SECTION I

THEORIES, HYPOTHESES, CONSIDERATIONS OF A GENERAL CHARACTER

SUB-SECTION Ia

GENERAL CONSIDERATIONS

Ia1 EARLY HISTORY AND BIBLIOGRAPHY OF SOIL MECHANICS

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INTRODUCTION.

Both the art and the science of control and utilization of soil as a building material have their beginnings in prehistoric days. Some ten thousand years ago, Neolithic man built huge earth mounds to mark burial sites or for other commemorative, or possibly, useful, reasons. Mound building was continued by the early Greeks, the early Saxons, and even by the prehistoric American Indians, and is even now an important problem in soil mechanics as applied to embankments and earth dams. Near Silbury, England, Megolithic man built not only a huge mound but also a circular ditch to surround his stone erection project. Possibly pre-dating any of these earth-works were the pile foundations erected for supporting the shelters of Neolithic man along lake shores. Earth tunnelling dates back to at least 800 B.C. in the Persian underground galleries ("Kanats" or "karezes"), thousands of miles in total length to tap underground water and to artificially dewater the sub-soil. The art of this method of water production was brought to Egypt by Scylox about 500 B.C., in the irrigation of the El Khargeh oasis, and its use spread as a standard method from Baluchistan to Morrocco.

Archeologic explorations indicate very little positive information of knowledge on the necessity for foundations under ancient structures. When structures settled too much, they were demolished and the rubble was used as a base for the succeeding structure. A critical examination made in 1931 by the writer of the walls of Jericho (four levels) as exposed in the excavations made there by Major Toulok, indicated that a special layer of stones had been placed as a base for each succeeding wall. The lowest construction dates back to about 2400 B.C. Major Toulok was quite convinced that he had solved the mystery of the Jericho wall failure when Joshua (1400 B.C.) took the city. The excavations showed the foundation tier of stones (for the wall of that period) displaced laterally to the outside and tipped forward, as if a trench had been dug along the bottom of the wall to undermine the base. A possible solution to an age old question, and an application of soil mechanics knowledge.

Ancient and mediaeval philosophers contributed to many sciences and there are references in the technical literature of the 17th and 18th centuries which gave credit to Galileo, Lambert, and others for basic ideas. The existing contributions in earth and soil studies, as an independent problem, date from the latter part of the 17th century. From the French military engineers, there came a succession of empirical and analytical analyses of earth pressures and earth slopes, necessary data for the design of fortifications. During the same period, the English seem to have been more interested in the study of soil control and classification for application to agriculture. About the middle of the 18th century, contributions on lateral earth pressure begin to appear in Italian, Dutch and Swedish scientific publications, at first as applied to fortifications and later as a scientific problem attacked experimentally and analytically. Coulomb's essay in 1773 changed the entire method of approach to the problem of soil slopes and lateral earth pressure and was closely followed by many experimental attempts to prove and to disprove his theoritical results. Before the end of the 18th century, there appeared contributions in the French, Dutch, German, Italian and Russian scientific societies on Coulomb's theory and modifications of the formulae, chiefly simplifications to make the results of empirical value.

In the last quarter of the 18th century, Böhms "Magazin" must have been an important medium for the dissemination of new ideas, for it carried translations into German of almost all the contributions found in the printed transactions of the scientific societies in all the countries of Europe. Extensive summaries of earlier work are given by Brunings (1803, Dutch) and Mayniel (1808, French). The early part of the 19th century brings studies of other soil problems, such as shore erosion, pressures on the inside and outside of bins and cells, flow of soils from orifices, pile foundations and soil control by wood pile and by "sand pile" introduction, together with a continuous attack on the lateral earth pressure question.

The fifty earliest available references to soil mechanics contributions are listed in chronological order and a short discussion of the various contributions is given as an outline of the history in this subject, to record the origins of the study which is the subject of this Conference.

SOIL CLASSIFICATION AND IDENTIFICATION.

In a lengthy disertation presented before the Royal Society of London on April 29, 1675, Evelyn states that the Ancients classified soils as: Creta, Argilla, Smetica, Tophacea, Pulla, Alba, Rufa, Columbia, Macra, Cariosa and Rubrica, and that Anathesus Kircher in his "De Arte Combinatoria" computed that there were 179.100.060 different sorts of earths, of which only 8 or 9 need be considered practically. Evelyn describes the methods of identification and the expected actions of soils found in the three different layers or horizons: (1) top layer or under-turf earth, (2) soil layer, which may be loam, clay, plastic figuline, or smetic, and (3) sub-soil layer, which may be chalk, marle, fullers-earth, sandy, gravelly, stony, rock, shelly, coal or mineral. Each of the types is described and the suggestion presented that identification can be made by the use of the senses: smell, taste, touch and sight. Evelyn makes it clear that a composition of mixed soils does not exhibit the properties of all the constituent parts, since certain earths influence the soil behaviour far more than one would expect from the proportional content.

Lemaire (1737) revised the tables for fortification walls developed by Vauban by introducing the "tenacity" in the earth backing as helping the stability of the walls. Previous analysis had always been based on the assumption of a hypothetical solid earth.

Querlonde (1743) distinguishes between three types of soil backfill: vegetation soil, stiff earth and sand, having different natural slopes, namely 1:1, 3:2 and 1:2. Lorgna (1763) differentiates between various soil types, generally divided into four classes: various kinds of fresh earth, dried earth, sandy ground, and sands, which latter may be plain, mineral, river or sea sand. Rondelet (1767) divides all soil into earth and sand, and his monumental work influenced many later authors to disregard variations in different soils.

Chauvelot (1783) seems to be the first to attempt a soil classification by a numerical determination of physical properties; weight, friction and cohesion. When he presented his theory of lateral earth pressure determination before the Academy of Sciences in Paris (Jan. 22, 1783), in which he evaluates the pressure of any material where the weight, internal friction and cohesion are previously determined by experiment, that learned body declared that the problem of earth pressure was susceptible of a rigorous solution. It is strange that Coulomb's much more logical and complete solution of the problem was disregarded in this pronouncement.

Delanges (1788) studied the state of "semifluids", which he enumerated as sand, gravel, lead sparrow-shot, millet and similar materials. Mayniel (1808) in the practical applications of theory to retaining wall design, tabulates values for the following soil types: soil fill, sand, gravel, rubbish fill and clay fill. Sir Humphrey Davy (1813), from the agricultural point of view, shows that all soils are mixtures of various types of earth, four types being most common: aluminous clay, siliceous sand, calcareous marle or chalky sand and magnesian. In 1818, an unknown author apparently much influenced by Davy, wrote in the "Treatise on Soils and Manures", on the subject of soil identification:

"In framing a system of definitions, a soil is to take a particular denomination from a particular kind of earth, not exactly in proportion as that earth may preponderate, or not, over others in forming the basis of the soil, but rather in proportion to the influence which a particular kind of earth, forming part of the sample, has." This statement is in close agreement with the most modern recommendations in soil classification and identification.

LATERAL EARTH PRESSURE THEORIES.

A large majority of early contributions deals with the subject of lateral earth pressure. In comparison, the first International Conference at Harvard included only three papers on the subject, showing that there is fair agreement on the solutions of this problem in soil mechanics. A "History of the Development of Lateral Earth Pressure Theories" was published by the author in the Brooklyn (N.Y.) Engineers' Club Proceedings, January 1928, and only a summary is included here.

Revetments for the fortification of cities and camps have been built from the earliest days, noteworthy examples being the masonry walls of the Romans erected to withstand the shock of catapult projectiles and to retain the earth fills. The walls of the mediaeval ages were copies from the Roman structures which outlived the empire. The earliest existing recorded rules for the design of revetments are those of Vauban, the great French military engineer, (1687). In his treatise on the fortification of fortresses he mentions the formulas which were used in constructing over 150 fortifications of various heights, using 4,000,000 cu. yds. of masonry. In all probability these rules are based upon older empirical rules coupled with "cut and try" experiment. Vauban assumed that his walls would rotate as units about the toe, the counterforts acting as integral parts of the wall. He realized that the counterforts decrease the acting earth pressure because of the frictional resistance along the sides as well as by a decrease of the exposed wall area. Audoy has shown that the typical Vauban revetment has a factor of safety of 4.70 for sliding and 3.80 for overturning, assuming ideal condition.

Bullet of the French Royal Academy of Architecture develops the earliest theory based upon the principles of Mechanics (1691). Starting with the assumption that all the retained earth above a 45° plane through the heel of the wall tends to slide as a solid mass upon this plane, he says that the weight of the wall must be to a weight of this wedge as the length of the plane of rupture is to the height of the wall.

Couplet (1726) published three excellent articles concerning the pressure of earth against revetments and the necessary resistance of revetments to withstand such pressure, containing the earliest synthetic earth pressure theories. In the first article he assumes a frictionless wall acted upon by a fill of an infinite number of small spherical grains. In 1727, he generalized to the case of a rough wall, the pressure now acting normal to the irregularities or grains in the back of the wall. Two cases are considered, where each grain rests on three or on four others; in each case the plane of rupture will pass through the toe of the wall. For, he says, if the portion of the wall below this plane is omitted, the material below the new wall, being in the natural state of equilibrium, will not move. The method is the same as in the first theory, except that the unbalanced force may now act obliquely. The general result is in the form of a cubic equation from the solution of which one obtains the required width of wall for rotational stability.

Belidor (1729), starting with Bullet's assumption of a 45° prism of rupture, investigates the action of the wedge by dividing it into parts by planes parallel to the plane of rupture. He summates the effects of the individual sections of earth in causing rotation about the toe, the earth pressure being the horizontal component, and deducted half of the resulting overturning moment as a loss due to the presence of friction. In any case of oblique wall or surcharged fill the wedge of rupture is the material contained between two 45° planes passed through the bottom and the top of the back of the wall.

Querlonde (1743), of the French Military

Engineers, refuses to accept the idea of a 45° wedge for all cases, but considers three types of soil - vegetation soil, stiff earth and sand. The earth pressure is horizontal, however, he says that the sum of the earth pressure and the frictional loss must equal the weight of the wedge. Also, the ratio of the pressure to the friction loss equals the ratio of the height of the plane of rupture to the horizontal width. This comes, he says, from the principle of the inclined plane.

Gadroy (1745), tried to prove Belidor's theory by experiment. Using a small model wall he found that failure occurred by rotational displacement; hence, he concludes that the lateral pressure must act at the top of the wall. He noticed that the first slip of sand did not include all the material above the plane of repose, but he missed the significance of this fact, although he went to the trouble of investigating the effect of the height of fill on the plane of rupture.

Numerous contributions, usually modifications of earlier theories appeared from 1745 to 1770. Louis de Cormontaigne (1750) advises a correction to Couplet's theory - his "every day practical method" was to take the lateral pressure as half the weight of a 45° prism of rupture. Lorgna (1755) assumes the lateral pressure to act at 45° and to be equal to the weight of the 45° prism of rupture times the sine of 45°. Kinsky (1763) follows the same reasoning to obtain the overturning moment, and Ypey (1765) bases his theory on a 45° plane of rupture passing through the toe of the wall.

Sallonyer (1767) of the French Department of Fortification resolves the weight of the prism of rupture, assumed to slide on the plane of repose, into two components, one of which acts parallel to this slope and is equal in magnitude to the weight of the wedge. This tangential force acts through the center of gravity, and is resolved into horizontal and vertical components at the back of the wall. The overturning moment is the algebraic sum of the moments of these two forces about the toe. The width of the wall is found by equating the moments causing and resisting overturning. Blaveau worked with Sallonyer and develops a similar theory. The lateral pressure has the same direction and point of application but its magnitude is the component of the weight of the wedge parallel to the plane of rupture. In calculating walls he disregards the vertical component of this pressure. A great advance was his generalization from the case of a 45° wedge to the wedge with an undetermined angle.

Rondelet in describing his earth pressure theory makes no mention of any previous author except Belidor. Rondelet decomposes the weight of the wedge into components parallel and perpendicular to the plane of slope. The tangential force acting through the center of gravity of the wedge is the earth pressure. Experimentally he deduced that the pressure is always caused by a wedge sliding on the plane of slope, which both for sand and earth is a 45° slope. At about the same time, according to Mayniel, the Department of Fortifications was using this theory with the reduction of the tangential component by the frictional resistance along the plane of slope. Other engineers were resolving the weight of the wedge into two components, one horizontal and the other normal to the plane of slope.

Trincano goes back to the assumption of a 45° wedge causing a horizontal pressure at 2/3 h, but says that its value is 1/4 of the weight of the wedge. The Italian engineers, including d'Antony (1768), all assumed a 45° wedge of rupture. D'Antony made the same assumptions as in Trincano's theory and also recommended that the face of the wall be made parabolic in section since the pressure varies as the square of the depth. Another assumption in his theory was that the friction along the base of the wall aided the stability against overturning.

Up to 1773, all the attempts at the theoretic determination of the lateral pressure of granular materials began with the assumption of a definite plane of rupture, usually the plane of slope. Coulomb eliminated this assumption by deriving an expression for the pressure caused by a general wedge. Then letting the first derivative, with respect to the variable wedge angle, equal to zero, he obtained the value of the wedge angle corresponding to the maximum pressure. In this way he introduced the idea that a wall must be designed to withstand the maximum pressure; previous investigators had not considered the possibility that their methods might not picture the worst case.

Coulomb's essay on the application of the rules of maxima and minima to the statics of construction (1773) gives a remarkably complete analysis of the action of granular materials. He uses as his basis the laws of friction and cohesion for solid bodies which he assumed also hold for granular bodies:

1) The frictional resistance on any surface is equal to a constant, the coefficient of friction, times the normal pressure on that surface.
2) The cohesion resistance is equal to a constant times the area of the surface.

With but few exceptions, later writers have accepted these laws. Coulomb further assumes a plane surface of rupture for convenience of evaluation, and sliding of that wedge which will cause the maximum pressure. He gives no proof for this; later investigators have shown that these two assumptions are not consistent, for wedges bounded by curved surfaces of rupture may cause greater lateral pressures than Coulomb's wedge. The pressure exerted by this wedge is due to its weight and is decreased by the frictional and cohesive resistances along the plane of rupture. Disregarding friction along the wall, the pressure is horizontal. However, he states, if the wall is rough, there is frictional resistance, equal to the normal lateral pressure, times the coefficient of friction, which resistance must be subtracted from the weight of the wedge whenever there is motion between the wall and the fill.

To allow for cohesion, the true pressure equals the value obtained by disregarding cohesion less the pressure on the height of earth which is naturally self-sustaining. Nowhere in his discussion does he make mention of the angle of repose; his theory considers only the coefficient of friction inside the mass.

Woltmann (1790) translated Coulomb's theory into German and simplified the resulting equations by assuming that the tangent of the angle of repose was the coefficient of internal friction. Up to a very recent date this assumption has been included in practically every description of "Coulomb's theory." Prony (1797) simplified Coulomb's discussion by introducing trigonometric functions, and showed that, if the tangent of natural slope is the coefficient of friction, for the case of a vertical wall, the plane bounding the wedge maximum pressure bisects the angle between the wall and the natural slope. Since the coefficient of friction is a constant, the natural slope and the plane of rupture are constant. Coulomb used the width of the wedge as the variable with respect to which he differentiated to obtain the condition for a maximum. Prony used the angle of the wedge, which is really the independent variable; the width of the wedge is a function of this angle and the height. Prony's method is the more general one for it may be used where the surface of rupture is not assumed as plane.

Mayniel (1808) extended the wedge theory to the case of a sloping wall, assuming the pressure as normal to the back, and taking into consideration the friction and cohesion along the plane of rupture and the friction along the back of the wall. He does not accept the assumption of the equality of the angles of friction and natural repose, though he mentions that Prony had made such an assumption. The mathematical work is very detailed and complicated, but as he says: "That is because of the general nature of the solution; we must take into account all the points of the problem." In summarizing previous theories he distinguishes between two types of friction in soils:

1) Perfect friction, as in sand, is caused by the intercogging of particles, acted upon by a continuous pressure, and is to be distinguished from cohesion which is a reunion of masses, like a glueing together.
2) Imperfect friction is the rubbing or rolling of particles over each other, due entirely to their own individual weights.

Mayniel also gives a clear picture of how earth exerts a lateral pressure behind a wall: A certain part of the fill in the shape of a wedge with the apex at the heel of the wall slips down on a surface which is probably a plane; this material is not the entire volume which tends to slip, for later slips do occur if the wall slips or fails, but these do not concern the problem of the existing pressure.

Francois (1820) repeated Mayniel's work including in the discussion Woltmann's assumption. The total angle between the wall and the plane of rupture is taken as the variable. The effect of surcharges was studied by Navier (1813-1826) who also derived the most general formula for the lateral earth pressure acting normally to the wall. In the case of surcharge, he showed that the resultant must act at a point higher than 1/3 the height of the wall. Considering a bank of earth in equilibrium, the material above the plane of repose is prevented from sliding by the friction and cohesion along this plane. From this is evaluated an expression involving the tangent of the angle of natural repose in terms of the coefficient of friction and cohesion and the height. For small heights, he showed, the face of the earth bank may overhang and still be in equilibrium. When the cohesion is zero, the expression for the tangent of the angle of repose becomes the coefficient of friction, showing that Woltmann's assumption is only true when there is no cohesion.

Still tending towards a general solution, Audoy (1820) does not accept the assumptions of uniform density, friction and cohesion, but regards each as a general function of depth. Taking the pressure as normal to the wall, he derives a most complicated expression, which is of no use because of the lack of information of the factors involved. By accepting Coulomb's hypotheses the formula resolves into the result of Francois' theory.

But few advances in theory were made between 1820 and 1840; however, the experimental determination of the necessary facts upon which to base theory was begun. The work of Huber Burnand (1828) on the physical characteristics of sand and Hagen's experiments showing the presence of a vertical component are most noteworthy, (1833). The latter also developed the theory of pressures in bins, based on the Coulomb wedge theory.

In spite of the considerable advances made in the wedge theories, many authors have reverted to the older ideas, very often appearing quite ignorant of the fact that the older theories had been modified. The French Department of Fortifications had not immediately accepted Coulomb's theory but used the method of de Montlong (1774). The plane of rupture was assumed to pass through the toe of the wall and, in equating moments, the material between the plane and a parallel plane through the heel was assumed to aid stability.

Chauvelot (1783) rejects all previous theories (he does not mention Coulomb's) because of the large number of assumptions required. Experiments showed that the natural slope of sand was 39° 21 , yet he recommends that a 45° wedge be assumed for all materials. The weight of the wedge is resolved into components; the lateral pressure is equal to the component acting normal to the wall less a correction for friction and cohesion in the fill and the point of application is at 2/3 h from the base.

Gauthey (1785) obtained experimental data absolutely proving the existence of a wedge of maximum pressure, where the plane of rupture bisected the angle between the vertical wall and the plane of repose. However, he missed the significance of his results, advising the use of d'Antony's theory with the addition that 1/3 the weight of the wedge be subtracted to take into account the friction loss. He was a standard writer on engineering construction, see for example, his wonderful book on bridges. This may explain why his earth pressure theory was so widely accepted; as late as 1865, Curioni and de Benedict advised the use of Gauthey's formulas.

Delanges (1788) made some careful observations of the effect of the moisture content on the natural slope and density of soils, also experimentally determined the lateral pressure of various granular materials, but he applied his results to proving the older theories. Senguin (1792) edited the second edition of Bullet's "Traite", and inserts in a footnote his "newer" theory. The lateral pressure acts parallel to the plane of rupture and the wall is designed by the requirement that the resultant of the pressure and the weight of the wall pass through the toe. Goudriaan (1796) and Bruenings (1803) determine the effect of a 45° wedge; the latter also says that the surface of rupture may not be a plane but he assumes an average plane to derive a formula in the same way as the older methods. Similar disregard of the Coulomb contributions appeared regularly in the literature, even as late as 1911, the London "Architect and Contract Reporter" prints this statement in an unsigned article: "The earth pressure of loose earth is exactly the same as water pressure, being equal to the weight vertically above the area considered and the same in all directions."

EARTH PRESSURE EXPERIMENTAL WORK.

The earliest recorded experimental work is by Belidor, 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. Gadroy (1745), using a test wall 3 in. high, made to check Belidor's theory, concluded that the plane of rupture sloped at

2:3 and not at 1:1, even though the natural slope of the material was 1:1. Rondelet repeated these experiments with a test wall 17½ 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 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 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 counterbalanced by weights similar to the method of D'Antony. He then changed the wall to a gate made up of five parts, in a smaller bin, making each part 1-1/2 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 1-1/2, 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 67-1/2 deg. In this way he proved that the material below that plane had no effect on the pressure against the vertical wall.

Delanges, describes some experimental work on the shapes that semi-fluid materials will take and the vertical pressure in the 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.

The earliest large scale apparatus was built by Woltmann, a box 1.72 m long, 1.15 m high and 1.15 m wide. 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 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.

The experiments conducted at Alexandrie in 1805, at Piedmont in 1806 and at Juliers in 1806 and 1807, were started by Major of Engineers Laulanier, continued by Lieutenant Derche and were completed by Mayniel. The first apparatus built was a box 2 m wide, 1-1/2 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 experimenters 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, was 3 m long, 1½ m wide and 1½ 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 the 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 1/4 to 1/3 of the weight of the wedge of rupture when the fill is loose, and from 1/7 to 1/20 of the weight of the wedge of rupture when the fill is packed.

A very similar apparatus was used by Martony de Koszegh, 2.85 m long, 0.95 m wide and 1.90 m high. Pressures were also measured by a friction dynamometer. 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. A detailed report of all recorded experimental work was prepared by the author in 1923, and filed with the Engineering Societies Library in New York, and a summary was published in the Proceedings of the Highway Research Board, 1940.

PRESSURE ON BIN SIDES AND BOTTOM.

In addition to the military problem of fortification walls, the French Engineers spent considerable effort to solve the problem of bin storage, which had a practical application in the magazine silos. Moreau (1827) reported on the practical considerations of silo planning, above and below ground, and of square and circular sections. Both Moreau and Huber-Burnand knew that the base of a bin did not support the entire load above it. The latter proved it experimentally (1829), by weighing bottomless boxes filled with sand and with top soil, as they were lifted free of the supporting floor. Moreau and Niel(1835) experimented with a similar device, but with only part of the bin bottom detached, and showed how an arch formed over the opening and the pressure on the opening was independent of the height of the fill and of any surcharge placed thereon. In some cases, the surcharge loads actually decreased the pressure exerted on the bin bottom. Some of this experimental work was performed to determine the pressures at the bottom of the fills due to surcharge loads.

SOIL PHYSICS STUDIES.

Couplet (1726) pictured soil as a pile of spherical grains, arranged as tetrahedra, either one grain on three or one grain on four. Gauthey tried to check this picture experimentally, but found that soils did not fracture along a natural slope line, as did the piles of spheres. Gadroy (1745) studied the erosion of soil slopes and concluded that the windward side was more affected and the amount of erosion from wind and rain was smaller for soils with smaller natural slopes. That soil can stand vertically and even overhang seems to have been fairly well known, but Coulomb (1773) was the first to determine the height of soil which can stand vertically as a function of the cohesion and internal friction. This formula he obtained by determining the height for which his general formula showed a zero value for the lateral earth pressure.

Delanges (1788) quotes two earlier authorities as having distinguished soils from solids or liquids: Galileo stated that semi-fluids in contradistinction to liquids "when heaped together maintain their condition; and when hollowed up to a certain mark, the cavity remains, without the surrounding parts flowing to fill it again; and when agitated and disturbed they quickly settle, as soon as the outside motion slackens." And further he finds cause "to be able to very reasonably argue that the smallest parts of water into which it seems to be resolved (since it has less consistency than the finest powders whatsoever, in fact it has no consistency) are very different from the smallest divisible quantities." Lambert (1772) on the other hand, claimed that restrained bodies of soil reacted more like liquids.

Delanges carefully measured the natural slope of several materials and noted that each had a definite slope, which was greater for rougher surfaced and for larger sized grains. He states that liquids assume a level surface because they consist of a minute smooth-surfaced spherical grains. Experimentally, in cylindrical and conical vessels, with loose bottoms, he proved that the bottom supported less than the total weight, of the contained materials, and correctly deduced that the reduction was caused by the friction along the sidewalls. When openings of various sizes were opened in the bottom of the vessels, the flow of the various granular materials seemed to be independent of the depth of the fill, and always ended with a conical cavity of fixed slope for each type of material. Then using glass cylinders and placing horizontal layers of grains stained different colors, he could watch the sequence of flow from the different depths and the relative velocities of motion. In similar experiments to measure the flow through horizontal openings, Delanges derives a result analogous to the flow of liquids through an orifice, modified by taking into account the fact that the particles arrive at the orifice "with a rate of speed much less than that which would be suitable for a free drop." This work was later repeated and expanded by Huber-Burnand (1829) with the same conclusions.

Woltmann (1802) studied the stability of slopes in canal excavations and derived a formula for determining such stability. Goudriaan (1810) developed the effect of different shaped waves on shore erosion and understood the mechanics of wave action and energy transmission from water to sand along the beaches. In 1796, he wrote on wood sheet-pile and other shore protection methods.

FOUNDATION AND PILE STUDIES.

Although the art of foundation construction must have been well established by 1772, it was Lambert who first made an attempt to rationalize the design of spread foundations as well as the use of piles. Some of his conclusions were based upon observation, and others on the results of experimental determination of settlements from static and falling models resting upon and "immersed" in sand.

An extensive research into the value of sand piles for consolidation and stiffening of miry soil, made necessary for the design of foundations at Bayonne, France, was reported by Moreau (1827). Among the basic conclusions is found proof that soil can be consolidated to a much greater volume reduction by driving piles which are then withdrawn and replaced by "very friable stone reduced to powder," than by surface ramming. These sand pile foundations were test loaded, by load increments over long time periods, to a maximum of 66,000 lbs. on nine piles, 8½ in. diameter and 4½ ft. long, spaced about 16 in. on centers. Preference of sand piles over timber piles is also expressed because they act as wells into which the adjoining earth drains and therefore permits better consolidation.

In attempting to measure load distribution through soil by weighing the load carried on a loose panel in the bottom of bins, Moreau concludes: "Whatever may be the original pressures, when a portion of the bottom commences to give way, it is relieved of most of the weight upon it" and so "whatsoever may be the differences of resistance of the bed of the foundation, no part of this bed can yield without the pressure upon it decreasing or the neighbouring parts giving way at the same time and the settlement becoming uniform in sequence." Which is a simple and true description of what is now called "limit" design.

Neil (1835) experimentally determined the extent of load distribution through soils by noting how close to a load he could safely remove the soil slope. This information he applied to actual designs of foundations supported by layers of sand placed on soft clay and mire. Parallel loading tests on soil excavated in pits, with and without sand pads, were carried over 14 day periods. In a pit 4 ft. square and 9 ft. deep, a 4 ft. depth of sand reduced settlement values to almost one-third, the loading being 4000 lbs. per sq. ft. These methods of sand bases and sand piles to carry loads in alluvial silt soils were used at Bayonne, Marseilles and Paris, on a number of noteworthy projects in the first half of the 19th century and only recently have been recognized as proper methods.

Brünings in "Over de Zijdelingsche Drukking der Aarde", some 100 pages summarising earlier work, (1803), ends with a very fitting quotation for this paper: "If these our good intensions shall be of service to any and favourably received, we have our end."

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