

REVIEW OF PIONEER WORK IN EARTH PRESSURE DETERMINATION AND RECOMMENDATION FOR EARTH PRESSURE EVALUATION

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SYNOPSIS

A summary of experiments performed in lateral earth pressure determinations, is presented, giving a general description of the type and size of apparatus, the features which were new, the various phases of the subjects studied, and the general conclusions drawn by each experimenter

A bibliography of experimental researches in this subject (exclusive of bin and concrete pressures), from 1720 to 1940, is appended

As a result of a study of the experimental work performed, and of the writer's professional experience in engineering design, general conclusions are drawn in the form of rules which can be used as a basis for the evaluation of lateral forces and resistances resulting from earth loadings. These rules cover all cases of structural designs involving earth, either as the active force or as the resistance

The basic requirements and limitations of technical problems are often very clearly stated in non-technical literature. The problem of determination of the pressure of earth, affecting originally only the design of retaining walls, although probably not in the mind of the author, is very nicely given by Robert Frost in his poetical work entitled, "North of Boston." The first and last stanzas are

"Something there is that doesn't love a wall,
That sends the frozen ground-swell under it,
And spills the upper boulders in the sun,
And makes gaps even two can pass abreast

Before I'd build a wall I'd ask to know
What I was walling in or walling out,
And to whom I was like to give offense,
Something there is that doesn't love a wall,
That wants it down."

Many men have attempted to find that "something" and to evaluate it.

Undoubtedly, even in ancient times, studies must have been made of wall dimensions necessary for the retention earth fills. Construction of this nature is found in the archeological excavations covering the entire range of ancient civilizations. We know that in Babylonian times depressed gardens were built within retaining walls; that many of the ancient cities were surrounded by walls, on the inside faces of which fills were

placed to varying heights; that the Romans built many revetments as fortification walls for the protection of their camps. Many of these walls have withstood the ravages of natural elements, as well as man-made agencies of destruction, for centuries. Whether these walls were built by rule of thumb based upon the development of the art, on the basis of what previous construction did not fail, or whether actual experimental work was performed, is not known. The authentic history of earth pressure experimental work must, therefore, start with the contributions of the French military engineers in the early eighteenth century, the first to make a written record of their researches.

The earliest recorded experimental work is by Belidore, in 1720 (1)¹, who states that as a result of experiment he was led to the conclusion that the prism of rupture of earth fills was on a slope of 1:1.

Mayniel (2) in his summary of earth pressure contributions in the 18th Century describes experimental work by Godroy in 1745, using a test wall 3 in high; the experiments made to check Belidore's theory resulted in the conclusion that the

¹ Figures in parentheses refer to bibliography at end

plane of rupture sloped at 2:3 and not 1:1, even though the natural slope of the material was 1:1.

Rondelet in 1767 (2, 3), repeated these experiments with a test wall $17\frac{1}{2}$ in. high, using both sand and natural soil as fills, and came to the conclusion that the plane of rupture did not coincide with the plane of natural slope. However, for simplicity, he suggests that a plane of rupture on a 1:1 slope be assumed for all materials.

D'Antony, in 1768 (2) constructed a test box with one side hinged at the bottom and the top held by a cord which passed over a pulley and was balanced by weights hung in a pan. No reliable results were obtained from these tests.

Gauthey, in 1785 (2, 4) using a box 30 in. high and 12 in. wide was the first to perform a complete set of earth pressure experiments. A bottom hinged gate with a cord tied at one-third the height and passing through the fill was counter-balanced by weights similar to the method of D'Antony. The material he used was sand, but the friction of the cord in the fill must have effected the accuracy of the results. He then changed the wall to a gate made up of five parts, in a smaller bin, making each part $1\frac{1}{2}$ in. high and attaching two cords to each part. In this way he attempted to measure the pressure at each depth. In spite of the resistance of the imbedded cords, he did obtain an idea of the variation in pressure on the various slats, reporting that with a sand fill, the weights needed to balance the five slats were $1\frac{1}{2}$, 4, 6, 8 and 10 oz. To determine how much of the filling material in the bin was really responsible for the pressure against the test wall, he built a hinged sloping bottom in the bin and reported that the pressure against the vertical face was the same for the horizontal bottom and for a number of increasing slopes with the horizontal until he reached $67\frac{1}{2}$ deg. In this way he proved that the material below that plane

had no effect on the pressure against the vertical wall.

Delanges, in 1788 (14, 15) published a complete treatise on "Statics and Mechanics of Semi-fluids," and describes therein some experimental work on the shapes that these materials will take and the vertical pressures in small bins. In the lateral pressure experiments he used a small box with a hinged side 6 in. square, counter-balanced by two strings of silk, on which were hung equilibrium loadings. He points out very carefully that both the horizontal and the vertical pressures of semi-fluids contained in "vessels" is reduced below corresponding fluid pressures by the friction of the side walls. Some very interesting detailed basic studies of the flow of granular materials through openings makes up the greater portion of the report.

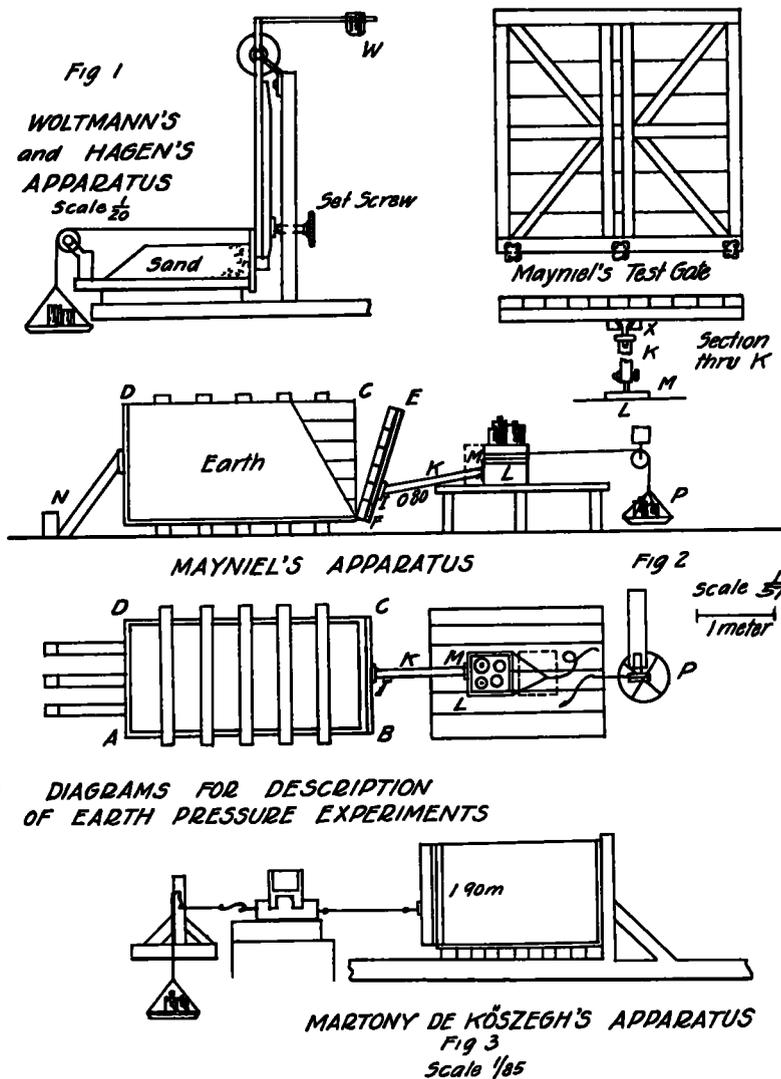
Delanges refers to two previous discussions on soil action,—one by Galileo, and the other by Lambert (1772). The discussion of the former points out the dissimilarities between granular substances and liquids.

The earliest large scale apparatus was built by Woltmann in 1791 (5). This was a box 1.72 m long, 1.15 m high and 1.15 m. wide (see Fig 1). The front wall was hinged on the top and prevented from excessive rotation by an adjustable stop at about one-third of the height. Two methods were used to measure the overturning moment on the front wall. The first was by means of a string tied to the back of the wall at its middle point and connecting to balancing weights placed before backfilling, which were removed gradually after back-filling, until movement occurred. The second method was to counterbalance the wall by a weighted crank arm beam attached rigidly to the wall. Materials tested included sand, gravel, soil and rye. The results obtained were approximately half of those given by the Coulomb formula, disregarding the vertical component. Hagen later sug-

gested that Woltmann's results should be increased by $\frac{1}{11}$ to take care of the loss in friction along the sides of the box.

The experiments conducted at Alexandria in 1805, at Piedmont in 1806 and

The first apparatus built was a box 2 m. wide, 1½ m. long and 1 m. high. When filled with sand, the bottom hinged gate broke its hinges and fell with a "sharp detonation." However, the experi-



at Juliers in 1806 and 1807, was started by Major of Engineers, Laulanier, continued by Lieutenant Derche and were completed by Mayniel (2). The report is given in detail in Mayniel's "Traite."

menters had curiosity enough to measure the surface of rupture and found it to be practically a plane at an angle of 64°42' to the horizontal.

The second apparatus built at Juliers,

probably by Derche, (see Fig. 2) was 3 m. long, $1\frac{1}{2}$ m. wide and $1\frac{1}{2}$ m. high. The box was of wood, but the gate was built much more substantially and also hinged at the bottom. At one-third the height an iron strut was hinged to the gate and pushed against weights on a friction block. The resistance of the friction block was first made larger than the expected pressure and was reduced by adding weights in the pan helping to pull the block. Mayniel states, as a conclusion from the experiments, that Coulomb's theory is the only true and simple theory. The resultant pressure acts at one-third of the height and equals from $\frac{1}{3}$ to $\frac{1}{2}$ of the weight of the wedge of rupture when the fill is loose, and from $\frac{1}{3}$ to $\frac{1}{4}$ of the weight of the wedge of rupture when the fill is packed.

Very similar apparatus was built and used by Martony de Koszegh, in 1828 (6, 7). The box was 2.85 m. long, 0.95 m. wide and 1.90 m. high. Pressures were also measured by a friction dynamometer (see Fig. 3). Of course this method prevented any measurement of a vertical component. The fill material was sand and also earth, and the results agreed fairly closely to those given by Coulomb's theory.

Hagen, (7, 8, 9) repeated the Woltmann experiments using practically the same apparatus. However, he reports that the total pressure is inclined to the back of the wall. To avoid the effect of side walls, he revised the test apparatus (see Fig. 4) eliminating the side walls entirely and allowing the fill to slope on each side, but within the width of the test wall. In his experiments he used both dry and wet sand, hinging the wall at *F* and counterbalancing it by a force at *E*. The area measured was the full cross section of the fill. Due to the sloping portions, comparison with theoretical results was quite difficult.

The first reported English experiments were by Lieutenant Hope of the Royal

Engineers in 1845, at Chatham (10). A complete program was first outlined and the problem was attacked from two directions. experimental tests on a wall 1-ft square and loading tests with full scale walls made of brick, 20 ft. long and 10 ft. high, of various sections. The apparatus (see Fig. 5) had glass sides and the test wall was hung by two strings counterbalanced by sand boxes hung at *R*. Horizontal component was measured by a bell crank arrangement hinged at *L* and bearing against the wall at *P*. Prior to filling, the sand box *S* was overloaded and after filling sand was released until movement occurred, as was seen through the glass side. Tests were made with dry and wet sand, both loose and packed, for determining the active earth pressure.

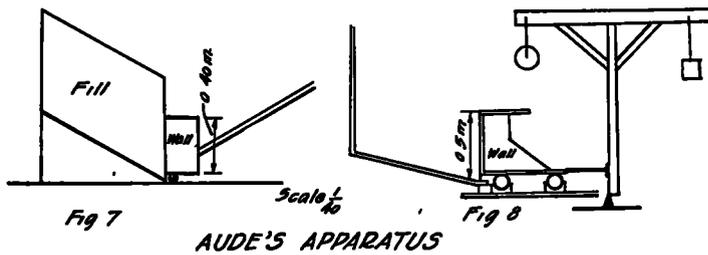
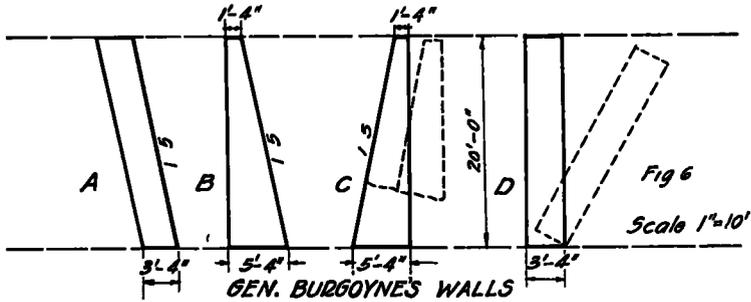
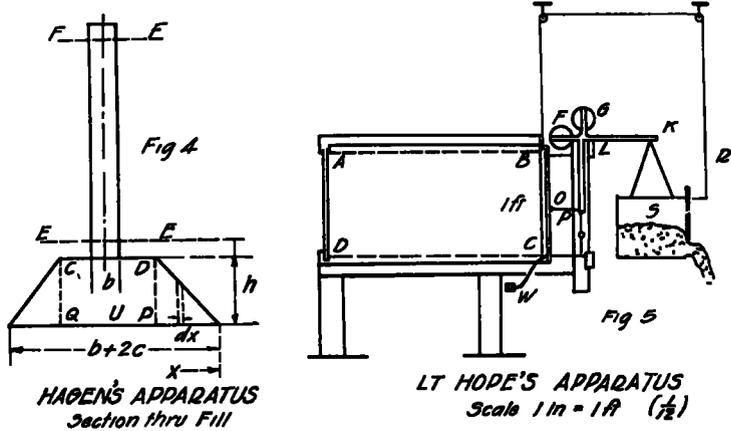
Tests were also made to determine the minimum wedge of rupture which would give the maximum pressure, controlling the volume of fill by a sloping bottom inserted in the bin. Hope agrees that the Coulomb wedge gives the maximum pressure. He then continued his experiments by sloping the front wall from 45 deg. to 129 deg. with the horizontal and measured the location of the surface of rupture. He concludes that the surface of rupture in all cases is a plane bisecting the angle between the wall and the plane of slope. Hope also measured the line of separation in the surface of fills 10 ft. high to determine the location of the plane of rupture, again checking its location as being in accord with the wedge theory.

The full scale tests consisted of several brick walls laid in wet sand and tested to destruction by back filling with ballast. The first wall was 20 ft. long and 23 in. thick. With a fill 8 ft. high the wall started to move and when the fill reached 10 ft. in height, the wall fell forward in one mass. The second wall consisted of panels 18 in. thick, laid between counterforts 27 in. thick. After a heavy rain, with a fill 8 ft. high, the panel bulged $1\frac{1}{2}$ in. The bulging increased to $4\frac{1}{2}$ in. with a fill

12 ft. 10 in high, and after several hours the wall fell under that load. A third wall was 18 in. thick and built on a batter of 1:5 with counterforts spaced 10 ft. apart and 3 ft. thick. This wall was carried to a height of 21½ ft. with only a

into consideration and the decrease in pressure due to movement of the walls is also considered, the pressure necessary to cause failure is given closely by the wedge theory.

Burgoynes, in 1834 (11, 12) built four



slight bulging about half way up, 2½ in. in the panel and 1½ in. at the counterfort.

Baker (11) discusses these tests, but by disregarding the vertical component of the pressure, comes to erroneous conclusions. If the vertical component is taken

walls of rubble masonry filled with loose mold at Kingstown. The reports of these tests are given by Owen in 1845. The four walls were each 20 ft. high and 20 ft. long of the types shown in Figure 6. The fill material weighed 87 lb. per cu. ft and

the tests were conducted during heavy rains, which leads Baker to contend that the material had a density of 112 lb. due to saturation. It is doubtful whether the density exceeded 100 lb. Wall *A*, back-filled level, remained stable for the duration of the test, forty days of rain. Wall *B*, after completion, showed some slight fissures and the batter decreased by $2\frac{1}{2}$ in., but the wall stood, probably because of the relief in pressure due to movement. Wall *C* failed when the fill reached 17 ft., by overturning. The top overhung 10 in. just before failure and the wall burst out at $5\frac{1}{2}$ ft. from the base. Wall *D* overturned as a unit when the fill was 17 ft. high, "falling like a board." Baker, in discussing these tests, claims that the walls had a factor of safety of two, even in the cases where failure occurred. However, the tests are consistent with the overturning moments as computed by the general wedge theory, taking into account wall friction.

Pasley (11) constructed several model retaining walls of various shapes, 26 in. high and 3 ft. long, at Chatham. These walls were backfilled with shingle, weighing 89 lb per cu. ft., and were pulled over before and after backfilling to determine the additional overturning moment of the fill. Cunningham tried to correct Pasley's results by using weighted models and also experimented with counterfort walls of somewhat greater size.

Collin, in 1846 (13) made a study of the nature and extent of earth slips occurring without outside influence. He concludes that rain has no effect, that a wedge of rupture exists, but that rupture is not due to any pre-existing surfaces. The mass falls out along a definite surface, shaped like a cycloid, but closely approximating a plane.

Aude of the French Engineers (16) in 1848 constructed a miniature wall, 0.4 m. high (see Figs 7 and 8) resting on rollers to prevent friction and measured the overturning moment by means of a bent lever.

His tests included some inclined walls and also some inclined fills. In general his tests have been shown by Domerque (17) and by Considere (18) to agree closely with the general wedge theory, taking into account the vertical component.

Michon, in 1863, (11) conducted a test on a wall of peculiar shape (see Fig. 9) 40 ft. high with closely spaced counterforts. The wall was of fieldstone, laid in lime and the filling progressed in horizontal layers. At a height of 29 ft. there was a slight bulge, failure occurring after the earth had been piled 3 to 4 ft. above the wall. The fall was preceded by a general dislocation of masonry at the base, a bulge at one-third the height and a slight movement at the top towards the bank. Baker's discussion of this test fails to take into consideration the fact that the closely spaced counterforts really made this a solid wall 4 ft. thick at the base and almost 11 ft. thick at the top, that the filling within the spaces must have been closely held by the friction of the counterforts.

Winkler (19) continued the work of deKoszegh in Vienna, under royal aid furnished to complete the solution of the earth pressure problem. In 1863, Winkler constructed a test bin (see Fig. 10) 25 cm. high and 40 cm. long and wide. The front wall was not attached to the bin but could rotate about two axes, B1 and B2. By allowing it to rotate about B1, only the horizontal component was measured. By allowing it to rotate about B2, the resultant of both components was measured. The overturning moment was counterbalanced by weights and sand, as illustrated. To determine the effect of side wall friction in his bin, he repeated his tests with a thin partition wall inserted in the middle of the bin, thereby doubling the number of friction faces. However, in doing so, he took no account of the fact that he also decreased the ratio of width to height of fill. The

experimental results checked almost exactly with the general wedge theory.

In 1872, Winkler built another apparatus of the same size (see Fig. 11) for the measurement of the horizontal component only. He states that the effect of side

Constable, in 1874 (20) reported the first experimental research in the United States. He built a box with glass sides and a test wall made up of pine blocks 1 in. square and 2 in. long inserted in an opening 16 in. square. To eliminate the

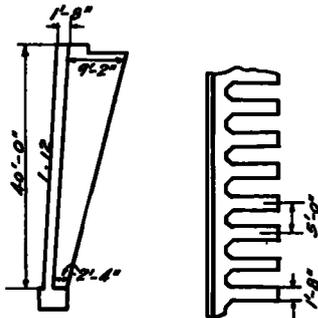


Fig 9
COL MICHON'S WALL

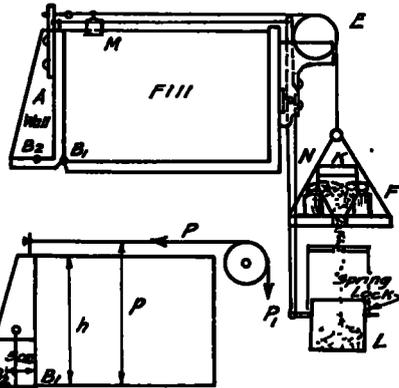


Fig. 10 Scale $\frac{1}{8}$
WINKLER'S APPARATUS
(1863)

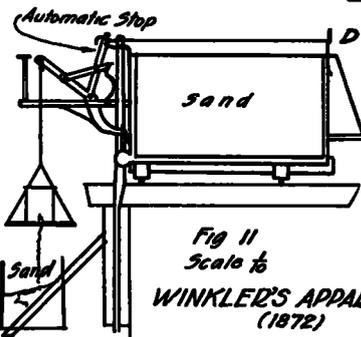


Fig 11
Scale $\frac{1}{16}$
WINKLER'S APPARATUS
(1872)

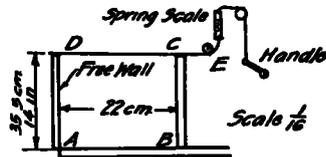


Fig 12
DARWIN'S APPARATUS

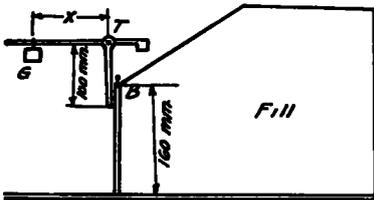


Fig 13
STRUKEL'S APPARATUS



Fig 14
ENGESSER'S APPARATUS

wall friction in his apparatus was affected by the change in bin shapes and also by the co-efficient of friction of the bin material. The results of the second group of tests are somewhat smaller than those given by the Coulomb theory.

effect of side wall friction, he only measured the pressure on 12 in. of width. Due to the use of peas as a filling material and because of the low heights, no conclusive results could be expected.

Curie (21) in 1873, built a test wall one

meter square hinged at the top. The necessary stability for any filling material was determined by piling bricks in front of the wall to prevent rotation. The test material was sand, both dry and humid, and tests were made for various inclinations of the wall. Experimental results for inclined walls agree closely with the general wedge theory; and are about 30 per cent greater for the vertical wall cases.

Darwin (22) in the summer of 1877, performed numerous experiments "to completely solve the problem of earth pressure." His apparatus (see Fig. 12) was 14 in. high and 12 in. wide. The test wall was hinged at the base and held by a cord at the top. The load on the cord was measured by a spring scale. By overstressing the scale, the wall was held in position until the backfill was placed and the active pressure was read at the point of wall movement as the spring was released. He tested the effect of side walls in the same manner as was done by Winkler. His experimental results for ordinary filling, shaken fill, using sand placed in horizontal layers and sand placed in layers sloping towards the wall and away from the wall, gave co-efficients of 0.18, 0.13, 0.17 and 0.19, respectively, as against the co-efficient of 0.27 by the Coulomb theory. Darwin's important contribution was the statement "Co-efficient of internal friction is very different in different parts of the mass and is a function of the pressure and of shaking."

Forchheimer (23) in 1882, continuing the Vienna experiments, used a very small box 8.4 cm. high, chiefly to determine the angle of the wedge of rupture. For various types of walls and very fine sand, his tests agree with the angle as determined by the wedge theory.

Gobin (24) in 1883, set out to disprove the Rankine theory by testing the pressure of sand, using sloped and level fills against vertical and inclined walls, 50 cm. high. His values are lower than required

by the wedge theory, which he states are the results of side wall friction in his bin. To determine the co-efficient of internal friction of his material, he measured the friction of the sand upon a sand-coated cylinder which was imbedded and pulled out.

Siegler (25) in 1887, was the first to build an apparatus where the amount of motion of the test wall could be controlled. He had four axes of rotation on his wall, which was 9 in. high and 8 in. wide. Tensions in the strings attached to the wall were measured by friction dynamometers. His results show the existence of a vertical component which decreased with the settlement of the fill. If the wall is rotated about its top, the resultant was a little higher than the one-third point; if the rotation is about the bottom of the wall, the resultant is a little lower.

Baker in 1881 (11), repeated Hope's experiment using a test wall 12 in. square, held by a string attached to the one-third point. He tested the pressure of ballast, sand, vibrated sand and ballast, coals of various types and broken rock. He reports that coarse materials give smaller pressures than fine materials, but that is apparently due to the small size of the test. His results in general are much lower than those reported by Hope.

Strukel in 1888 (26), continuing the work of Winkler, constructed two types of apparatus, the first to measure horizontal component (see Fig. 13) and the second to measure vertical component. The wall was only 16 cm. high, hinged at the base and resting against one arm of a bent lever. All tests were repeated with a centre partition in the bin and were made for sloping, as well as for level fillings. Due to the small size of the apparatus, he was more interested in the ratios of the pressures for various cases as against a level filling. The results check fairly closely with the wedge theory values.

Bland in 1890 (27), used peas as a filling material in testing lateral pressure against walls made up of wooden blocks 1 in. square by 4 in. long, within an 8 in. cubical box. The tests are too small to draw any conclusions.

Yankowsky in 1890 (28), reports the earliest work in Russia in his attempt to measure the effect of the water content upon a lateral pressure of sand. His pressure device was a manometer inserted in the side of a box and he reports that water increases the lateral pressure of granular materials.

Donath in 1889 (29), started the group of lateral earth pressure experiments at the Technische Hochschule at Charlottenberg. His apparatus was a box with a test gate 60 cm. square, hinged at the bottom and the overturning moment was measured by the pressure of a piston fixed to the gate against a cylinder of mercury. The amount of rotation of the gate could be governed to 14 sec. of arc, the exact value being measured with a microscope. By using two different axes of rotation, he can determine the value of the vertical component. To determine the effect of side walls, he employed a center partition in repeating his tests. Using sand as a fill, he finds that the moment decreases from 715 for a rotation of 14 sec. gradually for various intermediate positions to 610 for a rotation of 77 sec. Extrapolating backwards, he concludes that the actual moment at practically zero rotation is 762. As a result of his tests, he concludes that the lateral pressure is horizontal, but its amount is much closer to the horizontal component as given by the general wedge theory formula than the value given by any other theory.

Engesser in 1882 (30), started the investigation of the pressure of earth on tunnels, using small models. Later tests were to determine the existence of a vertical component (see Fig 14) and he concludes that there is a vertical component of varying amount.

Leygue in 1885 (31), submitted a 220 page report on the most complete tests on lateral earth pressure ever performed by one man. The first part concerns the verification of the hypotheses concerning cohesion, deformation of the wall, direction, point of application and magnitude of lateral pressure and a comparison of theory and experiment. His apparatus consisted of a box 14.4 cm. wide, and 3 cm high, inside of which rolled a smaller bottomless box, which was filled with the test material. Various materials were used and the angle of inclination of the larger box was measured at the point when the inner box started to roll down. He performed a great number of friction and cohesion tests in this apparatus, for sand, fine sand, mixture of sand and soil and humid soil under a great variety of loadings. These experiments conclusively prove the co-existence of frictional and cohesive resistances.

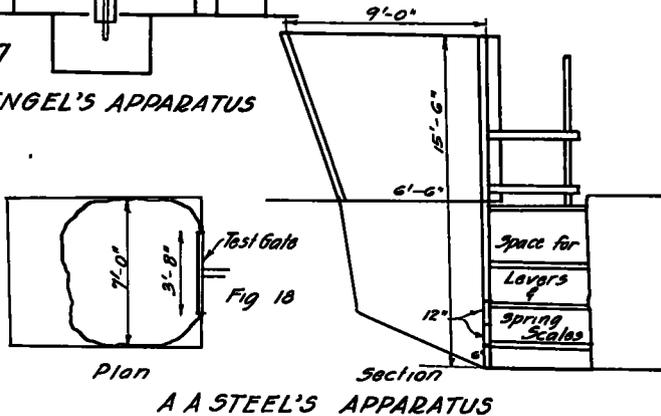
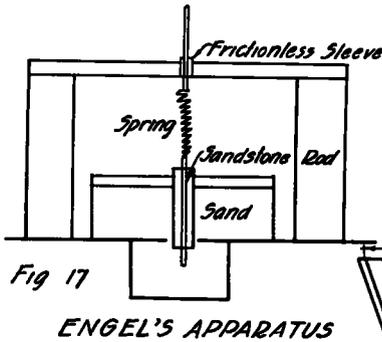
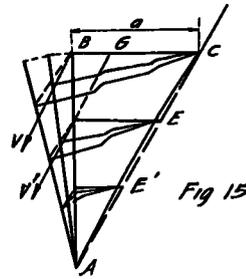
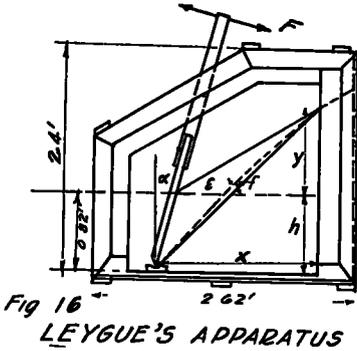
The next study was the shape of the prism of rupture as effected by rotation of a test wall (see Fig. 15). He concludes that the area of the prism does not depend on the nature of the wall movement, whether rotation or translation, nor on the amount up to about 30 deg. of arc. The particles in the wedge move in lines parallel to the surface of rupture. The influence of the top surface of the fill on the prism of maximum rupture is negligible. He tested the effect of different roughness of side walls on the shape and size of the prism of rupture.

The exhaustive study of the nature of prism of rupture resulted in the conclusions that the surface of rupture is not a plane, but a slightly convex curve independent of the height of fill, of the surface of the wall, of the inclination of the wall, and of the nature of the surface of the fill. It is a function of the material itself, and the surface of rupture approximately bisects a horizontal line drawn from the top of the wall to the intersection with the plane of natural slope.

The next group of tests were to determine the magnitude of earth pressure (see Fig. 16). He used Winkler's method of center partition for determining the effect of side wall friction. The results of the test are not reliable, because of the small

two readings being below 0.41 h. and the average being about 0.47 h.

Engels in 1896 (32), set out to prove that the lateral pressure on a vertical wall is horizontal. By accurate measurements on the movements of a rod imbed-



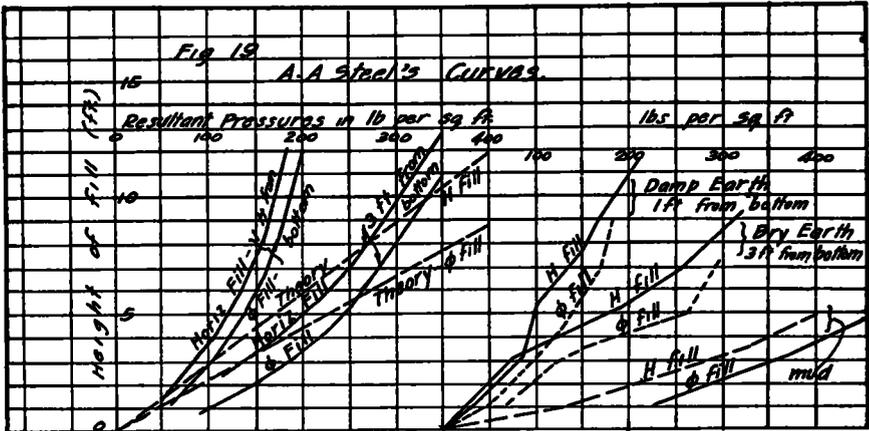
scale of the apparatus. However, he did show the variation in values with different slopes of the fill surface and definitely proved in his tests the existence of a vertical component. The point of application in all his tests is quite high, only

ded in a sand fill (see Fig. 17) he concludes that for a stable wall the lateral pressure is horizontal.

Steel in 1899 (33), at the University of Nebraska, constructed a test wall 14½ ft high, in which were two openings, each

12 m. square, located 6 in. and 30 in. above the base of the fill, (see Fig. 18). Boards were inserted in these openings to a close fit without binding and the horizontal and vertical force on each board was measured by connected spring scales. The curves shown in Figure 19 give the intensity of total pressure on the two test areas under various conditions. Materials used were dry and damp earth, with fills level and at the maximum slope. Comparison with the general wedge theory is indicated by a comparative curve. Steel noticed a peculiar drop in vertical components as the fill aged, a phenomena also observed in their experiments by

minish side wall friction. The test wall was a wooden slab lined with emory cloth to provide a rough surface and later lined with plate glass to provide a smooth surface. The material used was a fine sand dried for several months. Tests were run with fills at various slopes, but always with dry sand and vertical walls. The conclusions are that the measured earth pressure is greater than required by Coulomb's theory, is always inclined to the wall by the angle of wall friction from the normal, the point of application being no lower than one-third and higher for surcharges. Alternate loading and unloading causes the point of application to



Mueller-Breslau, by Terzaghi and by the writer

Mueller-Breslau in 1906 (34), reported the results of his large scale experiments at Charlottenberg. Closing one side of a large bin is a test wall 75 cm. high and 101.5 cm wide, suspended as a free body. By using two dynamometers to measure the vertical load and three dynamometers to measure the horizontal load, magnitude, direction and point of application could be determined in one test. (see Fig 20). The dynamometers were spring struts carefully calibrated for strain-stress curves

The sides of the box were covered with sheet steel rubbed with graphite to di-

rise Maximum pressure occurs immediately upon placing a fill with a decrease of about 10 per cent in 24 hours

Some photographic work was also done in a smaller glass bin and the only conclusion drawn is that within limits of 1 mm. and 6 mm , the movement of the wall has a remarkably small effect on the size and boundaries of the moving portions of the sand. Friction coefficients were tested by the apparatus in Figure 21

Jacquinet and Frontard in 1910 (37), performed considerable work in determining the friction and cohesion values of earth masses in connection with the failure of the Charmes Reservoir Dam. The results indicate that the percentage of

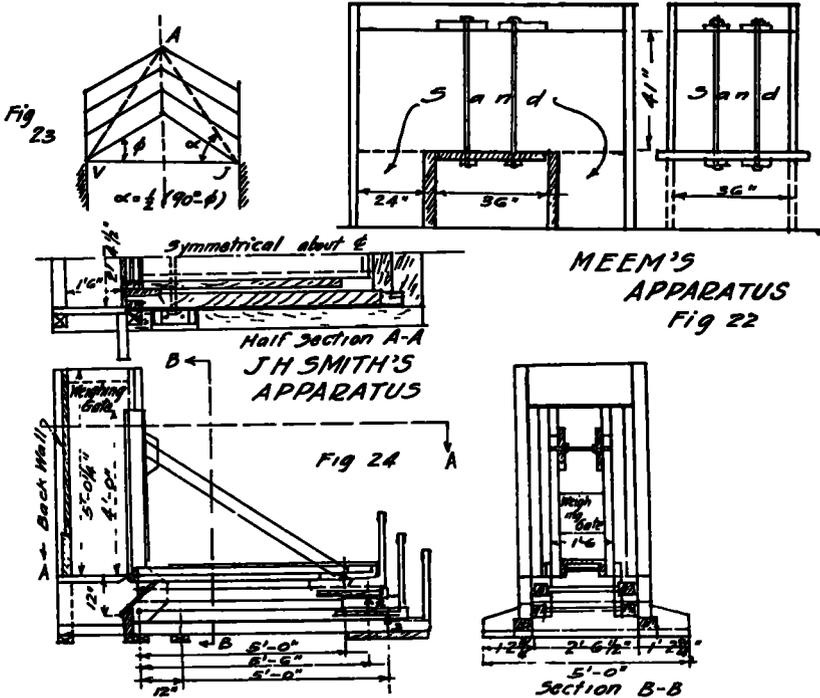
water influenced the co-efficient of friction to a considerable extent and it was also determined that both the friction and cohesion varied with the depth of fill.

Charmock in 1911 (35), of the Bradford Technical School in England performed some small size experiments on a 7 in. wall, the apparatus being so small that no conclusions could be drawn.

Mann at Cornell University in 1913 (36), reported some tests planned by Pro-

changes in temperature, which brought in large variations in the readings.

Meem (38) over a period from 1908 to 1920 performed several groups of tests for evaluating earth pressure and attempting to get a correlation between experimental values and the apparent pressures which he encountered in connection with large subway and excavation construction problems. One of the types of apparatus (see Fig. 22) consisted of a box with a free



fessor Mills, to determine the lateral earth pressure on a $\frac{3}{8}$ in. steel plate, 40 in wide and 60 in. high, by measuring the deflection of the plate. The work was originally started by Hoffert and Kimber, who abandoned the attempt because of the lack of consistency in test values. Later, Mann and Gons continued the work using a pressure cell consisting of a spring diaphragm pressing against water. This work was also abandoned because of the trouble encountered by air bubbles and

bottom, which would not fall when the box was fully loaded, proving the existence of some internal stresses similar to arch action, (see Fig. 23). Several tests by Meem to determine the pressure of saturated fills, led him to the conclusion that sand only transmits hydrostatic pressure through the void space, a conclusion which has been disproven. Meem also believed that his results indicated that liquid concrete did not give full fluid pressure.

Bie in 1923 (39), under the guidance of Meem, performed experiments to determine the pressure on a loose floor of a bin 2 ft. by 3 ft. - 8 in. in plan, measuring the load on a trap-door in the floor 7 in. by 23 in., resting on a platform scale. Materials used were sand and a rich garden soil. The box was filled to varying depths and superimposed loads placed on the fill. The amount of load on the opening in the bin floor was measured for each load increment. The tests were performed to show the existence of an arch in the fill and for the conditions of the test, horizontal transfer of the load was proven.

Smith of the University of Pittsburgh (40) in 1915, constructed a test bin 28 in. wide and 5 ft. high. The pressure against one end or gate 18 in. wide and 4 ft. high was measured by means of platform scales (see Fig. 24). However, the back wall was so close to the test wall that a true condition of retaining wall filling could not be tested. Materials used were gravel and sand of various moisture and compaction conditions.

Miller (41) of the Public Service Commission of New York City in 1916, measured the pressure acting on sheathing in a subway excavation in which the material was a fairly uniform glacial sand containing about 25 per cent of clay, by measuring the deflection of timber rangers over an area 22 ft., horizontally by 55 ft. vertical depth of excavation. His tests indicate a uniform unit pressure for a depth of 45 ft. and a much lower pressure (approximately one-third as large) at a depth of 55 ft. However there is no indication that any account was taken of the manner in which the rangers were inserted or the amount of wedging done in the needles prior to the measuring of the deflections of the rangers, or the condition at the bottom. This test is quoted very often by those who attempt to prove the decrease of earth pressure with depth in sheathed cuts.

Crosthwaite in 1916 (42), made several series of tests to determine a relationship between penetration of a plunger in soils and the internal friction of the material, using sands, garden earth, ashes, cinders and clay.

Later he experimented with a small vertical wall, hinged at the base, measuring the overturning moment by the tension in a string attached to the top of the wall. By inserting a sloping bottom in the bin, using a sand coated wood plank, he attempted to check the wedge theory by measuring the pressure with various inclinations of the bottom. He concludes that the general wedge theory gives correct values for earth pressure, except that for surcharged conditions calculated pressures are 30 per cent too great.

To determine the effect of wall friction on measured horizontal pressures, Crosthwaite took his apparatus and sawed it in half longitudinally, placing one-half of the apparatus on solid supports and the other on rollers. The pressure of the sand along the plane of the saw cut, after filling the apparatus, was measured by the tension on the strings connecting the two halves and preventing the rolling half from being pushed forward. The test was repeated with different coatings on the inside faces of walls, corresponding to different roughness of retaining walls and Crosthwaite concludes that the friction between the wall and the fill has no effect on the horizontal component of the earth pressure.

Fulton in 1920 (43), reports on the determination of the overturning moments on a rotating test wall in a bin 7 ft high, measuring the moment resulting from the pressure of fills of various types by observing the extension of a bar with a Ewing extensometer. His apparatus required him to assume the location of the resultant as well as its inclination, since only the overturning moment could be measured. Using clear river sand, gravel and garden soil, he concludes that the

general wedge theory gives results closely approximating the experimental values for levels fills, but gives results 20 per cent too great for surcharged fills with a vertical wall and 40 to 50 per cent too great for sloped walls.

Goldmark in 1915 (44), in connection with the design of the New Orleans Canal Locks, performed some tests on the pressure of the local clay in a box 2 ft. square and 6 ft. high. The front of the box was made up of three parts, two wood planks and one steel plate, each 8 in. wide by 6 ft. long. The steel plate was calibrated before being attached to the box and the pressures of the clay were interpreted from the measurement of the deflections of the steel plate. The consistency of the clay measured was quite fluid at the beginning of the test and the pressure variations were measured as the clay dried out and became stiffer. Over a period of four months the equivalent fluid pressure of the clay decreased from 73 to 25 lb. per cu. ft.

The foregoing is a summarized but fairly complete list of experimental work on record at the time the writer undertook his research work, which he performed at the University of Cincinnati from 1919 to 1922. Since that time, the subject of earth pressure has become a minor branch of the general subject of soil mechanics and experimental work of the nature described above has been relegated to a minor role in investigations of soil properties and soil action. It is noteworthy that at the Harvard Conference on Soil Mechanics, and Foundation Engineering in 1936, there were only three papers dealing with the experimental determination of earth pressure. At the Purdue Conference on Soil Mechanics in 1940, there was only the summary of previous work, prepared by Professor Rutledge.

Since the reports of the researches since 1920 are easily available, there is no neces-

sity in this paper to go into any further detail than to list the references to the description of apparatus and reports of results:

1921—Jacob Feld (45). Experimental work on sand pressures against a wall 5 ft wide and 6 ft high, for various types of surcharges, wall slopes and wall surfaces. Study was also included of the effect of time and other factors on pressures, (see Fig. 25)

1921—Hummel and Finnan (46): Pressures inside soil masses recorded on electric resistance cells

1922—Fargher (47): Experimental work with dry sand on vertical test wall.

1924—Campbell (48). Tests with sand on 12 in model walls

1924—Franzius (49): Experimental determination of passive resistance on a wall 1m. wide by 1.5m. high, including the effect of center walls to obtain the value of side wall friction and photographs of the shape of the slip through glass sides.

1925—McNary (50): Determination of pressure against abutments, by the use of pressure cells

1926—Krey (51): Experimental determination of slight movements for passive and active cases of wall displacement.

1927—Stroyer (52): Determination of pressures on flexible walls.

1929—Gerber (58). Distribution of lateral pressure.

1932—Jenkins (53): Pressures on retaining walls with dry granular materials and also pressure of sand under water, walls of many shapes. It is concluded that the resultant is inclined to the wall and the position of the resultant may be much higher than at the one-third point

1932—Monomobe and Matsuo (54): Experimental investigation of the effect of earthquake vibrations on lateral earth pressure showing increase due to vibration, with the amount of increase small if the backfill is compacted

1933—Parsons (55): Measuring horizontal pressures of bank sand and bank gravel, dry, saturated and drained against a stationary bulkhead 5 ft. wide and 7 ft. deep.

1934—Terzaghi (56): Measuring pressures of dry, saturated and drained sand, also fine grained till on a test wall 7 ft. high and 14 ft. wide, showing variation of pressures with amount of movement of the test wall and the effect of submergence of the fill.

1936—Spangler (57): Experimental determination of horizontal pressures on retaining

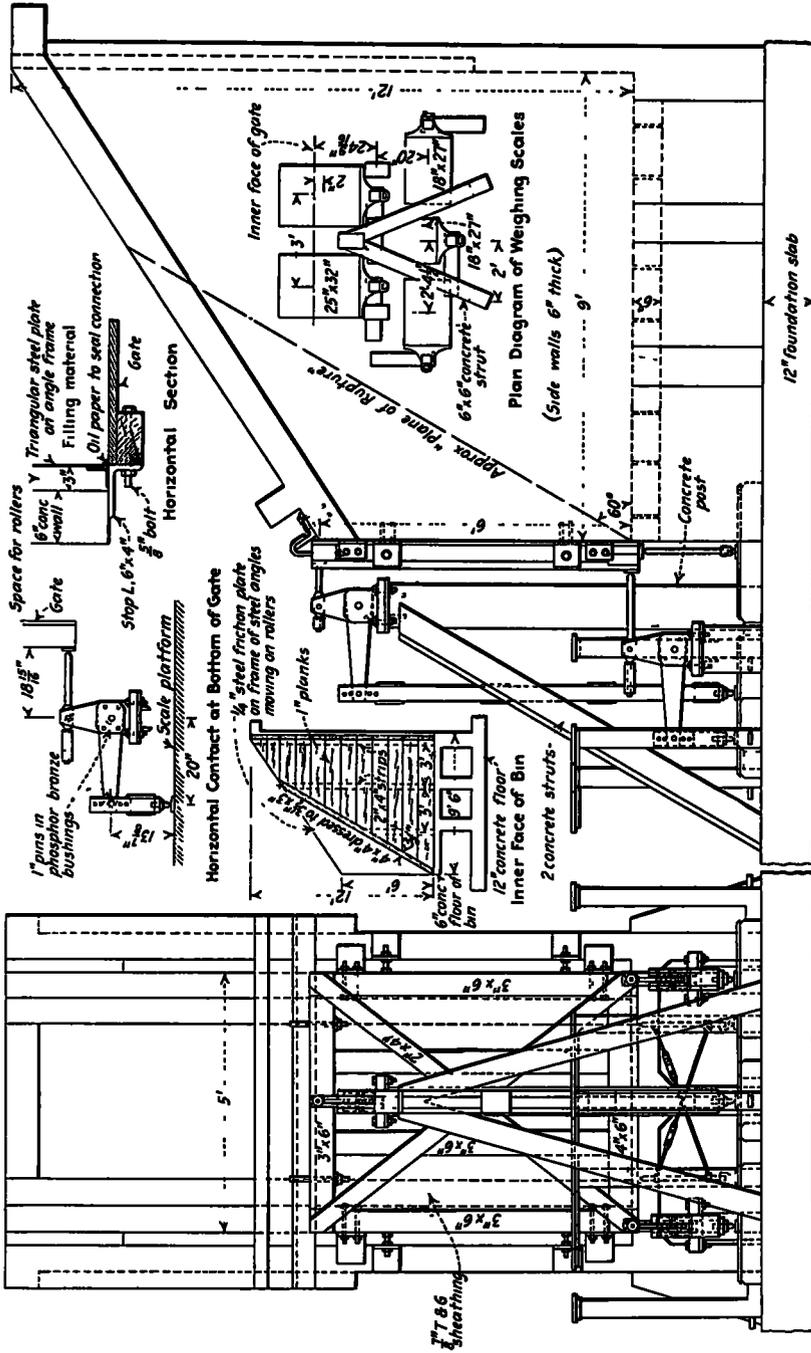


Figure 25. General Drawing, Earth Pressure Apparatus

walls due to surcharges using a test wall 6 ft high and a great variety of surcharged conditions

1937—White and Paaswell (59): Reporting some field tests on the pressures measured in a deep subway cut

1938—Terzaghi (56): Reporting field determinations of the pressure on timbering in the Berlin subway cut 36 ft deep

RECOMMENDATIONS FOR EARTH PRESSURE EVALUATION

A study of all experimental work herein described, after taking into account the accuracy to be expected from the various types of apparatus, shows much less

mental results and with observations in the field in so far as the conditions of the test comply with the assumptions of the theory. Exact correlation cannot be expected when dealing with materials like soils, due to the well known variation in physical characteristics because of non-uniformity.

However, certain rules can be set down as basically true for all conditions and the use of such rules will be found sufficient for the design of any engineering structure involving the necessity of determining the value of earth pressure. No accuracy is claimed for these rules, except that the

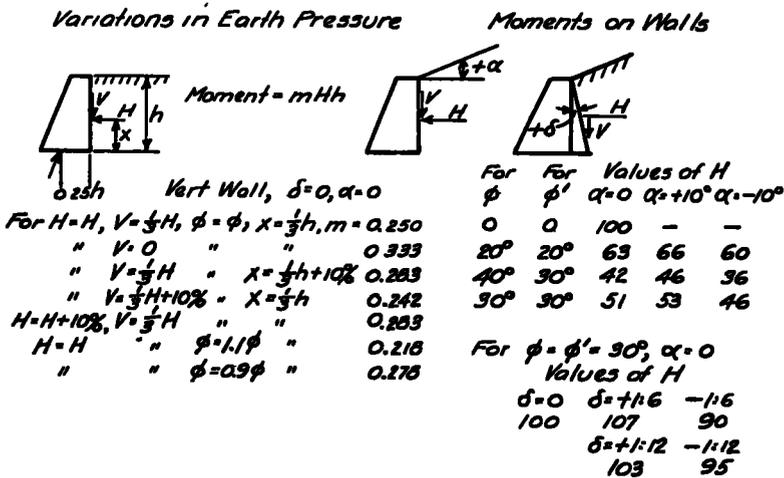


Figure 26

variation in results than one would at first expect.

The only purpose of experimental work is to check theories, except that where no theory exists, experimental work often can be tabulated in the form of empirical rules for the guidance of engineering design until such time as a theory consistent with experimental results and with actual observations is developed and becomes established design practice.

In the subject of lateral earth pressure, the basic principles formulated by the classic theories, chiefly the school of Coulomb, are generally consistent with experi-

mental results have no greater error because of the use of the rule or formula than is introduced by the necessary assumptions, whether based upon field tests or laboratory tests, or no tests at all, of the physical characteristics of the material encountered (see Fig. 26).

The following suggested rules used by the writer in common with many other engineers engaged in heavy construction and in the design of numerous structures, have been found satisfactory and will cover practically every condition:

1. The horizontal component of lateral pressure of any material which is not

fluid, is given closely by the general wedge theory for the case of vertical wall and substantially horizontal fills.

2. The same theory gives results somewhat too small for negative surcharges and somewhat too great for positive surcharges, but the differences are no greater than 10 per cent. The active pressures for special cases can be rapidly evaluated by ratios of the simplest case, (see Fig. 26).

3. The point of application for the earth pressure for horizontal fills or negative surcharges is at one-third the height. For positive surcharges, and in the presence of vibration for all cases, the point of application will be higher with a maximum position of 0.4 h.

4. The resultant pressure is inclined to the wall by the angle of wall friction from the normal.

5. The pressures of fills which are plastic, or the pressures of materials which because of lack of drainage and because of their nature may become fluid at any time, whether such fluid material is widespread or only a narrow layer against the wall, is the same as liquid pressure of a liquid having the same density as that material.

6. The pressure of submerged soils is given by rules 1 to 5 inclusive, except that the weight of the material is to be reduced by buoyancy and the other physical characteristics are to be evaluated for the submerged condition, and that in addition thereto there is acting the full hydrostatic pressure of water. The point of application of the water pressure is of course $\frac{1}{2}$ h. The point of application of the pressure of the submerged soil may be above that point.

7. The passive resistance of soil is somewhat greater than that given by the wedge theory. However, seldom is it necessary to assume more than the theoretical value.

8. Lateral earth pressure is reduced by movements away from the earth, passive resistance is increased by movements

towards the earth. Such changes cannot be taken into account except for temporary work, because the changes in the conditions of the filling in time will bring back the original pressures.

9. The pressure in sheathed pits is not given by the wedge theory unless a correction for side friction is made, in which case field observations of pressures are closely checked. Such correction will show that after certain depths, there is no additional pressure as long as the earth is prevented from movement. (See reference 45, page 1580-1 and also Purdue Conference on Soil Mechanics, Proceedings, 1940).

10. In sheathed cuts or excavations, the total pressure is given by the wedge theory, but the distribution of pressure between the various layers of supports depends upon the relative rigidity of these supports. With equal rigidity and simultaneous placing in position, the distribution would be close to the theoretical distribution. Any distribution can be assumed, subject to the limitations that the total pressure is taken care of and that the materials provided for holding the pressure will not be strained beyond the elastic limits. This is based upon the principle of least resistance and applies to any indeterminate structure, in which the amounts of exterior pressures are affected by elastic strains of the supporting materials.

11. *Most important of all:* The conditions of statics must be complied with, if a stable structure is desired.

12. Finally, in designing structures for the support of earth, or structures supported by earth, whether lateral or vertical, the designer must take into consideration the limitations of the accuracy of performance in the field and must not expect performance equivalent to a tooled or a precision job. He must have, as well, an honest appreciation of the errors involved because of his assumptions.

If the foregoing rules are complied with and kept in mind, there will be little necessity for going into long abstruse computations and the designs produced can be performed economically and will be safe.

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DISCUSSION ON EARTH PRESSURE DETERMINATION AND EVALUATION

PROFESSOR ROBERT F. LEGGET, *University of Toronto*: Dr. Feld has enhanced the value of his historical research by including in the paper twelve suggested rules for the calculation of lateral earth pressures in design work. In view of the vast amount of published data on the subject, these rules—based, as they are, on Dr. Feld's own wide experience in practice—should receive a wide welcome from practicing engineers. To the research worker they should serve as a stimulating reminder of the sort of guidance that the designing engineer wants to receive as the result of research work.

The rules are so well and succinctly expressed that the writer hesitates to suggest any amendment. Rule No. 7, regarding passive pressure, deals with so important a matter, however, that the writer ventures to ask if Dr. Feld would not agree to enlarge somewhat the second sentence of the suggested rule. Passive pressure is an important element in the design of flexible, or bulkhead, retaining walls such as are now frequently constructed of inter-locking steel sheet piling. In the design of such walls, those who follow Blum's method commonly use double the calculated passive pressure in front of the lower section of the wall, when the wall is built in sand or sandy material. This step is held to be justified by the experimental work of

Franzius, as recorded in *Bauingenieur* during 1924 and 1928. It effects appreciable economy in wall design, and successful practice suggests that this is achieved with no sacrifice of safety. Dr. Feld's comments on this practice would be valuable. In view of the wide use of bulkhead walls today, possibly he might be willing to enlarge his suggested rule No. 7 accordingly.

DR. FELD: Professor Legget has made a thorough study of the subject of sheetpiling and of the design of bulkheads, so that his suggestion must be given careful consideration. Experimental tests by Franzius as well as empirical deduction from field observations justify Professor Legget's statements. In sandy soils, the assumption made by Blum that the passive resistance in front of the lower section of sheetpiling is double the calculated value, seems justified. The danger that some designers will make the same assumption for other soils must be guarded against. The writer feels that the economy resulting from Blum's assumption can be obtained by taking into account the frictional components of the earth pressures as an aid to stability, in any kind of soil, without having to make the arbitrary assumption. Studies of this proposed method, a more generalized theory of sheetpiling action, are now being made by the writer.