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Dr. W. L. Schroeder

During construction of the embankment at Blue River Dam placement difficulties were occasionally experienced with the filter zone sands. In the extreme condition construction equipment became mired and part of the fill had to be removed and wasted. A laboratory investigation was conducted on materials from the above project to determine the amount of fines (material passing a No. 200 U.S. Standard sieve) which could be permitted without development of these problems. It was reasoned the construction difficulties were due to the development of pore pressures in the sand and a subsequent loss of shear strength. In this investigation the field condition was simulated by vibrating a saturated sand sample under constant surface load and allowing the sample to drain to its top surface. During the period of vibratory loading pore pressures were measured at different depths in the sample. It was found that for a fines content greater than five percent relatively impermeable layers and excessive changes in

pore pressures developed in the sample. It was concluded that these pressures were sufficient to cause construction difficulties. For a fines content less than five percent the pore pressure development was negligible.

A guiding axiom for the placement of graded wet filter sand that states, "If it can be placed and compacted the fines are not detrimental and likewise if the fines are not excessive it can be placed and compacted" was further verified by this investigation.

Vibration Induced Pore Pressure Development in Graded Sands

by

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VIBRATION INDUCED PORE PRESSURE DEVELOPMENT IN GRADED SANDS

I. INTRODUCTION

In construction of zoned earth dams, sand embankments are often placed with vibratory compaction, some to great heights. If the fines content and available moisture in these materials are not in proper proportion, pore pressures can be created during placement. Eventually construction activity may be hindered or curtailed until these pore pressures dissipate. The removal of all fines from the sand prior to placement by washing or screening is economically infeasible. A certain percentage of fines is permissible and desirable depending upon the purpose of the particular sand embankment. It would be helpful to determine the maximum percentage of fines which will permit rapid placement during construction and yet not significantly affect other qualities required of the embankment. If this allowed percentage could be determined within a very narrow range, a substantial monetary saving could be realized as removal of fines requires sophisticated equipment and leads to considerable expense.

The procedure followed in this investigation was to observe the change in pore water pressures developed in laboratory specimens of saturated sand subjected to a constant surface load and vibration.

By comparison of results from tests on laboratory specimens of varying gradation the maximum amount of fines which would not produce extreme pore pressures was determined. It was reasoned that this percentage represents the probable upper limit of fines content permissible from the standpoint of satisfactory workability during construction.

II. VIBRATORY PORE PRESSURE TESTS

Simulation

The testing program was formulated to simulate conditions of sand placement in a filter zone of a dam where vibratory compaction is used. In the field construction process it is reasonable to assume that the drainage of the filter zone embankment under the vibratory action of the roller would be mostly toward the surface. Immediate horizontal drainage is very likely inhibited by the width of the zone of sand. In accordance with this assumption the testing apparatus was constructed so that the top of the sample would be open to atmospheric pressure and free to drain.

Pore pressure development in free draining sands due to vibratory loading is dependent on permeability and is therefore related to void ratio, types of fines, temperature and soil structure. In this investigation the temperature of the individual tests varied from 63° to 73° Fahrenheit. This variation was not considered significant in its effect. However, a temperature decrease from this temperature to near freezing, which is probable during winter placement of sands, would decrease permeability by approximately 70 percent (Terzaghi, 1948). Such a decrease would increase the pore pressures developed under the action of vibratory loads by a similar amount. In the field this thermal factor is often overlooked and difficulties encountered in placement are blamed on rainfall rather than temperature change.

Air bubbles in a soil affect the permeability by forming tension membranes across the pores at air-water interfaces. Air segregation drastically reduces permeability of soils when permeability tests of several hours or more duration are performed with tap water (Bertram, 1960). These effects were not considered during this investigation since the duration of the tests was so short that the change in permeability due to air segreagation would be small. according to Bertram, permeability changes during tests of about five minutes duration should be less than three percent. Care was taken to exclude all free air from the samples and no consideration was given to the possibility that some air may have remained in the sample. If any free air bubbles existed in the sample it was reasoned the vibration would drive them to the surface as it does in the placement of saturated sand in the field.

The electro-chemical effects of the fines were disregarded as they were considered beyond the scope of this investigation. The similarity of each test was such that these effects would not vary the comparative test results. Fines from the same source were used for preparation of all specimens.

E. W. Barber (1959) has prepared a graph showing the effect of various types and amounts of fines on the coefficient of permeability for a wet but not saturated base material. Assuming a similarity between filter material and base material the above reference indicates that the coefficient of permeability for the tests of this investigation would range from 0.1 to 0.0001 feet per day. Further correlation of the results of this investigation with this graph indicate detrimental pore pressures will develop at a permeability equal to or less than 0.05 feet per day for the type of fines used in this study.

As the void ratio of a soil decreases the permeability also decreases because the passages through which the water travels become smaller. Terzaghi (1948) presents a graph of void ratio versus $k/k_{0.85}$, where k is the coefficient of permeability of the soil at a given void ratio and $k_{0.85}$ is the coefficient of permeability of the soil at a void ratio of 0.85. If detached fines are available in the sample any change in void ratio can have a twofold effect. It can reduce permeability by decreasing the seepage pore area and by providing pores which are subject to clogging by the detached fines. Both of these permeability reductions will result in increased pore pressures under a surcharge loading. The latter mechanism will generally have the most pronounced effect since a large change in permeability requires a substantial change in the void ratio according to the graph referenced above. Uniform sand probably will not exhibit pore pressures which would hinder placement at fines contents which are acceptable in well graded sands, because the larger pore spaces permit free drainage without clogging.

Apparatus

Components of the testing equipment included a hydraulic pressure reservoir, an All American Model 10 VA vibratory table, a compression cylinder, three Pace Wiancko Model KP15 pressure transducers with Pace Model CD 25 transducer indicators and a Honeywell Model 1508 Visicorder oscillograph. Figure 1 is a schematic drawing of the testing equipment. Photographs and essential details of the apparatus are shown in Figures 2 and 3. The sample follower was drilled with numerous vertical and radial holes and the leading face was covered with No. 100 U. S. Standard screen.

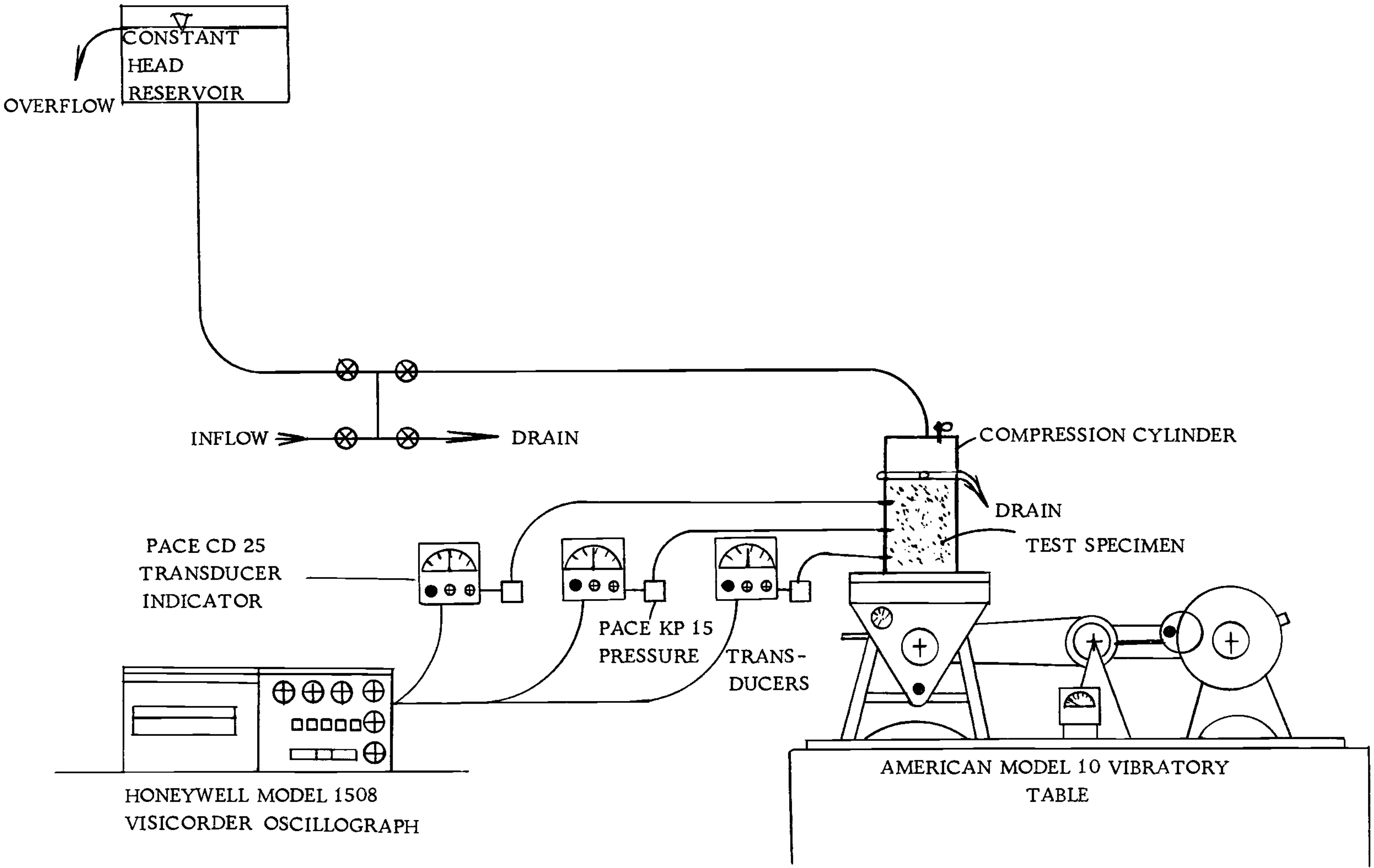
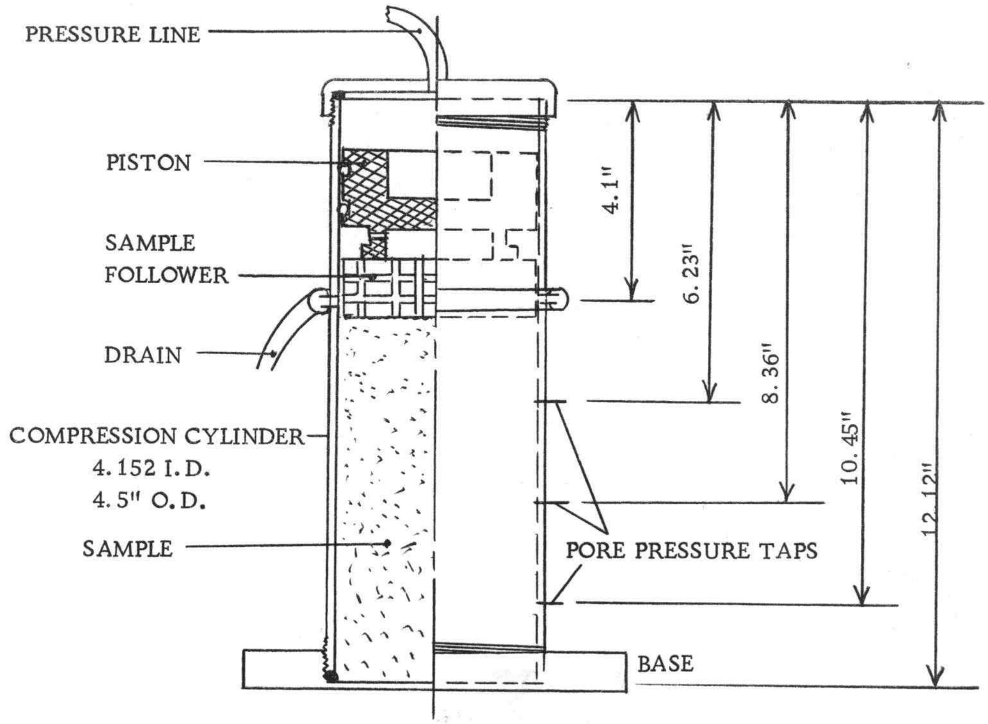


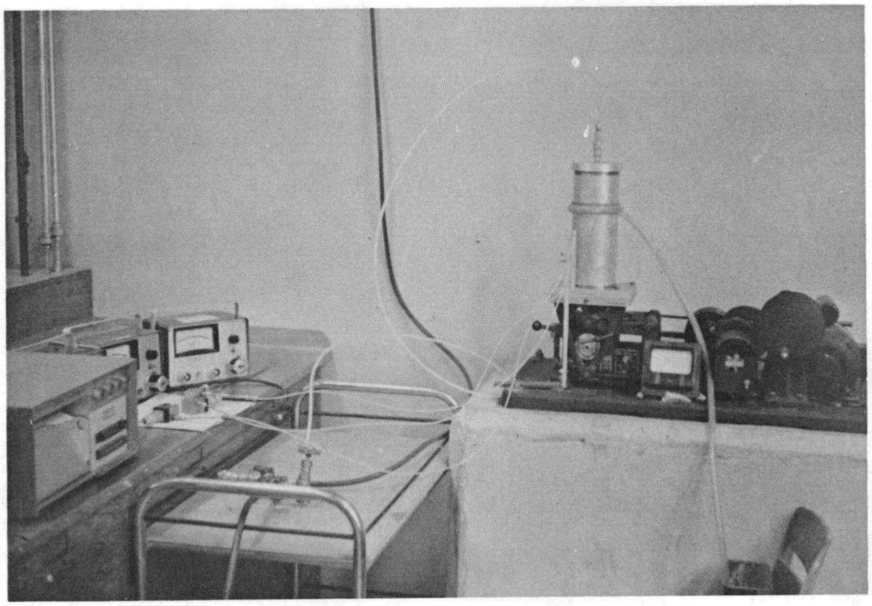
Figure 1. Schematic diagram of test equipment.



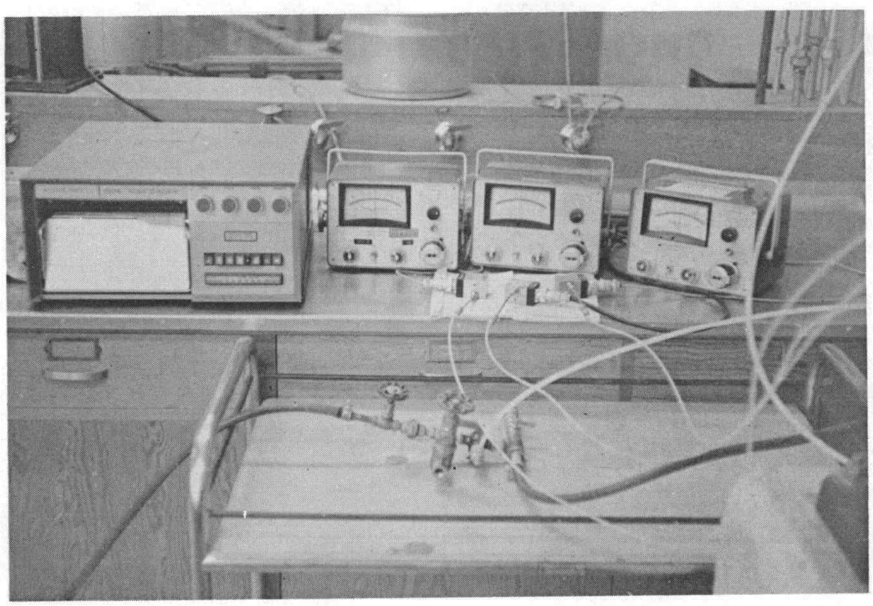
(a)

(b)

Figure 2. Test compression cylinder and sample loading device.



(a)



(b)

Figure 3. Apparatus ready for testing.

Preparation of Test Specimens

The source of the material used in the tests was the Upper Gravel Borrow Area for the Blue River Dam presently under construction on the lower western slope of the Cascade Mountain Range in Oregon. This is an alluvial deposit of Blue River, a tributary to the McKenzie River. The writer was associated with this project as Chief of the Foundations and Materials Branch for the U. S. Army Corps of Engineers from December 1965 to October 1967. During this time considerable effort was expended to remove fines (material passing the Number 200 sieve) from the sand used in the filter zones of the dam. It was believed that some of these fines could remain in the filter sand without changing its placeability. This belief provided the motivation for this study.

The material tested was a silty sand which had been screened from gravel sizes and washed in an aggregate plant. It was oven dried and separated into sizes retained on the following U. S. Standard sieves: Numbers 4, 8, 10, 20, 40, 100, 200, pan. The subrounded nature of the individual particles is shown in Figure 4. The grain size distributions of each specimen were similar but the fines content was varied as shown in the gradation curves in Figure 4.

The uniformity of the fines (material passing the No. 200 sieve) for each test is indicated by the hydrometer analysis curves

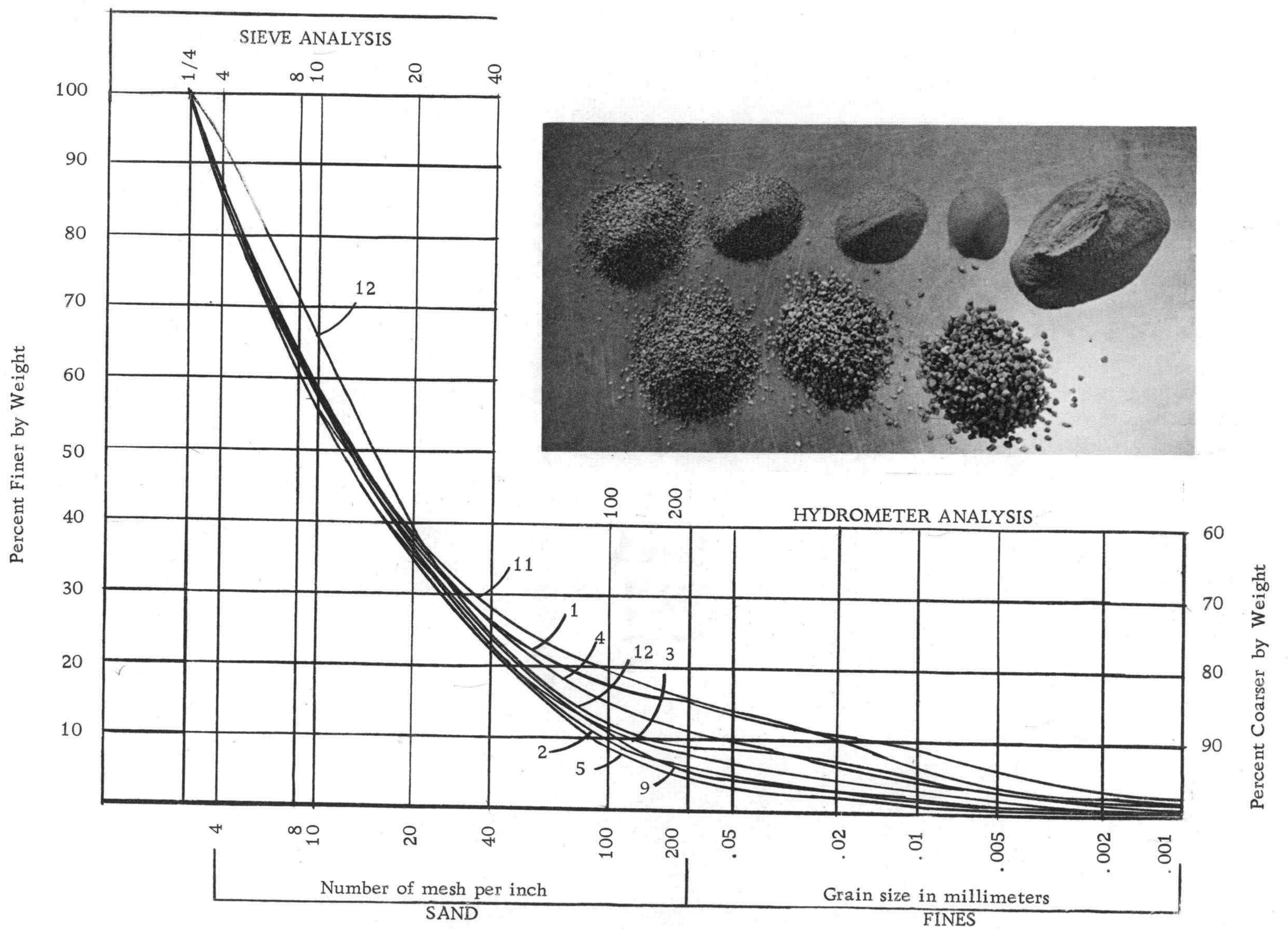


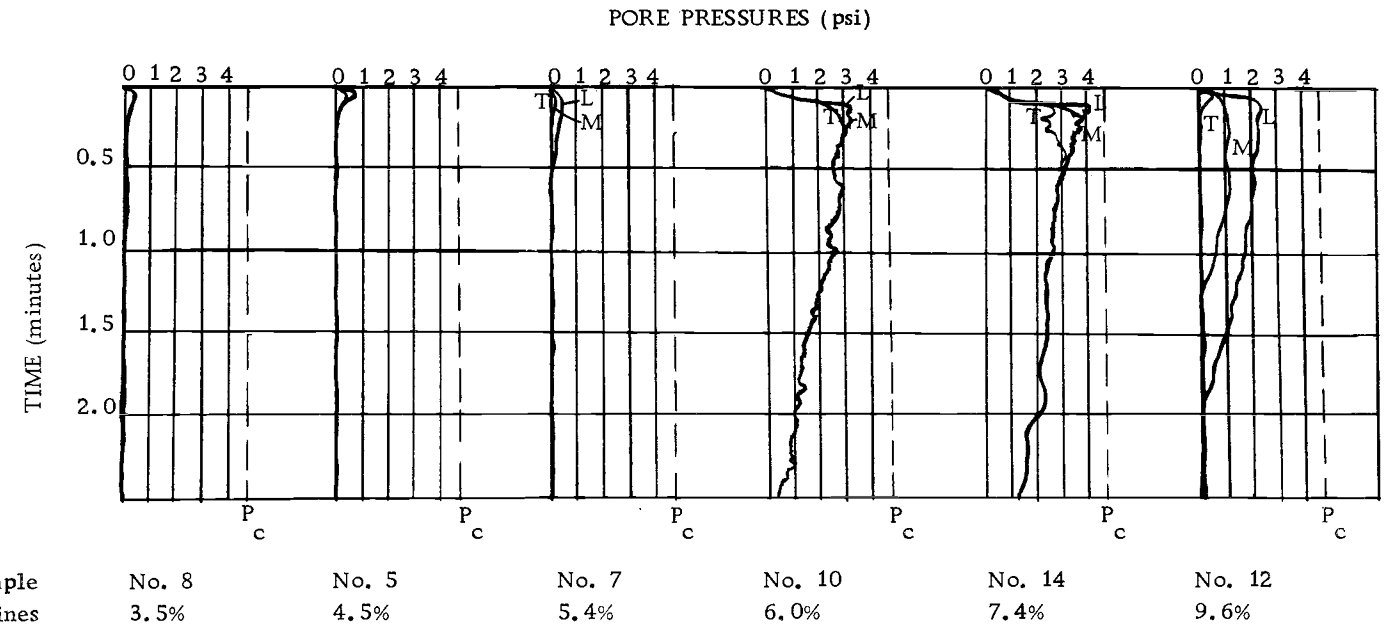
Figure 4. Gradation analysis curves.

in Figure 4. Quantities of fines were mixed with graded sand samples to produce specimens having various percentages of fines. The samples were thoroughly saturated prior to placement and testing. The sample was placed loosely into the compression cylinder through a one and one-fourth inch diameter plastic pipe. The lower end of the pipe was kept below the surface of water which had been previously placed in the compression cylinder. The funnel and plastic pipe assembly used to load the sample into the cylinder is shown in Figure 2(b). The volume of the sample was then measured and all excess muddy water was flushed from the top of the sample and wasted. This was accomplished by pouring water on the top of the sample follower and letting it drain out the side overflow drains. The apparatus was then closed and the sample taps connected to the pore pressure transducers. Special care was taken to exclude all air from the pressure lines and transducers. The sample was then ready for testing.

A number of samples were prepared by placing the material in the compression cylinder in an inverted position and then setting the compression cylinder upright for testing. This change in preparation procedure was made to determine if minor segregation during placement had any effect upon the results of the tests. It was reasoned that more fines would appear at the top of a sample placed in water as some of the finer material would remain in suspension and be concentrated there. The effect of this concentration was to be studied by testing these samples which had been placed in the inverted position.

Test Procedure

With the previously prepared sample in place in the compression cylinder the pore pressure recorder was started and the hydraulic pressure on the piston was raised to approximately five pounds per square inch. Pore pressures resulting from this static loading were allowed to return to near zero or to a steady state. The vibratory table was then started and operated at 1200 cycles per minute until the pore pressures again returned to zero or developed a definite trend. A test was performed for each gradation at a frequency of 1200 cycles per minute, an acceleration of 4.088 times that of gravity and 0.200 inches displacement on the vibratory table. During testing a continuous constant surface pressure was maintained and recordings of pore pressures at different depths of the sample and elapsed time were made. Figure 5 shows typical oscillograph records of results. The vibration was then stopped and the volume of the sample recorded. Upon disassembly of the compression cylinder the sample was extruded, examined and photographed. The procedure was varied slightly for samples 12 through 16 in that the time of static and vibratory loading were kept nearly the same for each test.



L = Lower Pore Pressure Tap
M = Middle Pore Pressure Tap
T = Top Pore Pressure Tap
P_c = Surface Confining Pressure

Figure 5. Pore pressure oscillograms.

In order to check the gradation established in preparation of the sample a washed gradation analysis was performed on the entire sample for all tests. The washed method yields 1.0 to 1.5 percent more fines than the dry method of gradation analysis. This was confirmed by tests performed in the field laboratory for the project at the sample source. These increased percentages are representative of samples with two to eight percent total fines and would be expected to be higher with increasing total fines content. Hydrometer analyses of the fines were performed on eight samples to verify the uniformity of their equivalent spherical sizes.

III. DISCUSSION OF RESULTS

Pore Pressure Development

The loss of shear strength in saturated sand at constant total stress is proportional to the increase in pore pressures in accordance with the principle of effective stress. An increase in pore pressure, P_w, in the presence of constant total stress P will decrease shearing strength, S, since the latter is governed by the equation $S = (P-P_w) \tan \phi$. Accordingly, shear strength decreases in direct proportion to an increase in pore pressures. As pore pressures rise and shearing strength decreases, the workability of the sand becomes poorer. As the pore pressures increase to detrimental values construction equipment becomes mired due to shear failures beneath the wheels.

Pore pressure values were recorded at several depths in each of the test specimens. The bottom tap gave the highest pressure values during the vibratory test with the exception of samples Numbered 16, 15, and 13. In Sample Number 15 the pressure line from the lower tap to the transducer malfunctioned and the pressure dropped to zero part way through the test. In samples Numbered 16 and 13 the middle tap developed the highest values. In these two tests the lower tap developed some pressure but it appeared inhibited, possibly due to an air bubble in the pressure tap housing. The curves in Figures 6, 7, and 10 are based on the values from the bottom tap with the exception of these three samples, where the values from the middle tap were used. If the lower tap had functioned properly it would have most likely recorded a higher value than the one used. The lower values are noticeable for Samples 13 and 16 in Figure 6 which shows plots of percent change in pore pressure, U, versus time, t, for various fines contents. Two figures, Figure 6 and Figure 7, were used to display these curves in order to avoid crowding and to present a better representation of the results. The curves in Figures 6 and 7 lie in two distinct groups on the graph; notably those with a fines content of six percent or less and those with a fines content of six percent or more. The peak value of U in the latter group is generally in excess of 60 percent of the surface load while those in the former group show only small pressure increases.

Repeatability of test results was considered good. Under similar test conditions similar results were obtained. It is noted that sample Number 1 did not yield the same results as sample Number 11 (Figures 6 and 7), although both have the same percent of fines. Sample Number 1 varies from sample Number 11 in that Number 1 was statically consolidated for seven and one-half minutes while Number 11 was statically consolidated under the same surcharge load for only four minutes before the vibratory test was started. Number 1 also had one percent more clay size fines than Number 11. At the start of

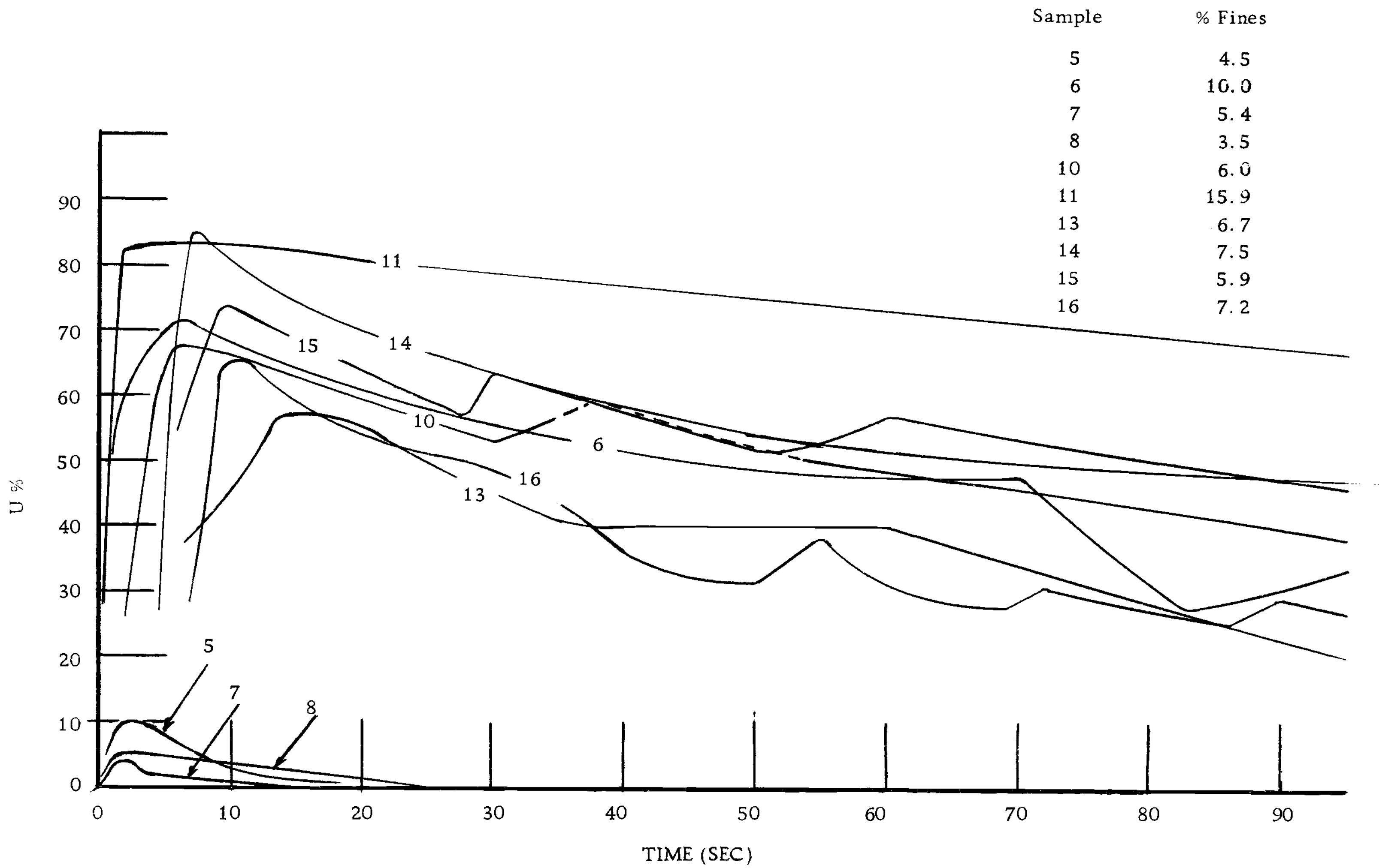


Figure 6. Percent change in pore pressure versus time curves, Series A.

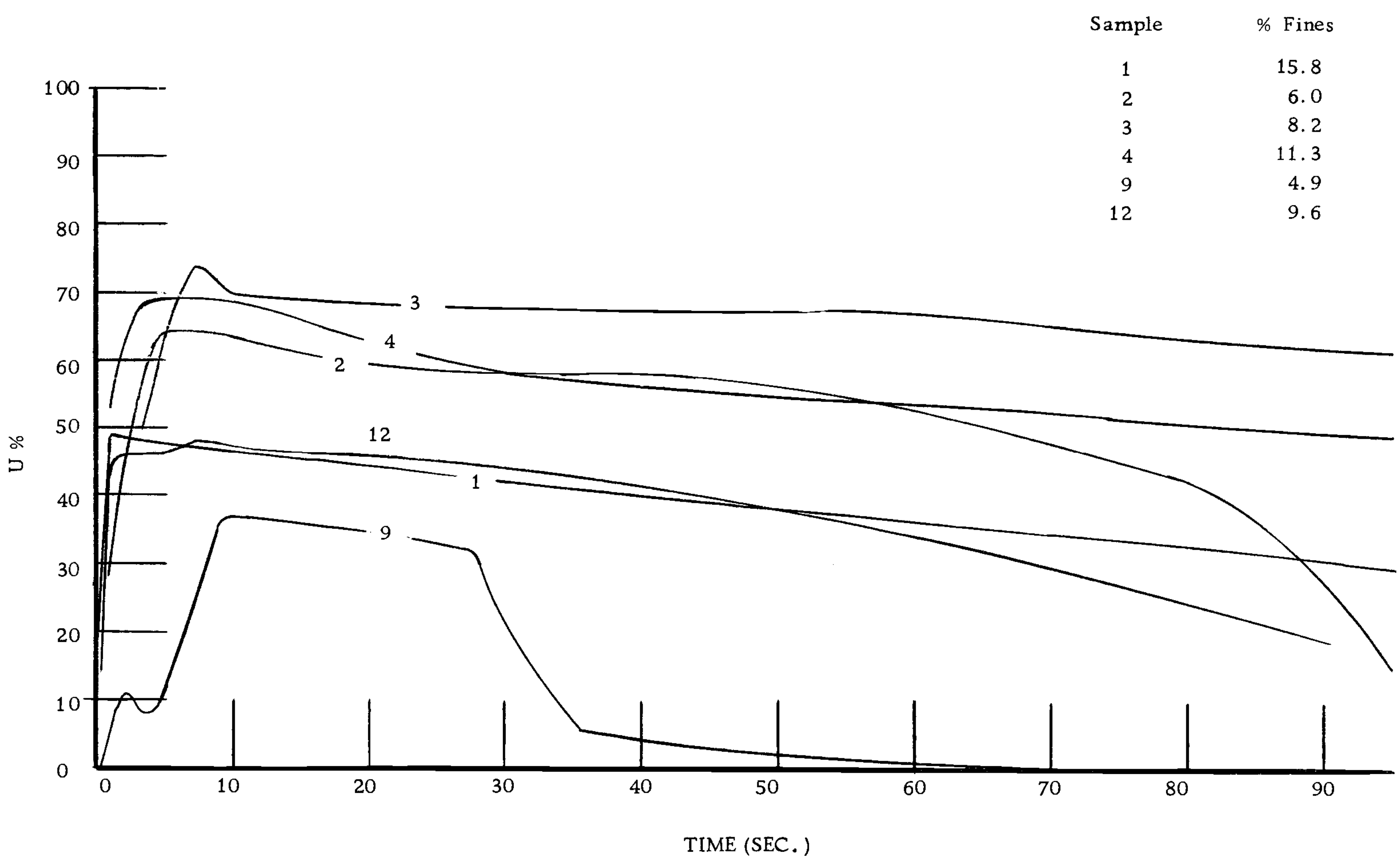


Figure 7. Percent change in pore pressure versus time curves, Series B.

vibratory loading both samples had an initial pore pressure of one psi.

Sample Number 12 did not develop as high a pore pressure as would be expected for a sample containing 9.6 percent fines. The gradation of this sample varied from the others noticeably. This specimen did not form a layer (see discussion of Layer Effect).

The percent change in pore pressure with respect to surface loading versus time curves, Figures 6 and 7, have a sharp peak which is due to the resistance to drainage. At this point drainage effects predominate over pore pressure increases and the pressure starts to drop, however the decay slope is soon interrupted and this is where the clogging begins. The trend is generally down, although some pressures go up again. This is particularly noticeable in samples Numbered 10, 15, and 16. Sample Number 9 has a distinct peak at near ten percent change in pore pressure (Figure 7). However, after a short period of decreasing pore pressure it suddenly rises above 36 percent. This increase may have been due to clogging at the follower screen, since after the test the sample was not laminated with a seam of fines (see discussion of Layer Effect).

Florin and Ivanov (1960) performed experiments which showed excess pore pressures in sands subjected to vibration to be fully developed to a depth of 20 centimeters after five seconds of vibration. This depth is similar to the depths of this investigation. In the sands with lower fines content the pore pressures were fully developed in less than five seconds after vibration started and for the sands with objectionable fines the fully developed pressures occurred within ten seconds after vibration started. Exceptions to this pattern were two specimens which were placed with the cylinder in the inverted position. These required 11 seconds and 14 seconds to develop peak pressures.

Samples which were placed in an inverted position and then set upright for testing developed peak pore pressures more slowly than samples placed and tested in the upright position. This was likely due to the longer time taken for accumulation of fines near the upper part of the sample since they originally were more concentrated near the bottom of the sample. This slow development was noticeable in samples Numbered 13 and 16. Placement of the sample in the upright position is more representative of field conditions. In the field hauling and dumping tends to bring the fines to the surface due to vibration and water seepage during densification. The condition when the vibratory roller first passes over it then is similar to that with the sample placed in the upright position; that is, there are more fines in the upper part of the lift than in the bottom part.

A graph of dry unit weight versus percent of fines was plotted for the different test specimens. In plotting the densities of the five tests vibrated for the same length of time there appeared to be an optimum density at seven percent, however, the points were scattered and no well-defined comparison to the findings of Holtz (1957) could be made. Holtz found an optimum density with loessial fines and a coarse sand at approximately nine percent fines. His gradation curve was approximately eight percent coarser on the Number 16 and Number 30 U.S. Standard sieves than the sand used in this investigation. The dry unit weights of the samples used in this investigation before and after testing are shown in Table 1.

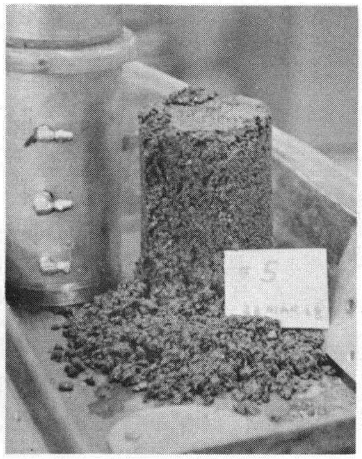
Table 1. Specimen characteristics.

Sample	Series	% Fines	Dry unit wt. in mold		Void ratio	
			Before test	After test	Before test	After test
8	A	3.5	106.3	112.3	0.59	0.50
5	A	4.5	104.7	113.8	0.61	0.48
9	B	4.9	108.8	116.9	0.55	0.44
7	A	5.4	107.6	118.4	0.56	0.42
*15	A	5.9	106.0	115.0	0.59	0.46
2	B	6.0	109.2	116.2	0.54	0.45
10	A	6.0	109.7	118.9	0.54	0.42
*13	A	6.7	107.0	114.7	0.57	0.47
*16	A	7.2	109.7	116.7	0.54	0.44
*14	A	7.4	106.9	113.6	0.58	0.48
3	B	8.2	108.2	113.9	0.56	0.48
*12	B	9.6	106.8	110.7	0.58	0.52
6	A	10.0				
4	B	11.3	110.2	116.0	0.53	0.45
1	B	15.8	107.9	114.2	0.56	0.48
11	A	15.9	109.0	116.5	0.55	0.45

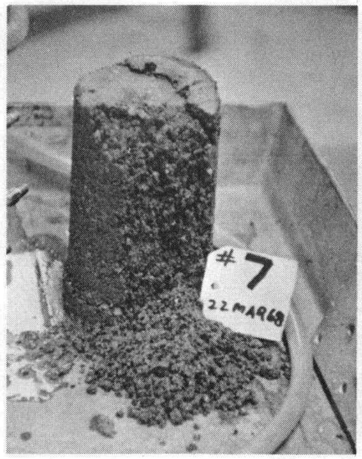
*Test time period near identical for these tests.

Layer Effect

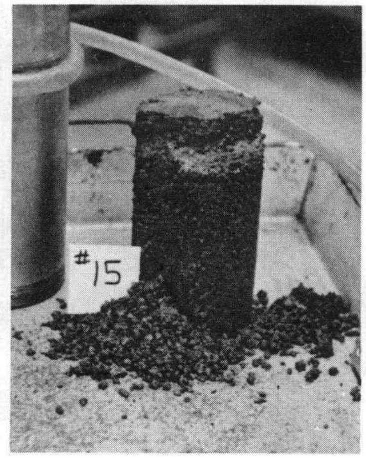
Examination, after testing, of the samples in the group exhibiting high pore pressure increases revealed a seam of fines 0. 05 inches to 0. 20 inches thick separating a cleaner lower portion of sample and an upper zone of higher fines content. This observation is apparent in Figures 8(c) through 8(i). The appearance of this layer could arise from several causes. The initial static pressure consolidation phase of the test may reduce the void ratio of the top one to two inches of the sample thereby forming an effective filter which stops the migration of fines during drainage and consolidation of the sample. During placing the sand under water it was expected that slightly more fines would accumulate at the top of the sample than throughout the sample. It was reasoned that as the water in the mold permeated the loose sand which was being placed some fines would be displaced into the water in the mold. By the time the sample was completely placed the water would be heavily sedimented and naturally the material placed last would have more fines in it than that placed first. This was confirmed by placing a sample and then extruding it for examination without testing. These fines along with any initial compaction may make the necessary combination to create a filter which retards flow, as fines from drainage come against it.



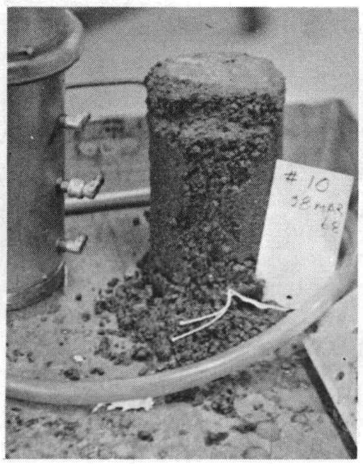
(a) 4.5% Fines



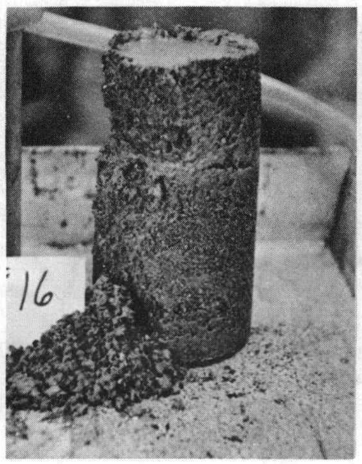
(b) 5.4% Fines



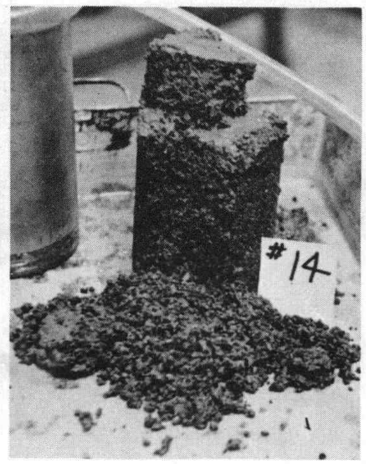
(c) 5.9% fines



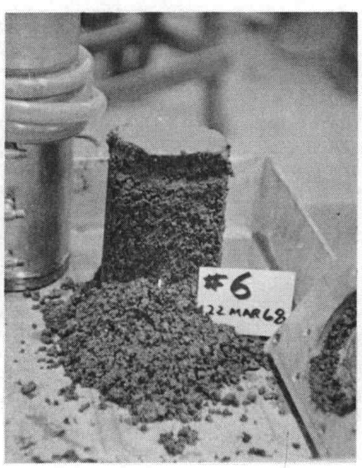
(d) 6.0% Fines



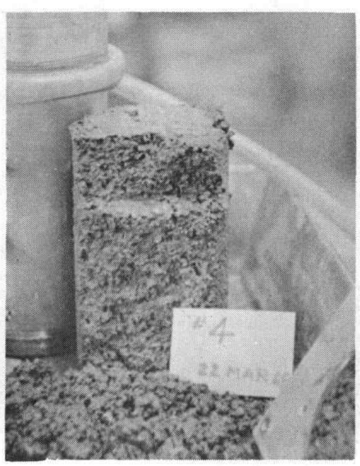
(e) 7.2% Fines



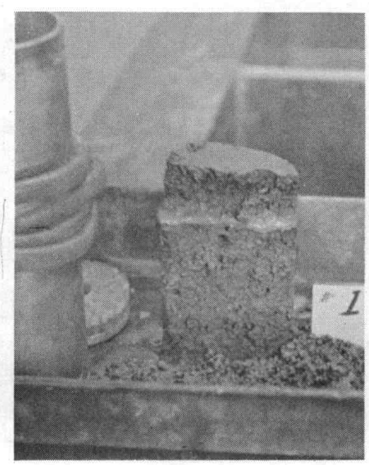
(f) 7.4% Fines



(g) 10.0% Fines



(h) 11.3% Fines



(i) 15.8% Fines

Figure 8. Samples after testing.

In order to eliminate the possibility that this layering was due to segregation during placement of the sample, a group of tests were performed in which the samples were placed in the cylinder in an inverted position then set upright and the test performed. These samples containing 5. 9, 7. 2, and 7. 4 percent fines also formed layers near the top. This is shown in Figures 8(c), 8(e), and 8(f), respectively. One sample with 6. 7 percent fines formed a layer over about one-third of the area of the mold at the one-third height of the sample. Sample Number 12 did not form a layer; however, its gradation is eight percent finer in the coarse sand fraction as shown in Figure 4. This would indicate the finer sand retarded the rate of migration of fines to the top of the sample.

In Figure 5 for samples Numbered 10 and 14 at time 15 seconds and 30 seconds respectively it is noticed the pressure oscillograms for the taps coincide. It is believed this is due to the sealing action of the layer that formed near the top of the sample. Sample Number 14 was placed in an inverted position and it is reasonable to expect the layer to seal off this sample at a later time than for sample Number 10 which was placed in an upright position. In this same figure note the linear relationship of pressure increase to depth for Sample Number 12 which did not form a layer. This indicates the layer controls the pressures though it may not be responsible for the peak pressure.

The samples with low fines content did not show this layering effect. In field placement of sands with vibratory compaction the fines come to the surface and form a band or layer about two inches thick of finer material on a 12 inch lift but a distinct layer of nothing but fines was not apparent at the base of this band as in some laboratory tests. This is shown in Figure 9.

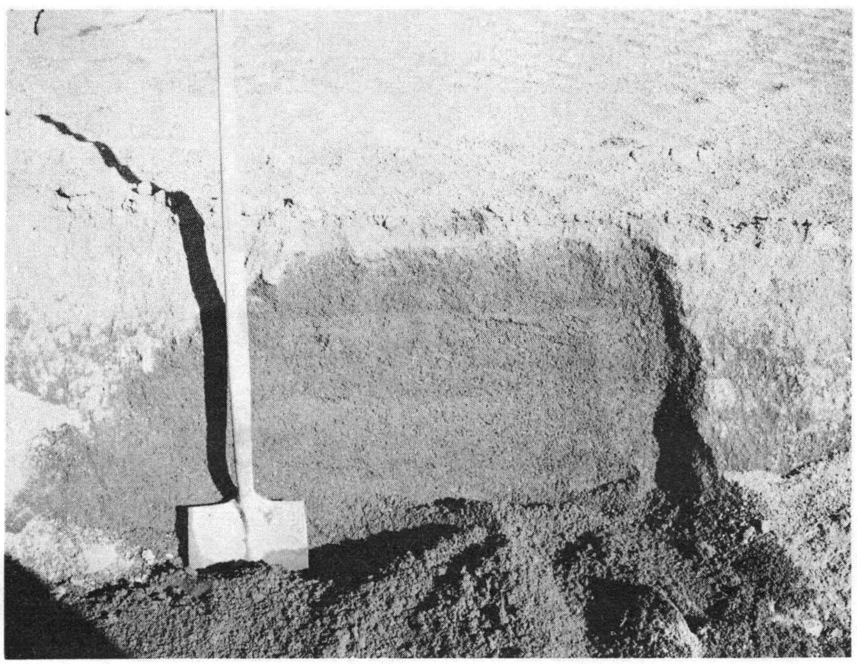


Figure 9. Layering effect in field.

Critical Fines Content

Critical fines content is defined as the fines content at which pore pressures increase to a value that inhibits or stops placement of a vibratory compacted sand zone.

Once the critical fines percentage is reached there is no well-defined relation between maximum pore pressure and percent of fines as variations in the sample, due to migration and clogging of the top of the sample with fines, control the drainage and the pore pressure values. This is true to a lesser degree for less than critical fines contents but in this case there are insufficient fines to create detrimental pore pressures. Partial clogging therefore results only in variations of the pore pressure-time curves at low values of pore pressure. Figure 10 depicts the relationship between U_{max} and percent fines for the tests previously discussed. The points are somewhat scattered but reasonable limiting curves indicating a range of values can be drawn. Consideration should be given to picking the higher values since they will be the controlling values in placement of the sand. From this curve (upper limit) it is very apparent that the critical fines content as determined by these tests is between five and six percent.

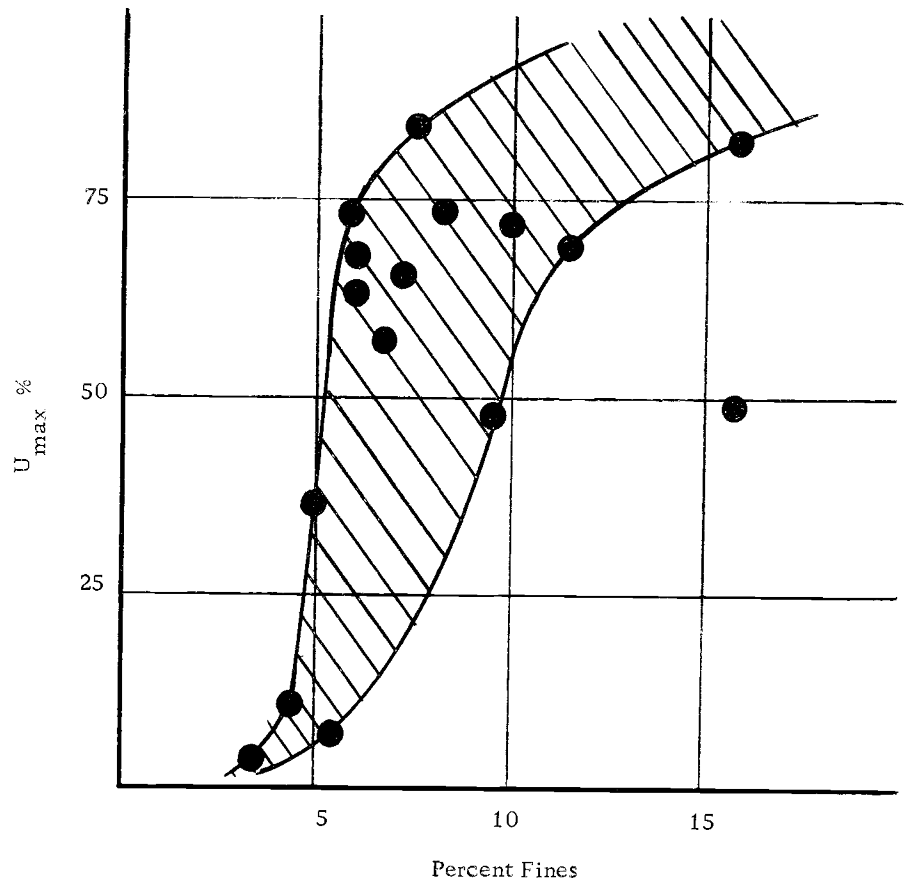


Figure 10. Maximum pore pressure versus fines content curves.

According to Lambe (1962) the quality of a gravel filter is detrimentally affected by fines in excess of seven percent. The investigation conducted by the writer indicates that this quantity of fines would produce detrimental pore pressures which would curtail timely placement. It thus appears that placement of wet filter sand can be guided by the axioms, "If it can be placed and compacted the fines are not detrimental to filter action and likewise if it is suitable for filter material it can be placed".

Consideration should be given to the source of material used in the tests. The presence of impurities such as fine organic particles could readily clog the sample and create large pore pressures. Similar results would not be found in the same gradation of clean sands.

Based on field observations Sherard (1963) says three to five percent is the amount of fines permissible before construction difficulties are encountered. This is slightly less than indicated by this investigation; however, it should be pointed out that fines composed mostly of silts were used in this investigation and that if clay fines were used the critical value may be less than five percent.

Suggestions for Further Study

Testing and analysis regarding uniform sand and other confining pressures would be useful to further clarify the results obtained in this testing program. Gradation analysis by one-third parts of the sample after testing might indicate which types of gradations are most likely to produce migration and clogging by fines. If the compression cylinder was constructed of Lucite material the progressive formation of the clogging layer could be readily studied.

Testing whereby the volume change was recorded throughout the test would permit a correlation between void ratio and change in pore pressure. This could be incorporated into the present testing equipment with a slight modification whereby a deformation gage would be set to follow the shortening of the sample during the test.

It would be useful to determine the effect layering has on filter quality if the sand embankment is to be used as a filter.

IV. SUMMARY AND CONCLUSIONS

Loss of shear strength in well graded sands being placed in a saturated condition containing fines in the amount of five to fifteen percent appears to be due to localized clogging of the sand with fines which have been scoured from the pores by drainage water during the densification process. This clogging results in increased pore pressures and reduction in shear strength.

The following conclusions are drawn from this investigation:

1. Silty fines in excess of five percent will likely cause difficulty in placing wet sand with vibratory compaction if the material is well graded.

2. In well graded sands a fines content of less than five percent should not result in placing difficulties arising from excess pore pressures.

BIBLIOGRAPHY

Barber, E. W. 1959. Subsurface drainage of highways and airports. Highway Research Board Bulletin 209:1-21.

Bertram, G. E. 1940. An investigation of protective filters. Cambridge. 21 p. (Harvard. Soil Mechanics Series. No. 7)

Florin, V. A. and Ivanov, P. L. 1961. Liquefaction of saturated sandy soils. In: Proceedings of the Fifth International Conference on Soil Mechanics and Foundation Engineering, Paris. Vol. 1. Paris. p. 107-111.

Holtz, W. G. 1957. Experiences with the consolidation of pipe bedding by vibration on the San Diego Aqueduct. In: Papers on soils. Philadelphia, American Society for Testing Materials. p. 50-65. (ASTM Special Technical Publication no. 206)

Lambe, T. W. Soil stabilization. 1962. In: Foundation engineering, ed. by G. A. Leonards. New York, McGraw-Hill. p. 367-368.

Sherard, J. L., R. J. Woodward, S. F. Gizienski and W. A. Clevenger. 1963. Earth and earth rock dams. New York, Wiley. 725 p.

Terzaghi, Karl and Ralph B. Peck. 1948. Soil mechanics in engineering practice. New York, Wiley. 566 p.

APPENDIX

APPENDIX I

Calibration of Test Apparatus

With the compression piston in the cylinder with atmospheric pressure on both sides, weight was added to the top of the piston until it moved downward. Four thousand grams were required to move it. The same test was performed with the vibratory table operating and 900 grams were required to move the piston. During calibration and testing, the piston "O" rings were greased with silicone grease. The friction loss at the "O" ring seal was calculated from these tests and the corresponding correction was made to the surface pressure on the sample. In the initial tests air was used to drive the compression piston, however the air supply was not steady and small deviations affected the test results appreciably. Therefore a reservoir of water was positioned at an equivalent height of five pounds per square inch pressure above the sample mold.

The three transducers were calibrated to read uniformly between zero and five pounds per square inch and to plot ten full half inch spaces on the recorder for a five pound per square inch pressure increment. Periodically this calibration was checked.

At the beginning of each test the transducer indicators were suppressed to zero and accordingly the change in pore pressure was plotted at one pound per square inch per inch on the oscillograph.