THE ROLE OF SOIL IN EARTH-FILL DAMS

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The Role of Soil in Earth-fill Dams

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CHAPTER I

INTRODUCTION

The particular purpose of this study was to investigate the functions of soil in earth dams and the various means used to attain these functions. It is further hoped to present at the end of this paper, suggestions, which might guide later students towards particular lines of study.

The subject of earth dams is perhaps one of the most hazy in the minds of students. And the average citizen of the United States would hardly have a thought that soil could be used as a building material other than in the form of aggregates.

Additional publicity will not harm anything and will perhaps save the citizen some money in the form of taxes.

There are two terms, consolidation and compaction, which are used in construction wark and which are often confused. They should be defined at this time to eliminate possible future confusion. Consolidation refers to the gradual increase in density of the soil due to static loads, generally its own weight or the action of water. Compaction refers to the increase in density of soil due to moving loads such as rolling, tamping, etc.

CHAPTER II

A BRIEF HISTORY AND REVIEW OF EARTH DAM FEATURES

A dam has been defined as a barrier to contain or keep back a body of water. During the days of early history, mankind had no access to engineering literature; but, nevertheless, he was pushed into making various types of crude structures to protect himself from the ravages of the swirling water. The earliest recorded notes concerning the restraint of the flow of water come from the Nile Valley, the Euphrates and Tigris River region, and parts of India. By this early date these areas were either already showing signs of being parched or had too much water in the wrong places from floods. It was the logical conclusion that artificial means must be resorted to if the people concerned were to stay on their paternal lands.

In India, the lower ends of natural depressions in the ground were walled off with earth and water was collected behind the walls to be used as needed. These undertakings were in the nature of community or area enterprises. Such bodies of water and their impounding walls are now called tanks in many lands, including the United States. The Veranum Tank in India has a water area of thirty five square miles restrained by a dam of silt-clay soil twelve miles long. This tank has existed for unnumbered centuries.[1]

How did these structures to store water come into being? Early writings show that man was building low

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1 John C. Page, "Dams," Encyclopedia Americana, VIII, p.433.

embankments of loose earth, perhaps using a few rocks and timbers that could be carried to the site on his back. His methods included carrying dirt to the site in baskets and, at a later stage, tamping the dirt with his feet to compact it, thus slowing down seepage and reducing settlement. Possibly even wooden or stone tampers were used. These last two items definitely showed up in construction a few centuries later. After these lowly beginnings came the basketwork dam of moderate height, fifteen to thirty feet, and now the great giants of today.

Single purpose dams have in most cases given way to multi-purpose projects which call for larger and larger amounts of stored water for power, recreation, flood control, etc. The ever expanding industries of today demand more and more power which is most effectively used in the form of electricity. More power demands in turn more feet head of water stored at the dam.

The reasons that earth was used in ancient times were controlled by economics and environment. The dirt was close at hand, at the most only a basket-haul distant. All that was generally needed was a little loosening. Ancient man was no stranger to the uses and presence of dirt as he not only lived on it, but beside it on his skin, and under it in the form of a cave or a hut. Also, at the beginning, there were no tools available with which to use other materials.

The reasons just stated still hold with the exception of the last. The study of soil mechanics has resulted in the advance of many theories as to why the earth reacts in certain situations and has enabled us to use earth to a much greater advantage than was ever thought possible. In the last fifteen years, earth moving machinery has advanced in great strides to the point where earth can be moved ten, and more, cubic yards at a time and at a speed of thirty miles an hour! But the fact still remains that earth dams are selected because the necessary fill is available nearby and can be utilized more economicly than the expensive process of hauling in cement and reinforcing steel. Then too, "No type of structure that man builds to confine water can compare in permanence with earth dams."[2]

This paper is concerned with the relatively large dams used for flood control purposes, power, and irrigation. Low embankments and levees will not be discussed although many of the things stated here will apply to them as well.

In the past the public has seen news items about levees during flood times, and when an earth dam was brought to their attention it was considered merely a matter of sand bags and piles of earth. This misconception resulted in several failures in early earth dams. These dams were not designed by qualified engineers and competent supervisory personnel were not placed in charge of the work. This

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2 Burr Bassell, Earth Dams, p. 6. ?

problem has been partially solved in the last few years, but the education of both the public and the engineering profession must continue until the place of the earth dam is understood by all.

Besides the points already suggested for the selection of an earth dam, there is one feature which lends its use very well to the landscape engineer or the conservation officer, in situations where looks are one of the guiding factors. This feature is the ease with which the earth dam can be blended in with its surroundings. If the country is primarily rocky, both slopes of the earth dam can be covered with rock riprap. If the country is predominantly grassy or wooded, the downstream slope can be completely sodded and the upstream slope sodded down to the predicted high water level, with the rock riprap below that covered by the water. Whereas, the concrete dam will always stand out with its characteristic color and in many cases, a downstream face which is very badly stained.

CHAPTER III

DESIGN AND CONSTRUCTION

Present dams are often a unit of a large overall program, examples of which are the Tennessee Valley Authority and the Missouri Basin Project. But whether for a large organization or for a small private power company, once it has been decided that a dam is needed in a certain area, the procedure then followed is essentially the same.

The first phase of the project is a series of preliminary studies, often called paper reconnaissance. The best maps of the area are procured, usually from the United States Geological Survey or from the United States Coast and Geodetic Survey. From these maps an outline of the catchment area is prepared. This outline is the basis for the gathering of all information regarding rainfall, floods, and other data which would influence the characteristics of the flow of water in this particular area. If the rainfall and rate of flow information cannot be obtained from reliable sources, this is the time to establish rainfall gaging stations and flow stations throughout the catchment area. A few months to several years may elapse between these preliminary studies and the final design of the complete dam structure; and any accurate information obtained during this interval will be welcomed by the designing engineers.

The reservoir basin is selected with land economy and water storage the controlling factors. Land economy is not a dominate factor in the western states but it has appeared in the Tennessee Valley Authority and the Missouri Basin Project.

in the eastern part of the country, land values are high and the area to be inundated must be carefully calculated. All land not a part of the public domain must be purchased from the private owners, sometimes at a very high cost, even without consideration of the legal expense involved.

In addition, the total water surface to be exposed to the air must be considered. In some parts of the country, an evaporation rate of ten to twenty inches of water a year can be expected with no detrimental effects. Swinging toward the other extreme in the Southwest, an evaporation rate of eighty to one hundred inches a year is not uncommon. In this area water is more of a concern to the people than the cold war now raging in other parts of the world. A loss of this proportion can be enough to reduce the water behind the dam to a point where the committments cannot be met.

A consideration of the preceeding information will narrow the possible dam sites to a minimum. Aerial photographs can be used very effectively at this point to clear up any questions which might arise concerning any particular point.

With the larger types of dams, the expense is not the greatest factor in influencing the final decision as to the final site. The amount of water that must be stored to prevent disastrous floods or to provide a sufficient amount for irrigation are primary, then the other factors will follow along.

At this point preliminary, on the spot, investigations will be initiated. These consist of the preparation of topographical maps of secondary order of the possible dam sites, random borings, and test pits in likely areas; and then, back in the office, tests of materials as found at the various sites. Finally fough estimates of the cost of the various types of dams at each location are figured to aid in the final decision.

The selection of the site can be influenced by the results of the borings and test pits; but these two items will have more effect on the shape and size of the dam. The decision to employ an earth dam can be influenced by many things other than have already been mentioned. The borings might show that bed rock lies one hundred fifty to two hundred feet beneath the layer of river fill. This would require an enormous amount of excavation and concrete to construct a safe masonry dam. Yet an earth dam can be built which will have a good safety factor.

This can be done by spreading the base of the earth fill out until the resultant soil pressure has been reduced to the point where settlement is of minor importance. In the spreading out process, the earth dam is exposed to another danger, that of erosion from heavy rains. One way to reduce the erosive action of the rains is to establish berms on the slopes of the dam as shown in fig. 1.

Dam Profile With Berms

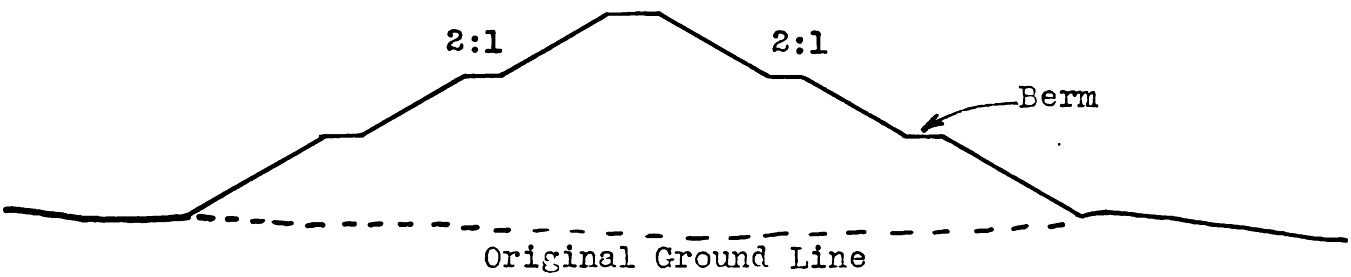


Figure 1.

The berms are pitched towards the center of the dam to collect the rainwater and conduct it by means of ditches to a masonry gutter which leads the water safely to the bottom of the slope. As can be seen, the berms are used to spread the base of the dam without flattening the slopes.

If a diversion channel is to be dug, a large amount of earth must be moved. The most economical method would be to use it right in the dam. There are always exceptions to the rule. The Anderson Ranch Dam has a spillway channel constructed in solid rock. Of course, if the bedrock is overlain by only a couple feet of topsoil, the selection of an earth dam is dependent on the finding of good barrow pits at a reasonable hauling distance. In this case the cost of hauling cement, aggregate, and steel reinforcement from the railhead must be balanced against the cost of hauling the fill dirt from the distant barrow pits.

With the site selected, a detailed topographic map, based on the preliminary map, will be built up with additional field work. This map, or copies, will be kept up to date as the construction progresses, showing the true picture of the area.

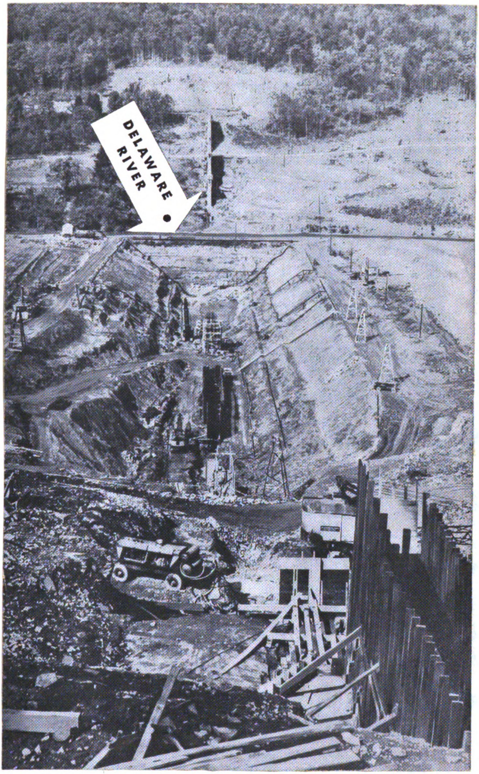
Systematic borings and test pits will be made at the dam site, the diversion channel site, and at the proposed barrow pits. The results obtained will influence the design and the methods of construction. A coordinated system of borings is more likely to reveal faults and slippage planes. These planes will be hard to find in the foundation. The extent of the possible fill material upstream from the dam can be obtained from the borings. It is a good thing to deepen the channel for a ways upstream from the dam as this will provide a place for the silt to settle out. It will be dependent upon whether or not excavation in front of the dam will weaken the foundation.

All of the preceeding information is now correlated and placed in the hands of the designers. Detailed plans are made for each part of the structure, including the dam itself, the spillway, intake, forebay, outlet, powerhouse, access roads, bridges, temporary or permanent, and other details peculiar to each dam. From these plans the engineers prepare the engineer's estimate. This estimate is used to compare with the bids entered on the construction of the dam and also to form a basis for the financial maneuvering which must now begin if not already in progress. In many cases the original appropriations will not be large enough and more money must be procured.

With the letting of contracts, the construction starts. Access roads, bridges, and living quarters are started initially. As soon as the working force can be built up, the preliminary operations are started at the dam site. One of the first problems is to move the river out of its course so that the foundation area may be prepared. This can be done by means of a diversion channel, a tunnel, or by cofferdams. The method of construction of an earth dam is such that the use of cofferdams is limited, with the exception in the case of a cofferdam thrown across the breadth of the river upstream of the main dam to divert the water from the construction area. Then during construction, the cofferdam can be made a part of the dam at the upstream toe.

The damsite is cleared of all vegetation and, if the inundated area is not too large, it would pay to remove the trees and large brush in the reservoir basin. A benefit from this activity would be the use of the lumber and timbers that could be sawn at the site. The clearing operations would lessen the possibility of stoppage of the intake or damage to the turbines by driftwood.

Depending upon the design, the foundation area may have all soil stripped down to bedrock, or trenches may be sunk down to the rock or to the desired depth for the erection of cutoff walls. Figure 2 shows some details of a foundation trench with the construction of a cutoff wall in



DOWNSVILLE DAM

Figure 2.

progress. In the distance can be seen wingwalls on the sides of the embankments. These are actually cutoff walls extending as shown to prevent percolation through the ends of the dam. As can be seen in the figure, the cutoff walls are concrete with steel sheet piling as forms. Sometimes the cutoff walls are made of steel sheet piling only.

Another form of cutoff wall is the clay puddle. The term puddle does not necessarily mean mixing a gooey mass of clay and water. One type of clay puddle consists of a mixture of clay, sand, and gravel mixed with water to a stiff consistency and then tamped into place. This will form a watertight membrane. The function of a cutoff wall sunk either to bedrock or to a predetermined depth below the dam, is to reduce seepage through the foundation and to lower the line of saturation.

Very careful preparations are made to assure a bond between the first layer of earth fill and the foundation. In the case of bedrock, compressed air is used to clean the rock; and, at this point, the plans might call for grouting all cracks and crevices in the rock. This will depend upon the condition of the bedrock. The concrete cutoff walls are usually extended a few feet into the main body of the dam or almost to the top to aid in keeping seepage down and to provide stability.

With earth covered foundation, the top layer of soil is scarified so that the first layer of fill will be able to mix with it.

If the spillway is a part of the dam, its construction should be accelerated so that the concrete walls will always be higher than the fill surrounding them during compaction. This will enable special small rollers and hand tampers to compact the soil right up to the wall. Hand tamping with hand operated vibratory hammers is an expensive process. To cut the hand work to a minimum, a small sheepsfoot roller has been developed which has no frame on the outside except for the hitch to the prime mover. This enables the roller to be moved right up next to the wall.

The fill for the impervious section can be moved into place by carryall, truck, conveyor, or combinations of these. The movement of carryalls and trucks should be routed carefully on the fill to prevent too much travel in one section. The large rubber tires of the vehicles tend to form a crust on the fill with little compaction underneath the surface. Many specifications call for the crusted section of the fill to be disked or broken in some way immediately before the succeeding layer is laid to assure maximum bond. A moistening operation might also be carried out before the new layer is laid. The layers should be sloped away from the center of the dam to shed rain water readily. A well compacted surface sloped in the correct manner will shed a night's rain and be ready to receive more fill by the beginning of the next day's operations.

Again to assure bond and stability between sections, the semi-impervious and pervious sections are carried up along with the center core. The semi-impervious sections usually consist of moistened rock screenings and the pervious sections are of rock.

The dam is completed by laying riprap on the upstream slope for wave and ice protection and either sodding or laying riprap on the downstream slope.

The operation of the dam consists of maintaining the proper flow of water through the outlets and spillways and taking all measures to prevent the water from overtopping the dam as this has been disastrous in all cases. The construction is such that large masses of water moving over the top will erode masses of fill away and collapse others.

Maintenance consists of keeping the outer surfaces of the dam in repair and a schedule of inspections to assure the continued safety of the dam. One of the things to look for is seepage from the downstream toe or moist areas on the downstream face. This is an indication of undesired high percolation and must be taken care of.

CHAPTER IV

LABORATORY INVESTIGATIONS OF SOIL

As stated earlier, soil mechanics has played an important part in the construction of earth dams in the past few years. The latest findings have enabled us to build the dams bigger and higher and in locations where, at the turn of the century, an engineer would have been called crazy to even consider the possibility of constructing a dam there. An example is the Garrison Dam on the Missouri River. A rock formation was found at a considerable distance below the surface under deposits of well consolidated silt and clay. This material is subject to much deformation under heavy loads, but the dam was designed as an earth dam and allowances made for two-way settlement. Today even the textbooks on soil mechanics admit that their subject is not an exact science, but enough information can be obtained from the application of soil mechanics to help us measureably in the design of earth dams.

When the soil samples are procured from the site investigations, four major laboratory tests are performed upon the samples: compressibility, shear, permeability, and optimum moisture content. Several other tests are performed to identify the various soil types encountered. They are: void ratio, specific gravity, specific weight, porosity, water content, degree of saturation, effective size, and the Atterberg limits. The four major tests mentioned first, however, are the ones that actively affect the design of a dam by making possible a prediction of the behavior of the soil.

PART I

COMPRESSIBILITY

The first test, compressibility, can be defined as the measure of the volume change produced by an increase of pressure acting on the soil. The volume change can be accomplished by a decrease in the volume of the voids, or by a reduction of the contained water through squeezing the water out of the soil. The soil itself is not being compressed but rather is shifting and deforming under the pressure to meet the changed conditions. The water must flow through the soil to escape, thus compressibility is contingent upon the permeability of the soil.

Pressure can be applied to the soil in three dimensions, but the science of soil mechanics is limited at the present to one dimension. Consolidation was defined at the beginning in order to definitely limit the word in its meaning. The reason for this is apparent when one looks through several soil mechanics books. Taylor in Fundamentals of Soil Mechanics says "This one-dimensional compression involving a slow escape of water, gradual compression, and a gradual pressure adjustment is called consolidation."[3] Here compression and consolidation are linked together. In other writings compression and compaction are used interchangeably with no distinction made between the two. It would be best to use compression as defined first in sonnection with soils

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3. D.W. Taylor, Fundamentals of Soil Mechanics, p. 212

to eliminate confusion.

There are several different types of equipment which have been designed to determine a coefficient of compressibility. they can be divided into two groups. It is necesary in all cases to duplicate the moisture content and density which will be found in the field. In the first group are the tests in which a sample of soil is placed into a cylinder and then confined at each end in such a manner that only water can escape. Pressure is applied and the deflection of the moving end recorded. The information is plotted on a load deflection diagram and a coefficient determined for the particular pressure to which the soil will be subjected. The coefficient is defined as the volume change per unit volume divided by the pressure. $C_c = \frac{\Delta}{nd}$, in which Δ is the measured deflection in inches, d is the thickness of sample in inches, and n is the applied pressure in pounds per square inch. A steel cylinder is used with one movable end. This method keeps two dimensions constant and allows only one to change.

In the second group are the unconfined compression tests. An example of which are the tests performed during the site investigation for the San Jacinto Dam near Houston, Texas. These tests are performed in the field immediately after the samples are removed from the core sampler. The speed used is to cut down evaporation losses which would affect the test if not retarded. The same principles apply as in the first group except the sample is not rigidly contained. As long as standard conditions are maintained, a load-deflection diagram may be drawn up and the desired information extracted.

The equipment needed is a simple bench with a pulley arrangement for applying the load and a means of reading deflections. A sample of sandy or gravel soil would offer no resistance on this machine and have little or no values. The advantages of this method is its simplicity and light weight of the testing frame making it ideal for field work.

The effect of compression on two different types of soil illustrates the reasons why the compression test is a part of the standard testing procedure. When a load is applied to a sample of sand, 95% of the ultimate deflection occurs within one minute of the application. On the other hand, a sample of clay will take considerable time to reach the ultimate deflection; there will probably be an appreciable amount of deflection between thirty minutes of application and one day of application.[4]

4. Ibid., p. 215-9.

PART II

SHEAR

In addition to the vertical forces producing compression in the foundation, there will be horizontal forces acting on the dam tending to slide the dam or portions of the dam downstream. These horizontal forces produce a condition or a result called shear. This shear can be accomplished in two ways. In one, part of the mass remains stationary and the rest of the mass moves relative to the first. In the other, one part of the mass moves in a direction opposite to the direction of movement of the other portion. This movement tends to take place along a plane or a series of closely related planes.

In general, vertical shear planes are curved due to the internal friction of the soil. This internal friction is thought to be one of the elements of the resistance to shear along with the surface tension of the capillary water contained within the soil. This is illustrated by the fact that a dry soil has less shearing resistance than when it is wet. Sand which usually is considered as having no shearing resistance, will develop a small shear resistance when moistened. Shear is a phenomenon such that when it occurs, failure has taken place or is impending.

The possible rupture or shear plane may be in one of three locations. First in the dam itself. This is generally manifested in the form of a lateral movement of a portion of the dam. It is possible to produce this condition in all soils by increasing the height and slope of the earth fill. Flattened slopes are a means to stabilize the fill in an earth dam. This location will require tests of the fill material after it has been compacted to determine the resistance to shear which has been developed through compaction.

Secondly, shear may occur between the base of the dam and the foundation. This would be very difficult to test. The safest way is to be guided by the experience of others, and do every thing possible to assure the maximum bond at this juncture.

Thirdly, the failure may occur within the foundation. When the foundation consists of rock, a series of well chosen samples should be taken to determine the condition of the rock in the foundation. The presence of small or large fault lines will have an effect on the design of the dam. A study of the angles of inclination of the fault lines will give the experienced observer a clue as to the possible points of shear. Good design is the best corrective measure.

A foundation material of soil also has to be well sampled. Shear tests conducted on the samples can lead to predictions as to future slides and also to possible corrective measures which might be taken, such as wooden or steel pile walls, or excavation of the offending material. The latter might be done in the case of a layer of fat clay which lies a short distance below the surface of the original soil. This condition is more than likely to result in a slide of a portion of the dam due to shear taking place within the layer of low shear resisting clay.

The determination of shear resistance is as approximate as the other tests used in the study of soil mechanics. Taylor in Fundamentals of Soil Mechanics[5], lists seventeen different factors affecting shear strength. They are of such diverse nature that the engineer in the field can only set up a shear testing procedure and then make sure the testing standards are kept the same at all times. Included in these standards should be one which requires that the structure of the samples to be tested should be the same. This will require undisturbed samples or samples compacted to the same density. Another important item is the fact that confined water will carry part of the applied load. Thus, the water content must remain the same for each sample during the test, in order for comparable results to be obtained.

There are two shear tests which are perhaps more adapted for use in the field than other more complicated ones. In one the sample is an undisturbed core which is tested in the same cylinder that originally received the soil. In this way disturbance of the soil structure is reduced to a minimum. The cylinder is especially made for this test. It consists of two cylinders about three inches

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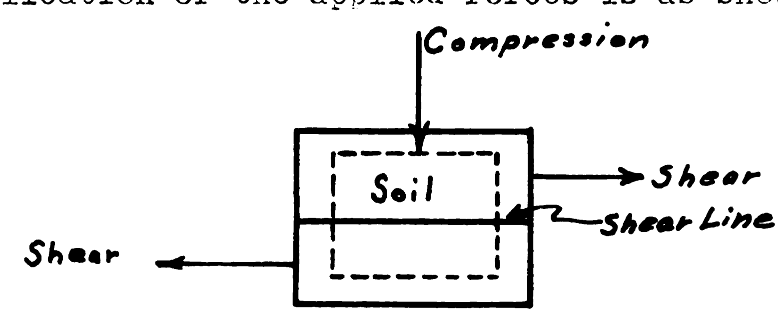
5. Ibid., p. 364-5.

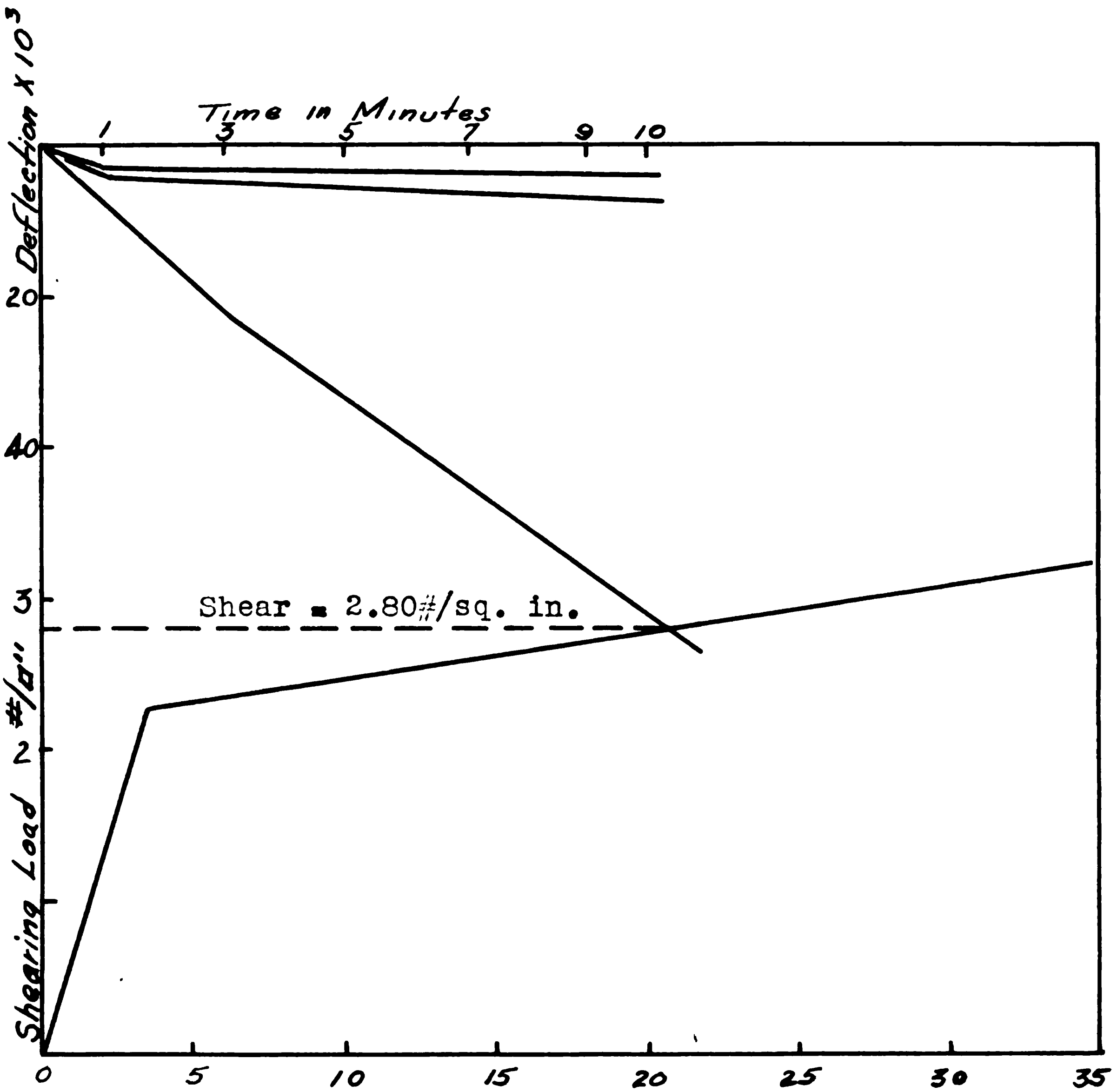
long separated by a short cylinder seven eights of an inch long. The three inch cylinders are clamped in a jig and a deformation dial is mounted to bear on the top of the short cylinder. At the bottom of the short cylinder is attached a loading tray. After the setup is complete, the dial is zeroed and increments of loads are added until failure. Each increment is left on the tray for a period of ten minutes.[6]

The information gained is plotted on a graph as shown in figure 3, and a value is obtained for the ultimate shearing resistance in pounds per square inch. This test is for cohesive clay soils only and would not give satisfactory results when used with sand. No attempt is made to keep the contained moisture constant other than using the sample immediately after the paraffin is removed. In this test the clay soils retain the water while the more granular soils would let the water escape.

The second shear test is similar to the first except that there is single shear and a compressive load can be applied at the same time the shearing force is applied. The application of the applied forces is as shown:



6. William S. Housel, Applied Soil Mechanics, p. 61-6.



SHEAR RESISTANCE TEST

FIGURE 3.

This test is representative of the forces that will be applied to the foundation and fill material , and perhaps is more used in connection with earth dams than the first test. With the compression load constant for each run, the plotting of the results could be accomplished in the same manner as in the first test. Several runs could be taken varying the compressive load in each run.

The distinctive feature of this test is that disturbed samples may be used. Each sample may be compacted to the desired density using the proper moisture content. Provisions can be made for the escape of the water throughout the test, depending upon what is desired of the test. The test can be used to examine samples of sand. Too much value should not be attached to the test in this case. Sand has very little cohesion and therefore little shear strength. This is one reason why earth dams are not generaly built on a foundation of sand. There are exceptions, but if a strata of sand is encountered in the foundation, a careful study should be made. Perhaps it can be left there or possibly removed. It is a point of weakness and will affect the design.

PART III

PERMEABILITY

The third major test is measuring the ease with which water travels through the voids in the soil. This property is called permeability, and, in the case of earth dams, is one of the most important tests to be made, both for the foundation and the dam itself. The purpose of the dam determines the amount of seepage that is to be allowed through the dam. A watertight dam could be used for irrigation or power where the water is costly and must not be wasted. Whereas, a flood control dam is used to lower the flood crest and seepage is not too important as long as the dam is not endangered. All earth dams are saturated to some extent, but if the water finds a path by which it can move through the dam and come out on the downstream face of the dam with any velocity at all, trouble will start and, unless preventative measures are taken, a failure will occur. In some cases the water moves through the foundation with enough velocity to carry small particles of soil along with it. The flow path is enlarged and piping results. This will show up at the downstream toe in the form of sand boils. The usual cure for this is the dumping of rock at the point of boiling until no further movement is detected.

A machine used to determine the permeability of samples of soil is called a permeameter. These machines are divided into two groups, the constant head and the variable head designs.

The constant head permeameter is one constructed so that the head or water pressure is kept constant at both the point of influx and efflux. It requires a more elaborate setup to perform the test than the variable head permeameter and is not too suitable for tests of impervious soils as it takes such a long time to complete the test.[7]

The variable head permeameter in its simplest form has a graduated glass pipe fixed in position over the apparatus containing the sample to be tested. A valve is turned and a record is kept of the time required for a certain amount of water to pass through the sample by the action of gravity only. This test can be simply set up for use in the field and will give accurate results.

Because of the stratification of soils, samples should be taken both vertically and horizontally as the seepage will take both paths to pass obstacles. The horizontal samples are the ones which will interest us the most; but in some cases, a layer of soil will run vertically for a distance and then run horizontally. If this happens, the tests are run on the samples of each type to give an idea of what to expect. Test pits are of great help here.

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7. Fred L. Plummer, etc., Soil Mechanics & Foundations, p. 89.

Items affecting permeability are: grain size, properties of the liquid, The void ratio, the soil structure, amount of gas present, and the temperature.[8] For earth dams the liquid will always be water and the properties will not be changing. The amount of gas present would not be too hard to determine in the field, but keeping the amount constant during a series of tests would be rather difficult in this situation.

The other items, grain size, void ratio, soil structure, and temperature are of major concern and a reasonably accurate account must be kept of them, especially the temperature. The others are controlled during the compaction prior to the test if disturbed samples are used. Accuracy of the highest degree need not be strived for as it is common knowledge that widely varying coefficients of permeability will be obtained in the same soil from samples taken just a few feet apart.

It is best to use undisturbed samples for the tests but, if they are not available, disturbed samples may be effectively used as will have to be done in the case of the compacted fill. The method used is to compact the samples to varying densities to represent the possible combinations, obtain the permeability coefficients, and plot them on a graph to the void ratios. The resulting curve will provide information as to what to expect.

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8. D. W. Taylor, Fundamentals of Soil Mechanics, p. 111-2

Darcy's Law, $k = \frac{Ait}{q}$, can be rearranged so that the quanity of flow through a soil may be predicted. k, as the coefficient of permeability, can be expressed in feet per minute, with A as the area in square feet, i as the hydraulic gradient, and t the time in seconds.[9] The difference in head between influx and efflux can be designated H and the length of travel of the water as L. " Then $i = \frac{H}{L}$. The Darcy formula furnishes very reliable results, if the value of the hydraulic gradient i is small".[10]

The knowledge of permeability can be used to construct a flow net for a dam. A flow net consists of a cross section of a dam and foundation, both upstream and downstream from the dam. The net consists of flow lines and lines representing equal pressure heads through and under the dam. The flow lines are always perpendicular to the equal pressure lines. A lot of experience is needed to construct a reasonably accurate flow net; but, when once accomplished, the information gained can be used to great advantage in the design of a dam.

The upper boundary line of flow is called the line of saturation and represents the most critical flow line to be obtained.

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9. Dimitri P. Krynine, Soil Mechanics, p. 52-3.
10. Ibid., p. 53.

If this line of saturation comes out of the dam above the downstream toe, danger is eminent, as explained earlier, and safety measures must be taken. Dense blankets of earth on upstream slope and floor, dense core walls, cutoff walls, interior drains, toe drains, and toe blankets are all measures to keep the line of saturation below the downstream toe.

PART IV

OPTIMUM MOISTURE CONTENT

As areas for excavation are determined, the soil therein is tested to determine its suitability for use in the dam. If suitable, it is stockpiled for future use. In most cases it will be necessary to find borrow pits in order to obtain enough fill. The test for optimum moisture content will be run on the prospective fill material to determine some of the compaction characteristics of the soil mixtures. The procedure was originally intended to duplicate the degree of compaction possible to be obtained with standard rolling equipment under field conditions. The present rolling equipment is now constructed so that the pressure per square inch obtainable can be changed at will. Again, experience is the best teacher in performing the test and determining the specifications for the field compaction.

The test stems from the relation that there is one water content at which maximum density is reached by a particular degree of compaction. The first step of the test is to take a disturbed sample, pulverize it throughly, and then dry it.

The equipment is a standard cylinder of two parts and a tamper which is sometimes used with a guide. The cylinder is assembled and filled one third full with the dried earth. It is then tamped, using a certain number of prescribed blows. Two more layers are compacted in the same manner, after which the top part of the cylinder is removed.

The excess soil is struck off and the cylinder is weighed to find the net bulk weight of the soil, from which the density is computed. A small sample is then removed for determining the water content. This procedure is followed until the density of the compacted soil begins to decrease. After the first weighing and the sample is taken, water is added to the soil sample by increments of a specified percentage of the bulk dry weight. This water must be throughly mixed into the sample before the next compaction is begun.

As with the other tests described, there are many variables present. The number of blows per layer or the height of hammer fall can be changed and a different optimum moisture content will be obtained. The type of support for the cylinder during tamping will have an effect on the results. The National Park Service prescribes a sand box support to duplicate the conditions in the field.[11]

The weight per cubic foot of the sample obtained with each compaction in the test is converted to compacted dry weight per cubic foot. The dry weight densities are used so that all tests can be referred to a standard.

The information is then plotted on a graph with the unit weight plotted against their respective moisture percentages. The graph will show two curves, one for the unit dry weights and one for the unit wet weights.

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11. National Resources Committee, Low Dams, p. 298

The high points on the curves will represent the optimum moisture content. It has been established in the field that it is best to stay one or two percentage points on the dry side of the optimum moisture content for best results during construction. Some clays when too wet and compacted tend to form small shear planes. If these are distributed throughout a whole layer of fill, a dangerous condition exists and will probably cause a failure. With a dryer soil, it is easier and takes less time to add water than it does to dry the soil in case it is too wet. For this reason many borrow pits have to be abandoned because they cannot be drained properly. This possibility should be considered when investigations of the borrow pits are proceeding. Sometimes an adequate drainage system will salvage the pit and save expensive hauling of the fill, or it may be possible to loosen the fill dirt and let it lay for a few days to dry out before using it.

The Anderson Ranch Dam used a belt feeder to move the fill from the borrow pit to the site. The fill in most cases had the proper moisture content, but at times it was too dry. It was then necessary to spray water onto the fill at the discharge end of the conveyor system. An inexpensive method compared to that used at other sites. The impervious material consisted of a sandy clay, of which 95% passed a one quarter inch screen and 33% passed a two hundred mesh. The density obtained under standard compaction was 119 pounds percubic foot with an optimum moisture content of 12.5

The pervious material used was an alluvial sand and gravel. Not so much care was taken with this material, and the material from slides was also used in the pervious zones. It was compacted by sluicing with no effort made to control the amount of moisture present.[12]

Up to now no comment has been made as to the cost and size of the laboratory unit. This can vary from an outfit costing a couple hundred dollars to a setup costing twenty or thirty thousand dollars. The size will in almost all cases vary in proportion with the size of the project. Minimum equipment will include an accurate balance, seives, containers, tools, and some special small equipment for the classification of soils. In addition there will be the special items of equipment already mentioned.

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12. D. S. Walter, "Reclamation's Biggest Earthfill Dam," Engineering News-Record, V. 139, 18 Sept 1947, p. 396-402.

PART I

ROLLED FILL

There are, at present, two methods of consolidating or compacting the earth fill during the construction of earth dams. They are the rolled fill method and the hydraulic fill method. In addition, there are combinations and variations of these two methods, but none are used extensively and will not be discussed here.

Thirty and forty years ago, the hydraulic fill method was much used. This was because in most cases the fill could be moved cheaply and faster by water, and the consolidation was more complete than was possible with the smooth rollers and other equipment used at that time. The inventions and innovations introduced in the design of the earth moving equipment and in the compaction equipment has reduced the advantage of the hydraulic fill to the point where the rolled fill method is used almost entirely on small dams and to a greater extent on the large dams.

The rolled fill method can be more effectively and easily controlled by the laboratory. Whereas, the hydraulic fill method always has the possibility that fingers of pervious material will be extended through the core during the sluicing operations. The limits of the hydraulicked dense core cannot be as well defined as in the rolled fill method.

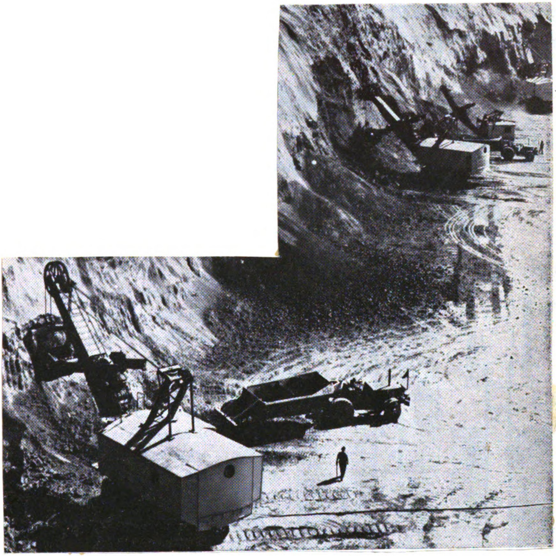
The first step in the construction of an earth dam by the rolled fill method is to determine the dry weight density which is considered desirable for the dense core of the dam. The weight which is to be above a point in the fill should be considered in the determination of the dry weight density. Thus, the desired dry weight density would vary from a heavier weight at the bottom to a lighter weight at the top of the dense core as the fill progresses upwards. The procedure for the determination of the dry weight density has already been discussed. This density will be the goal towards which all the compaction operations will be aimed.

As mentioned earlier, the foundation should be carefully cleaned before the first layer of fill is spread. All loose and weathered rock, trees and bushes, and roots are removed. The fill dirt is brought to the site by trucks, carryalls, or by conveyor belts. The trucks and carryalls can partially spread the dirt as they unload. The conveyor belt will need some sort of supplementary transportation in order to move the fill dirt over the whole length of the site. A large capacity rubber tired wagon called the Mississippi Dump Wagon or Euclid Bottom Dump Wagon is used. This vehicle can move very large loads over short and medium distances. Fig. 4 shows the carryall or scraper in operation. Fig. 5 is a view of a bottom dump wagon.

Part of R. A. Heintz's "Caterpillar" Zoned Equipment fleet, building highway near Moscow, Idaho. In the background a D8 pulls a "Caterpillar" No. 80 Scraper on a medium-length haul. The scraper in the foreground is being push-loaded by a D8. In a moment the "Caterpillar" Diesel DW10 Tractor will roll off with it to a distant fill.

Scrapers

Figure 4.



Bottom Dump Wagon

Figure 5.

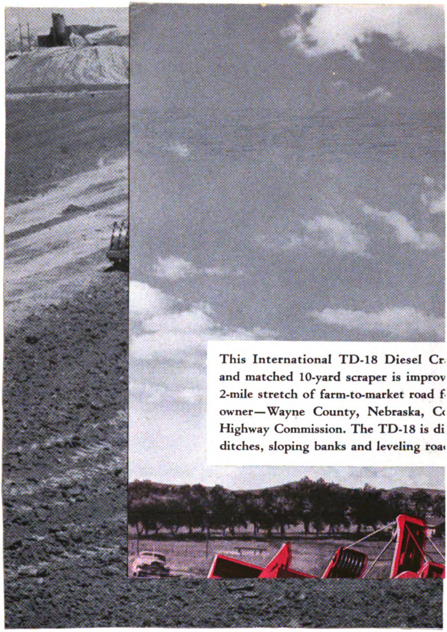
The fill is usually spread to a depth of ten to twelve inches and is then compacted to a depth of six to eight inches. Dozers and road graders are used to spread the fill before compaction. The first layer of fill is very carefully compacted. This is a necessity as one of the most probable routes for seepage through the dam is at the juncture between the foundation and the fill. This is especially true for a rock foundation. An earth foundation can be plowed up or disked before the fill is spread to assure a bond.

Succeeding layers are spread and compacted in the same manner as the first layer. If the vehicle traffic over the fill tends to form a surface crust, it may be necessary to disk these areas before the next layer is spread, again to obtain a bond. One means of avoiding this particular trouble is to route the traffic over the surface of the fill in such a manner as to minimize the traffic over any one section.

Another point for possible failure in the dam is at the line between the concrete structures and the fill. One attempt to avoid this trouble is to construct concrete wing walls extending out into the fill from the main body of concrete to act in the same manner as cutoff walls. But no matter what is put up in the line of concrete work, the fill should be carefully compacted in these areas.

One means of speeding up this operation has been to have on hand a few sheep's-foot rollers which are smaller versions of the larger types used on the main fill. These miniatures are constructed so that there is no framework on the outside of the roller except the hitch to the prime mover. With the use of these midgets, it is possible to compact the dirt by roller within a very few inches of the concrete. The final few inches left are finished off with the aid of pneumatic air tampers operated by hand. The special cuts down the amount of time needed by the hand tampers, thus cutting down on some of the costs. Another way to assure a tight fit between the concrete wall and the fill is to build a slight batter in the wall, so that as the fill is compacted, it is wedged outward from the wall, thus eliminating any tendency for the wall and the fill to separate.

The sheep's-foot roller mentioned above is one of the reasons for the increased popularity of earth dams. Figure 6 shows a view of a sheep's-foot roller in action. The roller consists of a circular drum on which is attached a number of projections which appear similar to small legs with a slight elongation on the front edge which look like small feet. As the roller is turned, the feet and then the legs move down through the loose soil to compact a small portion of the soil at the bottom of the loose layer. The projections are so arranged that they will not enter the same spot previously touched by the roller ahead.



Sheep's-foot Roller

Figure 6.

Also the arrangement is such that only one row of feet are in complete contact with the fill at any one time. This assures maximum load per foot. These rollers act in the same manner as the hooves of animals, whence the name. In fact, before the advent of modern machinery, bands of horses and herds of sheep were driven over new fill in order to achieve compaction at some dam sites. The only improvement has been the mechanization to gain more control over the operation. Further refinements are accomplished by removing projections, adding them, or by adding sand or water to the interior of the drums, in order to increase or decrease the pressure per square inch out at the ends of the feet.

The other earth moving equipment used on the jobs are power shovels, bulldozers, road graders, draglines, and mechanical loaders. These machines are the same as used in other types of construction and will not be discussed here.

As the various operations on the fill are carried out, it is necessary to maintain constant check on the effectiveness of the compaction. This is done by taking samples from the compacted portions of the embankment and performing the test for the dry weight density.

The procedure followed is to use a cylindrical sampler which can be forced into the earth and then withdrawn with the sample inside. To obtain the exact volume of the sample, sand is placed into the hole from a previously measured quanity.

The amount of sand used to fill the hole to the original level can be used to compute the volume of the sample. From this point on, the test is identical with those mentioned earlier.

If the density has varied from that desired, it may be necessary to add or reduce the amount of water in the fill, or to increase or decrease the compaction produced by the equipment. The moisture content should be carefully controlled by the laboratory, using a value slightly lower than the optimum moisture content. To vary the compaction mechanically, it will be necessary to either vary the number of passes of the compacting equipment, or to vary the pressures obtainable from them. Too great a variation would be cause for plowing or disking and recompaction.

There is a danger from over-compaction that should be recognized; this is especially true with impervious material high in clay content. Over compaction will compress the clay to the point where shear planes will be formed, and, if this condition prevails all through a layer of fill, there will be a danger of slides as the embankment is carried higher. The laboratory should be on the watch for this condition, and if found to exist, it should be taken care of before any more material is deposited on the fill. The bad layer can be plowed up and thoroughly pulverized before being compacted again. If the moisture content is at fault, the material will have to be spread out for drying before it can be used again.

Once the embankment has been built up away from the foundation, it will be found desirable to slope the top of the fill away from the center of the dam. The compacted earth will shed water very readily, and, if given the slope of two or three percent, a very heavy and sustained rain can be drained off so that construction can proceed within a very short time after its cessation. If the top had been sloped towards the middle, the water would have collected there and in a short time, traffic would have made an impassable quagmire at the center.

The preceeding material has concerned the impervious portion of the earth dam. On each side of the impervious core will be placed a semi-impervious section and then a pervious section. Their purpose being to contain the impervious core and to protect it from outside dangers. The latter two sections are free draining. The pervious section will consist of graded rock and the semi-impervious section will usually be of the rock screenings plus other graded material if needed.

Because of the porous nature of these fill materials, their compaction is more simple. It matters little if the semi-impervious fill is placed too wet, so it is usually thoroughly sprayed with water before compaction. The rock fill can be dumped in place from trucks and then smoothed up to grade with a dragline.

PART II

HYDRAULIC FILL

The hydraulic fill method of constructing earth dams is still used at times and probably never will be completely abandoned. Its distinctive method of placing fill will always be the most economical at some locations. Actually there is a method of fill called the semi-hyraulic method; but this method is very crude in comparison with the two methods analyzed here and should not be used if at all possible to use a better method. It consists of dumping the fill dirt into the pool of water from trucks or shovels, with no attempt made to separate the fines from the coarser materials. It is true that some consolidation will take place, but no separate dense core will be built up and percolation will not be hindered. This method could be used on the construction of a small water tank on a farm, but it should not be used on anything larger.

The most efficient use of the hydraulic fill method will take place when a good supply of water is on hand, and when the borrow pit is located at an elevation higher then that of the dam site. The fill will be loosened hydraulicly at the pit by means of a stream of water from a pressure nozzle. A view of this operation is shown in Figure 7. The mud is collected in a pool and is sluiced down through pipes to the dam site.

Hydraulic Sluicing Operation

Figure 7.

Before actual sluicing operations begin, it will be necessary to build both upstream and downstream banks or dikes of the fill dirt to contain the stilling pool. This initial operation is similar to that described in the rolled fill method, including the care taken to secure a bond with the foundation.

A pipe line will be laid on the inner side of each of these banks near the top. These pipes will have openings in the sides at intervals which can be opened and closed. The flow of the hydraulicked material can be directed to any point desired with the use of these gates.

As the fill laden water leaves the pipe, it flows over a beach for a short distance and enters the stilling pool, where it tends to move towards the center of the pool. The instant the water leaves the pipe, its velocity is retarded, until at the center of the pool, there is no movement. As a result of the falling velocity, the larger particles tend to settle out first in the area next to the pipes and the finer materials are carried towards the center of the pool. These finer materials will be in suspension in the pool in the middle of the depression. As these materials settle out, a very dense mass will be formed.

The limits of the dense core will be determined by the actual area covered by the still water. This is a very difficult operation to control and all dams with a hydraulic core tend to be indefinite in regards to the dividing line between the impervious core and the semi-impervious layer next to the core. Shoddy construction methods can easily lead to trouble because of this fact.

As the stilling pool nears the top of the outside shells, the tops of the shells are built up and the sluicing pipes are raised to the new elevation. This procedure is repeated until the desired elevation is reached for the core. The dam is usually topped off by the rolled fill method.

As has been explained, a very dense core can be obtained. The necessary items needed to make a hydraulic fill dam one of the best is plenty of competent supervision and inspection. The progress of the stilling pool must be watched carefully, and if it is found that the water is carrying too many fines that won't settle out, a remedy should be found at once. A change in borrow pits might be necessary. Usually some of the still water in the middle of the pool is pumped out at intervals to prevent a semi-liquid core being formed due to the particles which won't settle out.

If the water and borrow pit cannot be found at the desired elevations, other means can be used to fill hydraulicly. The fill can be sluiced out and pumped up to the dam site. The fill can be trucked, shoveled, or run on a conveyor belt to a sluice box, from which it can also be pumped to the site. This method is liable to have a bottleneck develop at the sluice box.

What happens is that the water currents in the box do not cover the whole area of the box interior; consequently some of the material settles out and in time forms a series of baffle plates within the box, slowing down the currents some more. The remedy is to test models of sluice boxes until an efficient shape is found, and then to make sure, arrange for several nozzles to be attached to the box. If any dead areas then develop, water under high pressure is introduced to prevent settling.

The fill material must be of the right sizes. Because of the method of placing used in the hydraulic fill dam, the fill dirt must be of non-uniform sizes so that there will be the larger particles to form the beaches on which the finer materials can be washed down to the center. Too much of the large sizes will leave a porous core; and too much of the smaller sizes will lead to an unstable dam section.

CHAPTER VI

FAILURES

There is one method of learning that is successful where others fail. That is the method of learning from the observation and study of the mistakes and failures of others. This is a means of gaining experience second hand; but this method can be very successfully used when a study of earth dams is being made.

Today's dams are more massive than yesterday's; as a consequence, they receive much more public attention when a failure occurs. Then too, an earth dam does not seem as safe to the layman as the concrete dam. It can be proved on paper that one is as safe as the other, and through careful design and construction, they can be made that way.

A few earth dam failures will be presented on the following pages. An effort was made to confine these examples to ones in which the fill was the cause or indirect cause of the failure. Many earth dams have failed because of faulty design, inadequate spillways, drain pipes not collared right, and other items of design. No analysis will be made of these last.

THE FORT PECK DAM

The Fort Peck Dam on the Missouri River is an example of a hydraulic fill dam which had a partial failure during construction. Its finished height is two hundred forty two feet, the length of the main dam is ten thousand six hundred feet, and the volume is 124, 000, 000 cubic yards.

> "On 22 September 1938, when the hydraulic fill was within twenty feet of the top of the dam, a slide occured in the upstream portion of the dam near the right abutment.
>
> The total length of time consumed in the slide was about ten minutes. Approximately 5,000,000 cubic yards, or less than 5% of the material in the dam moved. There were about 180 men in the slide area at the time it started and eight of them lost their lives.
>
> Then portions of the upstream shell nearest the pool began to slide into the sinking core pool. In a lesser degree, similar cracks and sliding and slumping were taking place on the upstream portion of the downstream beach. Simultaneously with these developments, the main mass of the upstream shell, almost intact, was moving out into the reservoir, in a swing similar to that of a gate hinged at the right abutment."[13]

Immediate investigations were ordered on the matter of the slide and also in view of continuing with the construction of the dam. Many drill holes were taken and some test holes were dug.

Many opinions have been advanced as to the cause of this slide. The investigating board decided that a formation of shale in the foundation was the immediate cause. This shale had a low shear resistance, the effect of which has been discussed previously.

13. Engineer Corps, U.S. Army, Report of the Slide of a Portion of the Upstream Face of Fort Peck Dam, July 39, p. 4

Once the shell begins to fail, the liquified portion of the core would exert a large hydrostatic pressure at the point of failure and would tend to increase the failure. This example illustrates the ever present danger during the construction of a hydraulic fill dam.

The presence of this shale had been discovered during the site investigations. The design of the dam was supposed to be such that this weakness had been covered. Curiously enough, one of the recommendations of the board was that the upstream slope be flattened to a 1:8 slope or flatter. Thirty foot berms were constructed in some places. The original plans called for an upstream slope twice as steep as the downstream slope.

One possible conclusion is that the low shear did not show up in the laboratory tests and that a large enough factor of safety was not provided.

THE ALEXANDER DAM

The failure of the Alexander Dam on the Island of Kauai in the Hawaiian group, 26 March 1930, is an excellant example in the hydraulic fill group. Extensive tests of the fill material were made before construction started. An overabundance of fines was noticed and steps were taken to reduce the danger from it. They included the addition of chemicals at certain stages of construction to aid in the settlement of the fines.

> "After the accident it was learned that men at work on the dam had noticed a cessation of drainage through the bank in the vicinity of the initial break at least ten days before failure. Up to this time, the drainage had appeared free and well distributed."[14]

The failure consisted of a break in the downstream shell, through which practically all the core pool moved downstream, washing away much of the shell.

The core of a hydraulic fill dam consolidates as the particles settle out and the water either drains out through the banks or is pumped out. In this case drainage in a certain area was retarded for some unknown reason. A liquid pocket was built up within the shell, and, when sufficient pressure was developed, broke out. The core pool moved into this void and on out carrying the downstream banks with it.[15]

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14. Joel B. Cox, "Hydraulic-Fill Dam of Fine Volcanic Ash Fails Disastrously," Engineering News-Record, 22 May 1930, p. 871.
15. Ibid., p. 869-71.

Two points should be stressed here. The workers had not been well enough informed as to cause and effect. A good information program to acquaint the workers with all phases of the project will pay dividends. Secondly, the inspections of the completed portions of the dam were not complete and thorough.

This dam was completed a few months later successfully. As the dam was built up, drainage systems were installed in the shell, to forestall the forming of liquid pockets.

An interesting note is that rolled fill dams generally fail after construction, whereas a hydraulic fill dam usually fails during construction. The latter is due to the high liquid pressure within the two constricting dikes forming the outer portions of the dam.

The Clendening Dam

The Clendening earth dam on the Muskingum River in Ohio was approximately completed in 1937 when a partial failure of the dam took place. The visual results of the failure consisted of a sagging of the top at one point of about five feet and a bulging of the upstream face at the same point of about five feet. The toe line of both the upstream and downstream faces showed no signs of movement.

An investigation showed the following facts. The foundation had a top layer of forty feet consisting of a fat clay and silt. The bedrock was one hundred feet below the surface. The borrow pit material was found to be the same material as the top layer of the foundation. The moisture content was above average in both the pits and the dam. The dry density of the dam was found to be ninety six pounds per cubic foot, a low value.

The semi-impervious shell on the outside of the core was a random fill, a large part of which was shale. This was supposed to be broken down by the rollers to form a dense mass. This was not done, and the saturated shale became very slippery and formed slickenslids, a name for slippage planes. This unstable mass was no help in containing the core.

The fact that the moisture was too high was realized at the time of construction, but no other material was available except at exorbitant hauling distances. Nothing was done to change the design of the dam because of this undesirable feature.

As a result of the investigations, as additional rock fill was added to the upstream face extending from within seventeen feet of the top down past the toe for a considerable distance. The new rock fill was about fifteen feet thick horizontally. This additional weight was sufficient to stop the movement and to stabilize the upstream part of the dam.[16]

An interesting result of the analysis of the test holes which were dug was that the fat clay in the foundation of the dam had very little effect on the failure. It was found that there was just the expected amount of settlement in the foundation. This is a proof of the statement made earlier that earth dams can be built on other than rock formation successfully.

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16. Creager, Justin, and Hinds, Engineering For Dams, p. 772-5.

The Horse Creek Dam

The Horse Creek Dam near Denver, Colorado is an example of the construction methods sometimes used in the early part of this century and of how not to build an earth dam. The one correct thing done, according to present day standards, was that substantial concrete collars were built in both the upstream and downstream portions of the dam around an outlet pipe laid through the bottom of the dam.

A description of the construction follows:

> " The material was deposited in layers as thick as four feet, ... As the layers were three to four feet thick, the Fresnos could hardly have been used very much for pulling down and leveling up the earth as it was dumped from the wagons.
>
> The bottom two feet of the dam are said to have been placed moist. The remainder of the material was very dry, and there was no effort made to moisten it to aid in compacting. Aside from the packing effect of teams and wagons, no effort at compaction was made. ...the structure settled seven feet the first season and 34,000 cubic yards of additional material had to be placed on the top to bring it to grade again.
>
> The dam was not provided with a puddled core or core wall of any kind, dependence apparently being placed on the concrete lining on the upstream face."[17]

Preliminary investigations showed that the bedrock came very close to the surface at intervals. It was proved later that the initial break occured at a point where the bedrock was within four feet of the surface. It was decided that this shallow rock forced the line of saturation up above the toe of the dam.

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17. Joel D. Justin, Earth Dam Projects, p. 27-9.

This meant that the exposed earth was saturated, piping started, and, as can be seen from the above description, there was nothing to retard the buildup of the flow through the dam and failure resulted.

Adequate compaction and a core wall might have combined to bring the line of saturation down to a safe point. There are innumerable ways to shape the core; and all types of cut-off walls, diaphragms, and impervious blankets are used to reduce percolation to the point where no harm can be done. The impervious blankets are constructed in the same manner as the dense core except they are usually not over six feet thick.

Delhi Dam

The failure of a small rolled fill dam at Delhi, Michigan, 8 April 1926, illustrates the results of poor compaction, insufficient slope to the upstream face, and insufficient spillway capacity. The dam was just completed prior to the coming of winter. Flood conditions from a thaw the following spring brought the water to within one foot of the top of the dam.

The only compaction effort had been the passage of tractors over the fill. This resulted in a very incomplete compaction. The rising water in the reservoir soaked the outer surface of the dam and froze. This formed a crust. As the fill within consolidated, it moved away from the crust creating voids. The unanticipated height of water was sufficient to break the crust at spots. The water rushed in and soon made a path through the entire dam, carrying large portions of the fill with it.

It was later recommended that the spillway be increased, and the upstream face protected by selected stone to take care of the 1:2 slope.[18]

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18. Engineering News-Record, V. 96, p. 942.

CHAPTER VII

SUMMARY

The requirements of an earth dam are thorough investigation, safe design, careful construction, and vigilant maintenance. These items have been illustrated in the preceeding pages.

There was not enough time available to examine each section of this study and present the details as regards to soil. As stated in the introduction, the use of soil in earth dams was to be scrutinized in all its aspects, which has been done in a general nature.

The study of soil seems to lead one into blind paths, yet when the soil is used carefully and intelligently, structures can be built which will be lasting. The constantly changing characteristics of soil must never be forgotten as one moves from one spot to another.

Further study is needed in all phases of earth dams. The laboratory test would be an especially fruitful subject. Particularly the determination of the optimum moisture content. This test could be set up by using the same sample and the same range of moisture contents. The variable would be the number of blows of the tamper. The object would be to determine the effect of increase or decrease of the compaction effort.

A further study could be made to correlate the number of blows of the tamper to the pressure obtainable from the roller.

The earth sample could be varied with the other factors kept constant. An indication would then be found in regards the effect of the same compaction on different types of soil.

The construction process of both the rolled fill and the hydraulic fill can be analyzed more thoroughly in an effort to uncover any inefficiencies or new methods not yet used.

BIBLIOGRAPHY

BIBLIOGRAPHY

A. BOOKS

Encyclopedia Americana, 30 vols., Americana Corporation, 1947, New York.

Bassell, Burr, Earth Dams, New York, The Engineering News Publishing Company, 68pp.

Taylor, Donald W., Fundamentals of Soil Mechanics, New York, John Wiley and Sons, Inc., 1948, 700 pp.

Housel, William S., Applied Soil Mechanics, University of Michigan, 1948, 189 pp.

Plummer, Fred L. and Dore, Stanley M., Soil Mechanics and Foundations, New York, Pitman Publishing Corp., 1940, 473 pp.

Krynine, Dimitri P., Soil Mechanics, New York, McGraw-Hill Book Company, Inc., 1941, 451 pp.

National Resources Committee., Low Dams, Washington, D.C., U.S. Government Printing Office, 1939, 431 pp.

Creager, Justin, and Hinds, Engineering for Dams, New York, John Wiley and Sons, Inc., 3 vols.

Justin, Joel D., Earth Dam Projects, New York, John Wiley and Sons, 345 pp.

Hanna and Kennedy, Design of Dams, New York, McGraw-Hill Book Company, Inc., 478 pp.

Terzaghi, Karl, Theoretical Soil Mechanics, New York, John Wiley and Sons, Inc.,

B. PERIODICAL ARTICLES

Walter, D.S., "Reclamation's Biggest Earthfill Dam," Engineering News-Record, CXIL (18 September 1947), 396-402.

Engineering News-Record, IVC (10 June 1926), 942.

Cox, Joel B., "Fill Dam of Fine Volcanic Ash Fails Disastrously," Engineering News-Record, CIV (21 May 1930) 869-71.

Leonard and Mattern, "Planning the Watauga Project," Civil Engineering, XVIII (March 1948)

Leonard and Mattern, "Constructing the Watauga Project," Civil Engineering, XVIII (May 1948) 21-6.

Rowan and Graham, "Proper Compaction Eliminates Curing Period in Cinstructing Fills," Civil Engineering, XVIII (July 1948) 50-1.

Armstrong, R.W., "Delaware Aqueduct to Increase New York's Water Supply Fifty Percent," Civil Engineering IXX (February 1949) 17-21.

"Davis Dam Completes Storage Regulation of Colorado River Below Boulder," Civil Engineering, XVII (January 1947)

"Garrison Dam on the Missouri River to Make Rolled Fill History," Engineering News-Record, CXXXVI 920-2.

Kramer, Hans, "Deep Cutoff Trench of Puddled Clay for Earth Dam and Levee Protection," Engineering News-Record, CXXXVI 986-90

Thompson, J.N., "Soil Studies for San Jacinto Dam," Civil Engineering, XVI 57-9

C. UNPUBLISHED MATERIAL

Corps of Engineers, U.S. Army, "Report of the Slide of a Portion of the Upstream Face of Fort Peck Dam," July 1939, 4.