of error is not great. Thus, the indications are that when a load of 44 lb. per sq. in. was initially applied to the bearing block, a load of 45.4 lb. per sq. in. was required to produce an additional indentation of 0.0001 in. On the other hand, under smaller loads, for instance, 3.4 lb. per sq. in., an increase of 0.4 lb. per sq. in. was required to indent the bearing block into the sand as much as 0.0001 in.

TABLE 1
DEFORMATION OF MOIST SILICA SAND PRODUCED BY INCREASE IN LOAD

Cylinder Loosely Filled		Sand Tamped in Cylinder	
Unit Load, lb. per sq. in.	Deformation, in.	Unit Load, lb. per sq. in.	Deformation, in.
5.0	. . . .	3.4	.....
5.2	0.00007	3.8	0.00010
5.4	0.00015	4.0	0.00016
5.6	0.00019	4.4	0.00023
5.8	0.00024		
9.4	.....	14.2	... ...
9.6	0.00009	14.6	0.00004
9.8	0.00017	15.0	0.00007
10.0	0.00030	15.4	0.00022
20.0	.. ....	26.7	.....
20.2	0.00010	27.2	0.00002
20.4	0.00028	27.6	0.00007
		28.4	0.00015
28.0	.. ....	44.0	.....
28.2	0.00010	44.6	0.00005
28.4	0.00020	45.4	0.00010
47.0	.... .	45.8	0.00022
48.0	0.00010	46.6	0.00035

Experiments such as these do not show definitely what the percentage of error in the instrument is, because they do not show the amount of deformation which takes place during the breaking of electrical contact. Accordingly, additional efforts were made to determine the error in another manner as illustrated in Figure 3. A soil pressure cell was placed on a bearing block having ten square inches which in turn was placed on top of soil which had been tamped in a box 22 in. square by 10 in. deep. This box rested on a platform

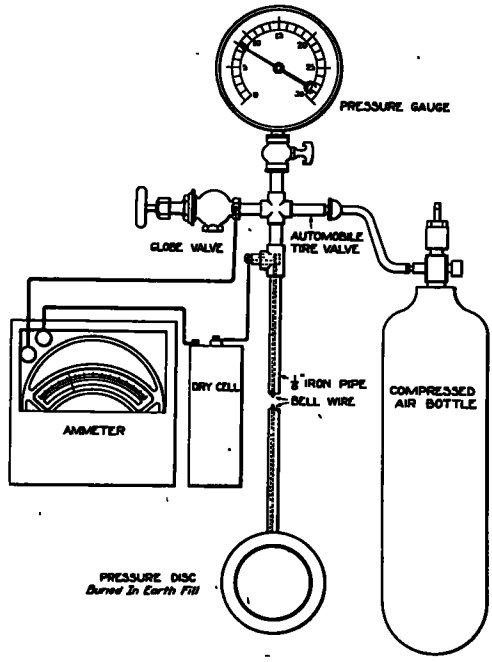

Figure 2. Apparatus for Determining Soil Pressure

scale. Load was then applied to the soil pressure cell by means of weights resting on an I-beam as shown in the illustration. By the use of a screw jack any load desired could be applied and could be weighed on the platform scale. This load was then measured by means of a soil pressure cell and simultaneously by the use of the platform scale. The results are shown in Table 2.

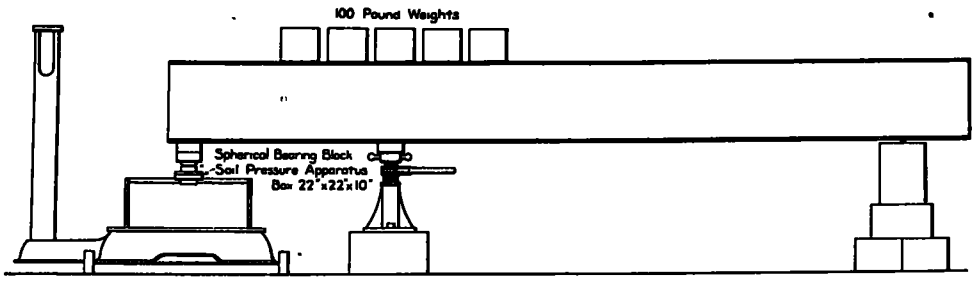

Figure 3. Sketch Showing Method of Calibration of Soil Pressure Apparatus

TABLE 2

RESULTS OF TESTS FOR ERROR OF INSTRUMENT

Initial Load on Disk, lb. per sq. in.	Load on Disk at Breaking of Contact, lb. per sq. in.	Load Indicated by Mercury Gage, lb. per sq. in.	Error, lb. per sq. in.	Error, %	Material
10.0	10.0	10.2	0.2	2	Damp sand, clay
15.0	15.0	15.6	0.6	4	Damp sand, clay
20.0	20.0	21.0	1.0	4.8	Damp sand, clay
5.3	5.3	4.7	0.5	−11.0	Dry sand
8.3	8.3	7.8	0.5	6.5	Dry sand
11.0	11.0	11.2	0.2	1.8	Dry sand
13.8	13 8	14.0	0.2	1.4	Dry sand

In general, the soil pressure cell indicated loads somewhat higher than those registered on the platform scale. The soil pressure cell used in this original calibration was of very crude design and was by no means as sensitive as the design shown in Figure 1. This method of calibration of course has the disadvantage that the soil pressure cell is not embedded in the earth as it would be in actual service and, consequently, there is some doubt as to whether the movement required to break electrical contact would be the same under these conditions as under actual conditions. The question of how to determine the error in the cell was one which was not easy to answer. It is a very simple matter to apply hydrostatic pressure to the outside of the cell and obtain readings under these conditions. It is not difficult to make soil pressure cells which invariably will give true indications of hydrostatic pressure. But even though a soil pressure cell may weigh hydrostatic pressure or dead load very accurately, there still remains the problem of determining how accurately it weighs soil pressures.

Some five years after the soil pressure cell was designed a method was devised for indicating the possible error in the cell when making a reading under actual conditions. The method used is shown in Figure 4. A standard soil pressure cell was altered to the extent of having the air pipe lead in from the bottom of the cell rather than from the side. Into this pipe was inserted a thin brass rod having an ivory tip. This tip rested in contact with the underside of the movable disk in the cell and the lower part of the rod rested on an Ames

dial which was attached rigidly to the air pipe leading to the cell. The lower end of the air pipe terminated in an air-tight glass jar. By means of this device it was possible to apply air pressure of any desired magnitude in the cell and at the same time read the movement of the weighing disk with the 0.0001 Ames dial.

The pressure cell thus arranged was mounted in a recess in a heavy reinforced concrete floor and damp sand was then tamped on this floor to a depth of 30 inches over the cell. Finally, different loads were applied on a bearing block placed on top of the damp sand and in this way pressures of different intensities reached the soil pressure cell, depending upon the load applied to the bearing block at the top of the earth fill.

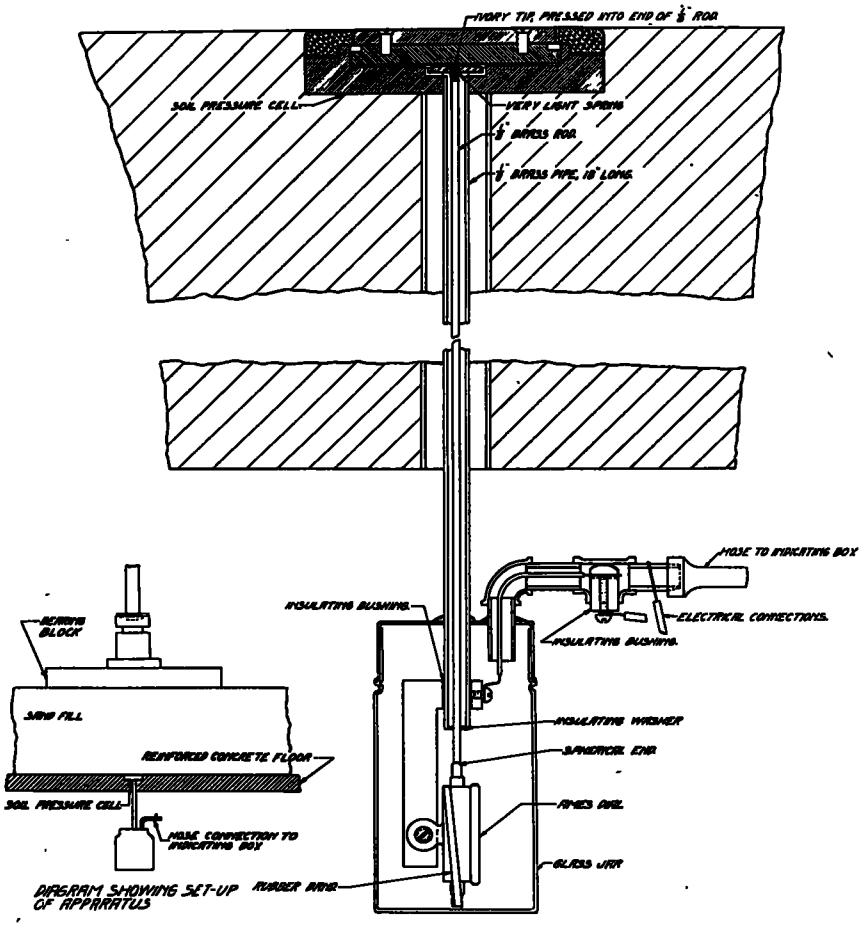

Figure 4. Apparatus for Measuring Error in Soil Pressure Cells Due to Small Movement Required to Break Electrical Contact

The procedure in making this test for the accuracy of the cell was to apply a load on the bearing block, obtain a reading on the Ames dial at zero air pressure and then gradually allow the air pressure to build up in the cell. At the instant of breaking of electrical

contact the Ames dial was again read and the air pressure was allowed to continue to build up within the cell, thus forcing the weighing disk out against the earth fill. Simultaneous readings of air pressure and movement of the disk were made. In this way, not only was it possible to determine the amount of movement of the weighing disk required to break electrical contact, but

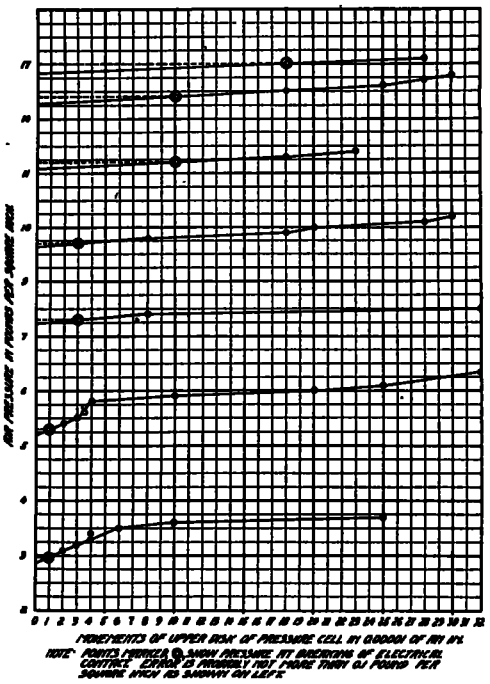

Figure 5. Curves Showing Movement of Upper Disk of Soil Pressure Cell after Breaking Electrical Contact. 30-in. moist sand fill.

simultaneously it was possible to determine what loads were being applied for different deformations of the earth as the disk moved upward under air pressure. The curve shown in Figure 5 resulted from this investigation and the points showing the pressures and movements at the times of breaking electrical contact are indicated by the large circles. The other points on the curves show simultaneous readings of air pressure and movement of the weighing disk.

It will be noted that when the load on the cell is small, the movement required to break electrical contact is small and that the movement required for breaking contact increases as the load on the cell increases. The movements required to break electrical contact for the different air pressures were as shown in Table 3.

It seems reasonable to believe that, if after breaking electrical contact the deformations continue at a given rate as shown by the pressure deformation curve, their rate will be the same prior to the breaking of contact. On this

TABLE 3

Air Pressure at Breaking of Electrical Contact	Movement of Weighing Disk at Breaking of Electrical Contact	Apparent Error, lb. per sq. in.	Percent Error
3.0	0.00001	0.10	+3.3
5.25	0.00001	0.10	+1.9
7.25	0.00003	0.05	+0.7
9.55	0.00003	0.05	+0.5
11.15	0.00010	0.15	+1.3
14.30	0.00010	0.10	+0.7
17.0	0.00018	0.15	+0.9

basis, it seems reasonable to extend the curve to the left of the point of electrical contact and where that curve intercepts the Y-axis, the original pressure on the soil pressure cell may be read and compared with the pressure required to break contact. In this manner, the apparent error in the instrument has been obtained as shown in the third column of Table 3. In the fourth column are shown the percentages of error. It will be noted that these percentages of error are quite small and there is a tendency for them to decrease with increasing loads. If, indeed, soil pressure cells could be relied upon to invariably give readings within the errors indicated in Table 3, they could be

accounted as an excellent device for their intended purpose.

THE USE OF SOIL PRESSURE CELLS IN TYPICAL CASES FOR MEASURING EARTH PRESSURES BACK OF RETAINING WALLS

Soil pressure cells have been used for measuring pressures under a great many different circumstances and in a great many different localities, sometimes with

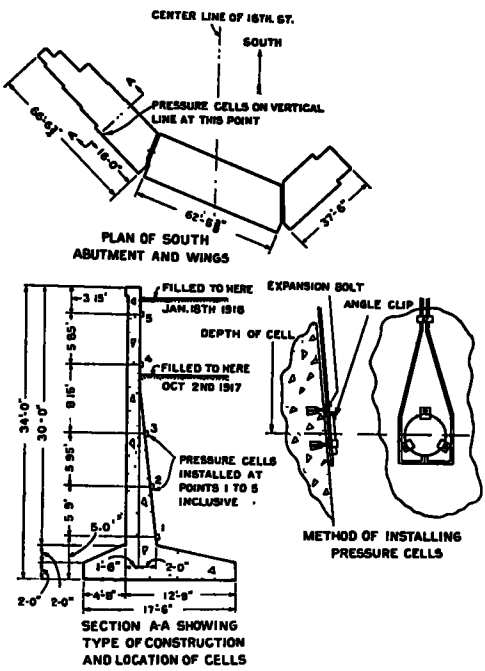

Figure 6. Position of Cells and Method of Attachment, Sixteenth Street Bridge

and unfortunately sometimes without a full appreciation of the manner in which they should be installed and the way in which they should be manipulated. Satisfactory readings have been obtained when the necessary precautions have been appreciated. It is proposed to describe a few typical installations and give a few typical results of pressure measurements on retaining walls.

Sixteenth Street Bridge Tests (Washington)

The Sixteenth Street Bridge in Washington, D. C., carries Sixteenth Street traffic over the Military Road. It is a reinforced concrete girder bridge with mass concrete abutments. The earth fill on Sixteenth Street was built to within some 30 ft. of the south abutment at

TABLE 4

Observation	Date	Pressure as Determined by Pressure Cells, lb. per sq. in.				
		No. 1	No. 2	No. 3	No. 4	No. 5
	1917					
1	Oct. 2	6.3	4.5	1.95	.....	....
2	Nov. 12	6.3	4.5	2.2	.....	.....
3	Dec. 4	6.3	4.2[1]	2.1	....	.....
	1918					
4	May 4	6.2	8.0	5.3	1.8[2]	[3]
5	May 9	6.6	8.4	5.7	1.6	0.2
6	May 14	[4]	8.5	5.7	1.8	0.2
7	June 17	5.4	8.4	5.0	1.4	0.1
8	June 28	5.5	8.4	4.8	1.4	0.7
9	Aug. 8	5.9	8.9	4.9	[5]	0.1
10	Oct. 11	5.8	8.5	4.8	1.7[6]	0.5
11	Dec. 20	6.65	5.15	9.15	[5, 6]	0.55
	1919					
12	Jan. 27	5.6	8.28	5.00	3.2[7]	0.15

[1] Air pressure ran to about 5 lb. per sq. in. before a short circuit was discovered.
[2] Cell No. 4 slightly clogged.
[3] Two feet broken off of wire pipe.
[4] Air pressure exceeded the earth pressure before a short circuit was discovered. Readings a few min. later showed only 1.5 lb. per sq. in. Cell should return to normal after fill readjusts itself.
[5] Wire pipe broken, pipe system partially clogged.
[6] Air pipe closed.
[7] Reading taken on wire pipe, pipe almost closed.

the time the soil pressure cells were installed in the Fall of 1917. The vertical position of the cells and their method of attachment is shown in Figure 6. It is important to notice the close proximity of cell No. 1 to the sloping upper face of the concrete footing. The earth filling which consisted of a rather dense clay-sand-gravel was

compacted against the abutment in horizontal layers perhaps from 1 to 3 in. thick. The filling was started on August 9, 1917 and by October 2, 1917, it had been carried to a point 6.85 ft. above cell No. 3, when work was discontinued. Around January 1, 1918, the filling work was resumed and was completed by January 18, 1918.

It will be noted that the air pipes in the soil pressure cells were brought off to one side and carried to the surface of the slope near one of the wing walls. The pressure observations on the various cells at different dates are given in Table 4 and these results are plotted on Figure 7. There are some results which seem to be erratic, especially those on cells No. 2 and No. 3 taken on December 20. It almost looks as if these readings are reversed. Except for these particular results, however, the remaining readings are quite consistent. Attention is directed to the reading on cell No. 1 which did not increase, in fact actually decreased after the filling was resumed. This cell was located just above the sloping top portion of the footing and as settlement took place it is not impossible that the pressure on this cell was relieved or at least not increased because of the wedge of concrete upon which the fill rested just below the cell.

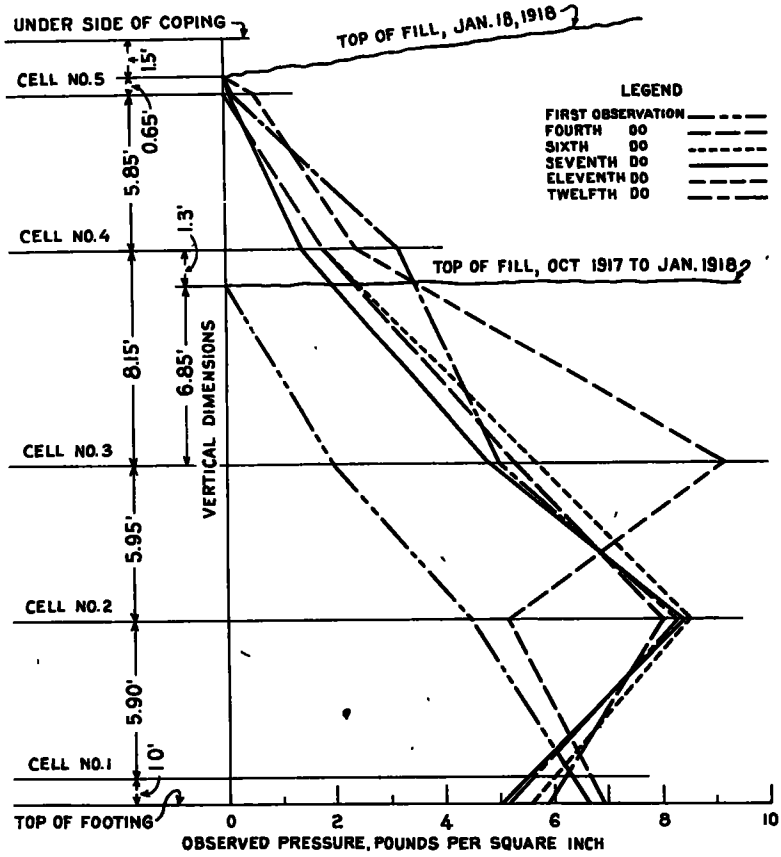

Figure 7. Pressure Observations, Sixteenth Street Bridge

Quoting from a description of this test

by J. V. McNary in *Public Roads*, July 1925:

"Although on good foundation material and of a cross-section that should satisfactorily support the ordinarily assumed loads, the wall has moved outward at the top about two inches, thus confirming the presence of the unusually high pressures shown by the pressure cells.

"The filling material was of a clayey nature and the initial observation was undoubtedly affected by the thoroughness of the mechanical compacting while it was being placed. Continued high pressure, however, is most probably due to a high moisture content. As previously stated the wall is so situated that it intercepts both ground water flow and surface drainage and is not provided with any means of drainage. The joint between the wing wall and the abutment wall discharges seepage throughout its entire height showing that the fill becomes saturated to the top. Comparison with the Weather Bureau records shows that the higher pressures were observed after a period of several days precipitation and the lowest pressure at the end of a period of no precipitation. The highest pressure, shown by observation No. 11, was noted six days after a precipitation of 2.87 inches in the form of snow on unfrozen ground with the temperature above freezing each day."

It seems reasonable to assume that the pressure varied practically as the ordinates to a straight line extending from 0 at the top to a maximum at the bottom and the slope of the pressure curve is such that these pressures would be created by an equivalent liquid weighing 48.4 lb. per cu. ft. This seems like a high pressure, but it is important to keep the method of compacting the fill against the abutment in mind. Fortunately, we have a contrasting experiment in which the fill was placed in a different manner.

Bennings Bridge Test

This test was conducted on a bridge at Bennings, Washington, D. C. The approach consists of an earth fill restrained by retaining walls of cellular construction. Soil pressure cells were fastened to the inner face of one of these walls prior to the placing of the fill. In Figure 8 are shown some of the cells attached to the retaining wall; in Figure 9 is shown

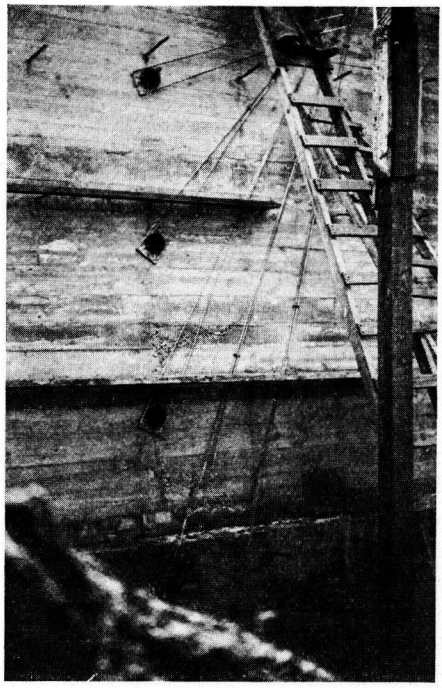

Figure 8. Cells Attached to Retaining Wall, Bennings Road Bridge, Washington, D. C.

Figure 9. Method of Placing Fill, Bennings Road Bridge

the method of placing the fill; and in Figure 10 is shown the loose condition of the fill after placing.

Cell readings were taken after the fill had been completed, the pressures ob-

tained having essentially a straight line distribution from zero at the top to a maximum at the bottom and equivalent to pressure of a fluid weighing 33.4 lb. per cu. ft., as contrasted with 48.4 lb. in the case of the Sixteenth Street Bridge. It seems reasonable to believe that this lesser pressure in the case of the Bennings Bridge was due largely to the loose filling method used as contrasted with the hard tamping given to the fill in the Sixteenth Street Bridge. A familiar analogy as between these two methods of filling is that of concrete which is dry and tamped in place as compared with concrete which is merely poured in place. Bulging of the forms

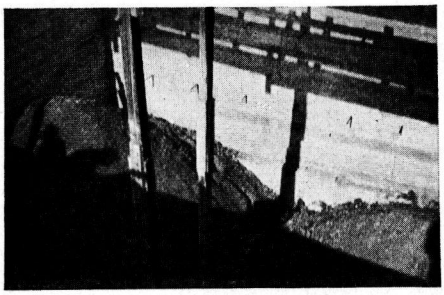

Figure 10. Loose Condition of Fill after Placing, Bennings Road Bridge

may result in the first case and not in the second.

Skellit Fork Bridge (Illinois)

Still another investigation for pressures back of a bridge abutment was made on the Skellit Fork Bridge over Skellit Fork, Illinois. These tests were made by the Bureau of Public Roads in cooperation with the Illinois Department of Highways. The approaches to the bridge abutment consist of earth fills raised a few feet above high water. The flood plain upon which the fills are built is subject to inundation practically every Spring. The abutment is of reinforced concrete, U-type, 32 ft. $3\frac{1}{4}$ in. from the top of the footing to the grade line and 24 ft. wide. The fill was constructed according to standard Illinois practice at the time which consisted of compacting in layers 12 in. thick.

The abutment is said to have been designed for a fluid pressure of 21 lb. per cu. ft. and the fact that similar abutments had shown signs of distress led to this experiment. The locations of the soil pressure cells are shown in Figure 11. The cells were embedded in the concrete so that the weighing face of the cell was flush with the back face of the abutment. In Figure 12 is shown the manner of installing the cells. The observations are given in Table 5 and

TABLE 5

OBSERVATIONS OF PRESSURES IN SKELLIT FORK BRIDGE ABUTMENT

Observation	Weight of Equivalent Fluid, lb. per cu. ft.
1	23.2
2	44.1
3	40.5
4	34.7
5	29.8
6	38.0

the average of cells located at the same elevation is shown in Figure 13.

Several points of interest should be noted in connection with these readings as follows:

1. They increase somewhat irregularly, depending upon the depth of the fill.

2. The proximity of the weep holes in the abutment seems to have the effect of decreasing the pressures in that vicinity.

3. Pressures increased in the Spring of the year when the fill was wet and decreased later on in the Summer as the fill dried out. A straight line of pressures averaging those obtained by the use of the cells at different levels is shown in Figure 14, curve No. 13, corresponding to pressures taken with low

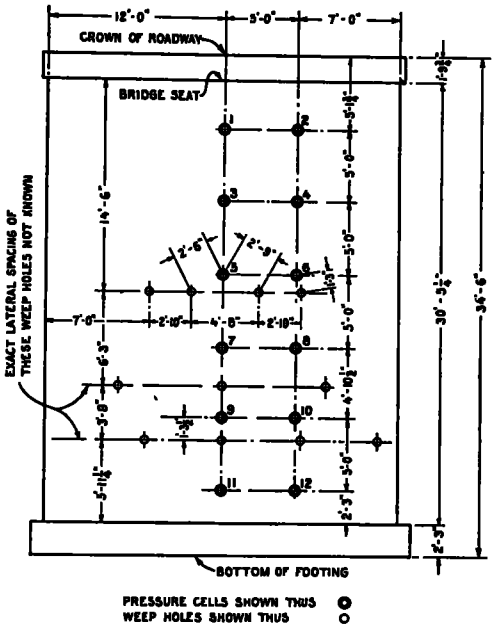

Figure 11. Locations of Cells, Skellit Fork Bridge, Illinois

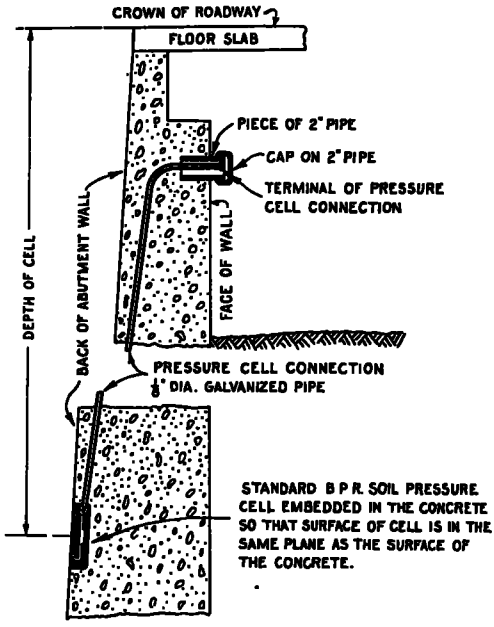

Figure 12. Manner of Installing Cells, Skellit Fork Bridge

moisture content in the filling material and no rain between time of filling and date of reading. This corresponds to a fluid weighing 23.2 lb. per cu. ft.

The second set of readings taken in April gave pressures which closely correspond to those which would be created by fluid weighing 41. lb. per cu. ft., some 80 per cent higher than those obtained under dry weather conditions. In Figure 14 a comparison of pressures is made between soil pressures as actu-

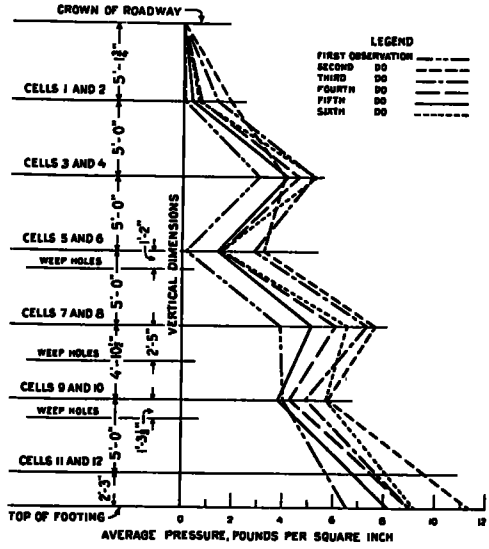

Figure 13. Observations, Skellit Fork Bridge

ally measured in different installations and the pressure given by calculation.

OTHER PRACTICAL USES FOR THE SOIL PRESSURE CELL

The soil pressure cells have been used in a practical way in a number of different kinds of structures. Thus, they have been employed for determining the pressure distribution under concrete road slabs. (See Public Roads, July, 1925.) In this connection it is important to note that the warping of the slab and even the passage of traffic very greatly affects the pressures. By no

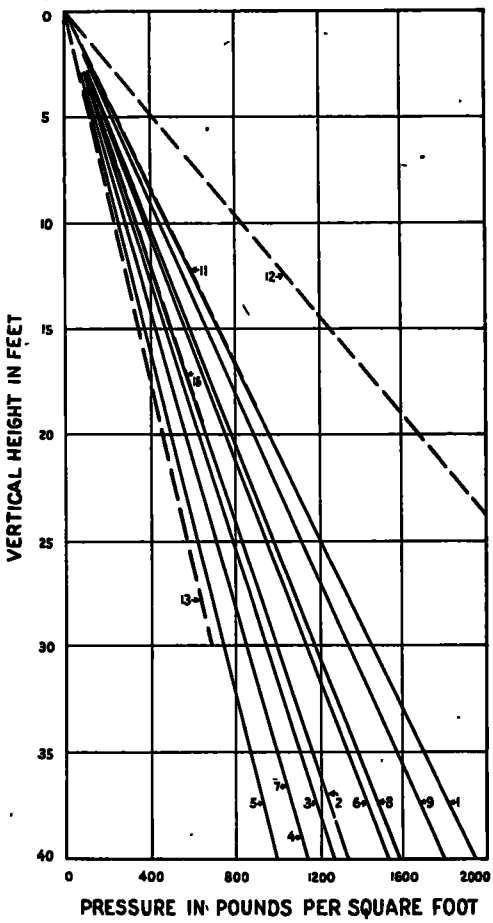

Figure 14. Pressures Determined by Rankine's Formula for Different Kinds and Conditions of Filling Compared with Pressures Determined by Bureau of Public Roads Soil Pressure Cells. Results from Rankines formula shown by solid lines and dash lines show experimental results.

(1) Worst case of "ordinary earth, wet; weight per cu. ft., 120 lb.; angle of repose, 25°." Equivalent to fluid weighing 48.7 lb. per cu. ft. Hool and Johnson, Concrete Engineers Hand Book.

(2) Most favorable case of "ordinary earth, wet; weight per cu. ft., 100 lb.; angle of repose, 30°." Equivalent to fluid weighing 33⅓ lb. per cu. ft. Hool and Johnson Concrete Engineers Hand Book.

(3) Retaining wall fill, weighing 100 lb. per cu. ft.; angle of repose, 30°. Equivalent to fluid weighing 33⅓ lb. per cu. ft. Author gives C = 16. Equivalent to fluid weighing 32 lb. per cu. ft. Paaswell.

(4) Customary assumptions; fill weighing 100 lb. per cu. ft.; angle of repose, 33°40′. Equivalent to fluid weighing 28.7 lb. per cu. ft.

(5) "Dry earth; weight per cu. ft., 100 lb.; angle of repose, 36°53′." Equivalent to fluid weighing 25 lb. per cu. ft. American Civil Engineers Pocket Book.

(6) "Mud; weight per cu. ft., 100 lb.; angle of repose, 26°34′." Equivalent to fluid weighing 38.2 lb. per cu. ft. American Civil Engineers Pocket Book.

(7) "Sand, gravel, and clay; wet; weight per cu. ft., 115 lb.; angle of repose, 36°53′." Equivalent to fluid weighing 28.7 lb. per cu. ft. American Civil Engineers Pocket Book.

(8) "Soil dumped into water; weight per cu. ft., 70 lb.; angle of repose, 15°57′." Equivalent to fluid weighing 39.5 lb. per cu. ft. American Civil Engineers Pocket Book.

(9) "Clay dumped into water; weight per cu. ft., 80 lb.; angle of repose, 15°57′." Equivalent to fluid weighing 45 lb. per cu. ft. American Civil Engineers Pocket Book.

(10) Bureau of Public Roads tests, Benning Road Bridge, D. C. Equivalent to fluid weighing 33.4 lb. per cu. ft.

(11) Bureau of Public Roads tests. Sixteenth Street Bridge, D. C. Equivalent to fluid weighing 48.4 lb. per cu. ft.

(12) Bureau of Public Roads tests on hydraulic fill of clay. Equivalent to fluid weighing 84.5 lb. per cu. ft.

(13) Bureau of Public Roads tests, Skellit Fork Bridge, Wayne City, Ill.; low moisture content in filling material; no rain between time of filling and date of readings. Equivalent to fluid weighing 23.2 lb. per cu. ft.

means are the pressures uniform under the slab and by no means are they constant. This result is directly in line with what we now know regarding the warping of slabs due to temperature and the bending of slabs under load. Pressures have been determined under pier footings and also in the cores of hydraulic fill dams. Radial pressures have been obtained on large tunnels and on small pipes used for drainage purposes. In not all of these installations have satisfactory readings been obtained and

it may not be amiss to point out briefly, some of the causes of trouble and the methods used to overcome these difficulties.

Some of the troubles which may occur are listed as follows:

1. Short circuiting of the electrical circuit so that the light refuses to be extinguished upon applying air pressure in the cell. This defect probably has occurred mostly during the operation of leading the insulated wire through the small galvanized air pipe. Minute points of zinc smelter project on the interior of such pipe and may cut the insulation. It is suggested that ¼ in. ungalvanized pipe or copper tubing be used.

2. Subsequent readings will not agree with the first reading. This is due to lack of care in immediate release of the air pressure upon breaking of electrical contact. The effect is to push the weighing face of the cell excessively against the earth, thereby causing it to arch over and thus decrease subsequent readings until a readjustment of the earth has taken place. The remedy is to allow the air pressure to build up slowly within the cell and to be on the alert for immediate reduction of the pressure upon taking the reading. The air pressure should not be allowed to exceed the soil pressure by more than a tenth of a pound per square inch after breaking electrical contact.

3. Water has leaked into the pipe and thus the readings are made uncertain because, not only the air pressure but also the head of water within the pipe now balances the soil pressure. The remedy for this situation is to:

(a) Be extremely careful with all joint connections.

(b) Use a double air pipe so that if a small amount of water has entered, it may be blown up into one of the pipes and thus not disturb the readings.

4. The electric light will not burn. Obviously, this is due to a break in the electrical circuit. Generally when installations are made, right angle turns are required in the pipe line and in making the pipe connections, the wire is twisted clock-wise as the small L connections are tightened. This may actually break the wire in torsion, or the wire may be twisted loose from its connection with the central contact button in the cell. Extreme care must be taken to avoid twisting the wire during the assembling of the pipe connections.

5. It may also happen that the cells are installed under conditions which naturally will produce no soil pressure on the weighing face. For illustration, this has happened in the measurement of the soil pressures under concrete roads. The warping of the slab has actually lifted it away from the subgrade and naturally there is no pressure on the cell and, consequently, the light will not burn for there is no contact between the weighing face of the cell and the contact button.

6. The cell should be very rigidly attached to the structure for otherwise pressures on the pipe or on the projecting edge of the cell may cause disturbances in the soil adjacent to the weighing face and, naturally, the cell will then give false indications of the pressure, even though the pressures which exist on the cell are correctly weighed.

7. If the structure to which the cell is attached is acted upon by external influences such as in the case of a road slab, portions of the structure may move and the expected uniformity of pressures will not be observed.

8. It is necessary that enough cells be used to permit of obtaining a fair average pressure. This is obvious when it is remembered that the weighing face of the cell has an area of only 10 sq. in. and uniformity in pressure due to the fill is not to be expected at any given depth.

9. If vertical readings are being taken in a fill, it must be remembered that there is bond stress existing between the fill and the pipe connections and, therefore, the vertical pipes leading down to a cell installed for obtaining vertical readings should be offset a considerable distance from the cell and should be led to the cell in a horizontal position. In this way the vertical pressures on the cell will not be influenced by the vertical pipe connections.

10. Spelter or iron rust from the interior of the air pipes may collect at a given spot, particularly at the bottom of the pipe connections and may actually clog the air pipe. One remedy for this situation is to provide an air pipe of ample diameter and likewise a trap should be installed at the bottom of the pipe connection into which loose sediment can fall instead of entering the cell.

CONCLUSION

The measurement of earth pressures, sometimes at depths of 100 ft. or more under the surface of the earth, obviously is an operation which is beset with difficulties. It is believed that the soil pressure cell in many cases has performed this task in a thoroughly satisfactory manner. To be successful the cells must be manufactured carefully and they must be installed with every atten-

tion to those details which are vital in influencing the effectiveness of the device Readings must be taken with deliberation and with extreme care to prevent the introduction of air pressure in excess of that required to break electrical contact When all of the vital details are attended to, including necessary care in manufacture, installation and operation, readings will be obtained which will indicate very closely the actual pressure conditions existing on the structure

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