wick drains increased with greater hydrostatic pressure due to embankment loading.

This project introduced the use of wick drains in California and several wicks are now available. Their application on other projects is proposed.

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Determining Maximum Void Ratio of Uniform Cohesionless Soils

JOHN E. WALTER, WILLIAM H. HIGHTER, AND ROBERT P. VALLEE

A testing program was conducted to evaluate several methods of determining the maximum void ratio of cohesionless soils. Preliminary test results indicated that a new procedure called the tube method was consistent in attaining reliable maximum void ratios. In performing the tube method, a long narrow tube or cylinder opened at both ends is placed upright in a mold of known volume. A quantity of dry sand sufficient to fill the mold is placed in the tube and then the tube is slowly extracted to allow sand to trickle into the mold until the mold overflows. The sand is then screeded level with the top of the mold and the void ratio is calculated from measured masses and volumes and the specific gravity of the sand. To evaluate various methods of determining maximum void ratios, a test series was carried out by using eight different test procedures on four sands. Statistical analyses of the data indicated that the tube method yielded higher values of maximum void ratio than did the other procedures. In addition, a testing program involving nine inexperienced operators demonstrated that by using the tube method an individual operator was able to reproduce results consistently and the operators were able to replicate one another's results well within limits mandated by practical applications.

Relative density (density index) is used to describe the state of compactness of cohesionless soils as a function of the loosest and densest states that the soil can attain. Knowledge of the density index (I_D) can give engineers valuable insight into the engineering behavior of a soil. However, since a particular soil can have different fabrics or arrangements of particles at the same void ratio, additional descriptors are required to characterize the soil.

The density index or relative density (D_r) of a soil at void ratio e and dry weight γ_d is defined in terms of void ratio as

$$I_D = D_r = [(e_{max} - e)/(e_{max} - e_{min})] \times 100\% \quad (1a)$$

and in terms of corresponding dry unit weight as

$$I_D = D_r = [\gamma_{d_{max}}(\gamma_d - \gamma_{d_{min}})/\gamma_d(\gamma_{d_{max}} - \gamma_{d_{min}})] \times 100\% \quad (1b)$$

where the subscripts refer to maximum and minimum states.

Dry unit weights or void ratios of the soil in the densest and loosest states are determined by laboratory tests. Errors in determining these values lead to significant errors in the estimation of the density index (1) and can mislead the engineer in an assessment of the likely in situ behavior of the soil under service loads. The determination of the loosest state of soil compactness has been particularly troublesome. The research reported here focuses on the procedures used in the determination of maximum void ratio for clean, medium to fine, uniform sands.

The choice of sands to use in the testing program was influenced by the findings of previous investigators. Burmister (2,3) reported the effects of particle shape, size, and gradation on limiting void ratios. Kolbuszewski (4) also studied parameters that controlled limiting void ratios in granular soils and found that particle shape and pluviation height have a strong influence on maximum void ratio. Youd (5) found particle size to have minimal effect on maximum void ratio. Studies by Dickin (6) and Norris (7) found particle shape to be the most influential soil factor in controlling maximum void ratio. Youd (5) prepared a plot from which maximum void ratio can be estimated from gradational and particle shape characteristics.

PROPERTIES OF SOILS TESTED

The four soils used in the investigation were medium to fine sands. The selection was based on particle shape, size, and gradation characteristics. Each sand contained less than 5 percent of particles finer than the no. 200 sieve and no more than 5 percent coarser than the no. 4 sieve. Because of the important effect of particle shape on limiting void ratio, a major criterion in selecting the soils was their shape characteristics.

Microphotographs of each candidate soil were obtained and, based on the method suggested by Wadell (8), the roundness of each soil was obtained. Wadell (8) defined roundness (ρ) as

$$\rho = (1/R)\left[(1/N)\sum_{i=1}^{N} r_i\right] \quad (2)$$

where the term within brackets is the arithmetic mean of the sum of N internal radii of the projected particle shape and R is the radius of the maximum

Table 1. Index properties of four soils.

Soil	Specific Gravity (G_s)	Particle Size: Effective [D_{10} (mm)]	Particle Size: Mean [D_{50} (mm)]	Coefficient of Uniformity (C_u)	Coefficient of Curvature (C_c)	Roundness[a] (ρ)
F-70 banding sand	2.65	0.10	0.15	1.5	1.1	0.30
ASTM C109 sand	2.65	0.22	0.38	1.9	1.0	0.42
ASTM C190 sand	2.65	0.56	0.75	1.4	1.0	0.60
Garnet mine tailings	3.16	0.06	0.19	3.3	1.2	0.19

[a]Results based on equations by Wadell (8) and charts by Powers (9).

Figure 1. Grain size distribution curves for four sands.

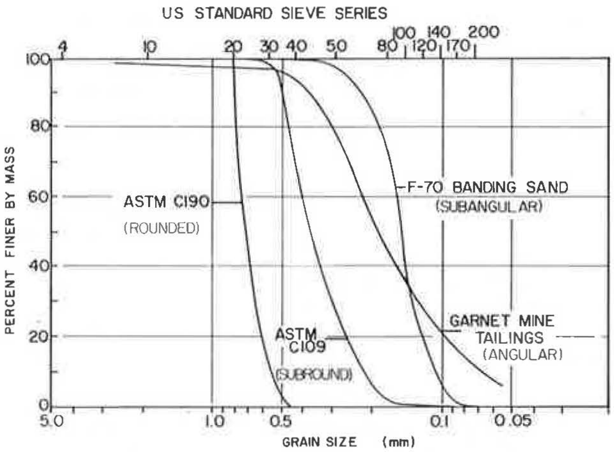


Table 2. Mean maximum void ratios from initial pluviation tests.

Funnel Diameter (in)	Pluviation Height (in)	Mean Max Void Ratios by Mold Diameter: 2.0 in	2.5 in	3.0 in	3.5 in	4.0 in	4.5 in
0.117	6	0.831	0.835	0.833	0.835	0.830	0.836
	12	0.800	0.808	0.815	0.822	0.818	0.821
	24	0.622	0.664	0.702	0.709	0.730	0.705
0.275	6	0.831	0.831	0.838	0.837	0.831	0.839
	12	0.827	0.824	0.836	0.835	0.825	0.824
	24	0.818	0.814	0.818	0.818	0.806	0.803
0.435	6	0.816	0.813	0.815	0.814	0.814	0.817
	12	0.812	0.811	0.809	0.811	0.807	0.814
	24	0.807	0.805	0.804	0.803	0.799	0.804

inscribed circle within the projected area. Based on its value of ρ, each soil was then classified according to angularity by using the system developed by Powers (9).

So that a wide range of particle shapes was represented in the study, the soils chosen were ASTM C190 sand (rounded), ASTM C109 sand (subrounded), F-70 banding sand (subangular), and (angular) mine tailings from a garnet mining operation.

Index properties of the four soils are given in Table 1 and in Figure 1 are the grain size distribution curves for each soil.

INITIAL TESTING SERIES

Deposition by pluviation involves the free fall of soil particles through a fluid median (air or water) so that the particles come to rest in a loose configuration. The rate of deposition is controlled by the aperture through which the soil flows. To determine the void ratio, the soil is pluviated into a mold of known volume and weighed. A preliminary series of dry pluviation tests that used air as the median was carried out to determine the effects of height of free fall, diameter of aperture (funnel) opening, and mold diameter on the void ratio. In these tests dry soil flowed through a funnel into a mold of known volume. The funnel was supported by a ring clamp, and when the center of the funnel and the center of the mold were aligned a stopper was held to the tip of the funnel while a quantity of banding sand sufficient to overflow the mold was placed in the funnel. The stopper was then removed and the soil rained down.

The excess soil was gently struck off flush with the top surface of the mold by using a straightedge or screed that had an edge bevelled at approximately 45°. The screeding procedure consisted of three steps.

The first step was to place the bevelled edge of the screed on a small area of the lip of the mold. This was sometimes difficult, depending on the size and shape of the soil particles. If possible the screed was pushed horizontally into the first layer of sand grains. Alternatively, the screed was held at an angle of 30°-45° to the horizontal, which caused the sand grains to separate slightly and allowed the screed to rest on the lip of the mold.

In the second step the bevelled edge of the screed was held approximately 30° to the horizontal. Application of a slow, continuous foreward motion to the screed caused the excess sand to overflow the mold and created the desired horizontal plane behind the screed. During this step care was taken to limit any vibration. Occasionally, to release particles wedged between the screed and the lip of the mold, a small side to side motion was applied to the screed as it was advanced across the top of the mold, but the screed was never reversed in its forward progress or raised.

The third step in the screeding procedure was necessary only if particles became wedged between the screed and lip of the mold. This occurred infrequently with angular particles only. Side to side motion usually freed trapped grains, but extraction of a particle was sometimes necessary. The void left in the surface was filled by lightly depositing sand with a spoon. The first two steps of the screeding procedure were then repeated to eliminate minor surface irregularities.

In the initial series of pluviation tests, 54 combinations of funnel opening size (3), pluviation height (3), and mold diameter (6) were chosen to examine the effects of these variables on the resulting void ratio. The results given in Table 2 are the average of five tests for each combination. The data show that the largest void ratio was obtained when the soil was pluviated from a 0.28-in diameter funnel through a 6-in free fall into a 4.5-in diameter mold.

The tube method evolved from the results of the initial testing series, which used the pluviation method and the research reported by Lucks (10) and Kolbuszewski (4). In the tube method a tube or right cylinder opened at both ends is positioned within the center of a mold that has one end supported by the bottom of the mold. A quantity of dry soil sufficient to fill the mold is placed in the tube and the tube is then extracted to allow the soil to flow into the mold. Excess soil is then screeded off.

An initial series of tests that used tubes was run to determine which combination of radius ratio (tube radius to mold radius) and extraction speed yielded the largest void ratio. For each of the four soils, a total of 30 combinations, each repeated 10 times, was performed. The following observations were made from a study of the data from all tests: the largest void ratio was obtained by using a tube-mold combination that had a small radius ratio (RR), and higher void ratios were obtained with the slower extraction rate than with the faster rate. Based on these observations, it was decided to use a tube-mold combination with a RR of 0.44 (2-in tube, 4.5-in mold) with a slow extraction speed in the evaluation test series designed to compare the results obtained from several published methods of determining maximum void ratio.

EVALUATION TESTS SERIES

The evaluation test series provided data and information so that comparisons could be made between several methods of determining the maximum void ratio of granular material. Of the eight procedures selected, four are variations of methods suggested by Kolbuszewski (4). In the notation of the listing that follows, the Kolbuszewski procedures are differentiated by the diameter of the cylinder used (2 or 3 in) and the fluid in which the soil particles are suspended--air (A) or water (W). The eight procedures were performed on each of the four soils in the following order:

1. Kolbuszewski 3A,
2. Modified ASTM D2049-69,
3. Kolbuszewski 2W,
4. Tube method,
5. Kolbuszewski 3W,
6. Castro method,
7. Kolbuszewski 2A, and
8. Mulilus, Chan, and Seed method.

The testing sequence was organized so that the data could be analyzed statistically and to separate similar procedures to minimize the influence of operator proficiency on the results. All eight procedures were carried out on one soil before another soil was tested. Each method was performed 30 times for each soil. Except for the two Kolbuszewski procedures, which used water as a medium, the soil used was air dry.

Procedures

ASTM D2049-69 Modified Method

A pouring device or funnel, with an inner spout diameter of 0.5 in was used to deposit the soil, as illustrated in Figure 2. The modification to ASTM D2049-69 (11) was that a 0.046 ft^3 rather than a 0.1 ft^3 mold was used. The decreased mold volume had no significant effect on the resulting e_{max} values. While the funnel was held firmly against the base of the mold, a quantity of soil sufficient to fill the mold was placed in the funnel. The funnel was then raised, which allowed a steady stream of soil to free fall 1 in into the mold, as shown in Figure 2. The pluviation (free fall) height was kept constant as the mold filled and the funnel was rotated in a spiral motion from the center to the edge of the mold to form a soil layer of uniform thickness. The excess soil was screeded from the mold.

Tube Method

As a result of the preliminary study, a 2-in inner diameter tube and a 4.5-in inner diameter mold (RR = 0.44) were used to perform the tube method test. The extraction rate was approximately 0.2 in/s. This method is illustrated in Figure 3.

Castro Method

The procedure used by Castro (12) is similar to ASTM D2049. The differences involve use of a dispersion plate, smaller diameter mold, and decreased height of pluviation. The dispersion plate was 0.5 in in diameter and was attached 0.2 in below the tip of the funnel by a thin wire harness (see Figure 2). Castro used a 2.9-in mold; however, a 3-in mold was used in this study. The same funnel motion used in the ASTM method was used.

Mulilus, Chan, and Seed Method

The ASTM method was modified by Mulilus, Chan, and Seed (13) to achieve a very loose soil structure within a 2.8-in diameter triaxial mold. This method of pluviation involved a larger free fall and a smaller mold than in the ASTM method. A variable pluviation height of from 6-20 in was used by Mulilus and others, but in this study, because the preliminary test results showed that a 6-in free fall yielded larger void ratios, a constant height of 6 in was used. This method is illustrated in Figure 2 with the 3-in diameter mold used in this study.

Kolbuszewski Methods

Whereas other methods used in this study involved the placing of an unknown mass of soil in a known volume and then measuring the mass, Kolbuszewski's approach (4) is to place a known mass of soil in an unknown volume and then measure the volume occupied by the soil.

A kilogram of soil was placed in a calibrated right cylinder 18-in high that was closed at one end. A rubber stopper was attached to the open end and the cylinder was inverted several times so that all sand particles were free from one another. An immediate inversion allowed the grains to settle into a loose soil structure. By use of a special apparatus developed specifically for the task (14), the unoccupied volume of the cylinder above the soil was measured. This volume was then subtracted from the known total volume of the cylinder to obtain the volume occupied by the soil.

Kolbuszewski (4) reported that the diameter of the cylinder influenced the void ratio obtained, so in this study cylinder diameters of 2 and 3 in were used. Another variable that affected the results was the fluid through which the soil pluviated. Both air (A) and water (W) were used in combination with the 2- and 3-in diameter cylinders. Hence, the method designations 2A, 3A, 2W, and 3W.

When using Kolbuszewski's method to deposit soil through water, care must be taken to eliminate entrapped air within the soil. This was done by tilting the cylinder slightly and pouring small amounts of deaired water down the cylinder wall, which allowed the water to percolate through the soil. When the soil was completely immersed, larger amounts of deaired water were added until the cylinder was full.

DISCUSSION OF RESULTS

The results of the testing program are given in the order that the soils were tested beginning with the banding sand. In the tables in which the results are tabulated the listing begins with the method that gives the highest value of void ratio and continues in decreasing order.

The data obtained from the Kolbuszewski 2W and 3W tests are not given because these methods gave unrealistically high values of void ratio due to arching or tridimensional bridging of particles and entrapped air bubbles. Frequently, after final inversion of the cylinder, air bubbles became entrapped and unable to escape the falling soil particles. A second phenomenon noted by Kolbuszewski (4) was arching in the soil, which caused the soil to form a local honeycomb structure (Figure 4). This structure may have been formed by the collapse of soil grain columns that were formed as the soil pluviated through the water medium. Although the entrapped air and arching phenomenon are similar in effect (both give inflated e_{max} values) the granular structures are quite different. In the case of entrapped air bubbles, the soil grains rested against the air-water interface and were supported by surface tension. In contrast, the granular structure of the arch was self-supporting.

The soil grain columns whose collapse probably was responsible for the arching observed was caused

Figure 2. Schematic of three funnel methods.

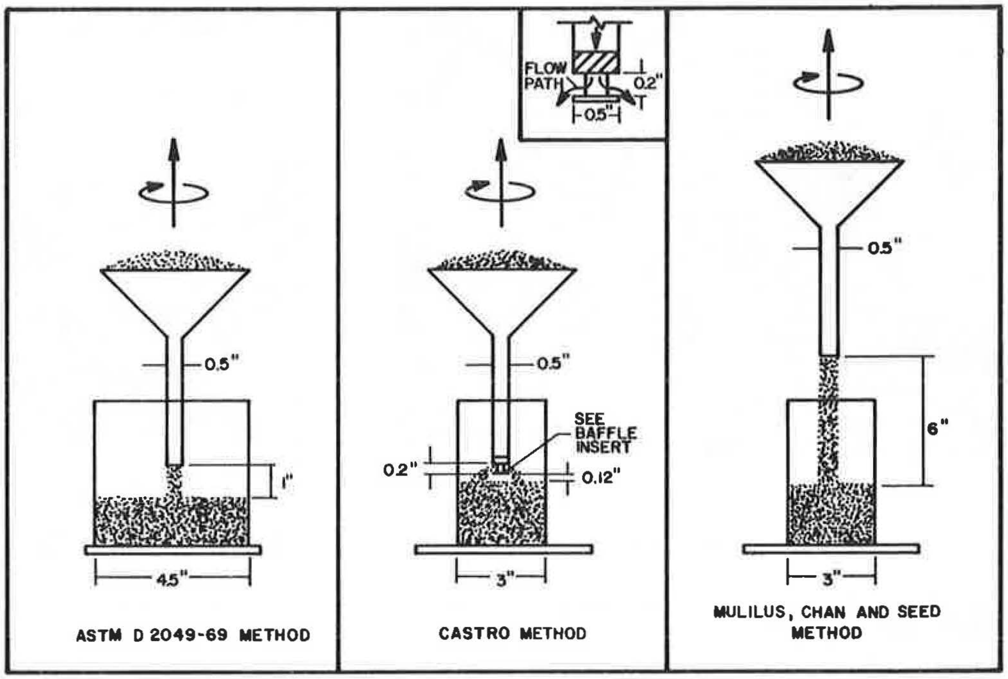
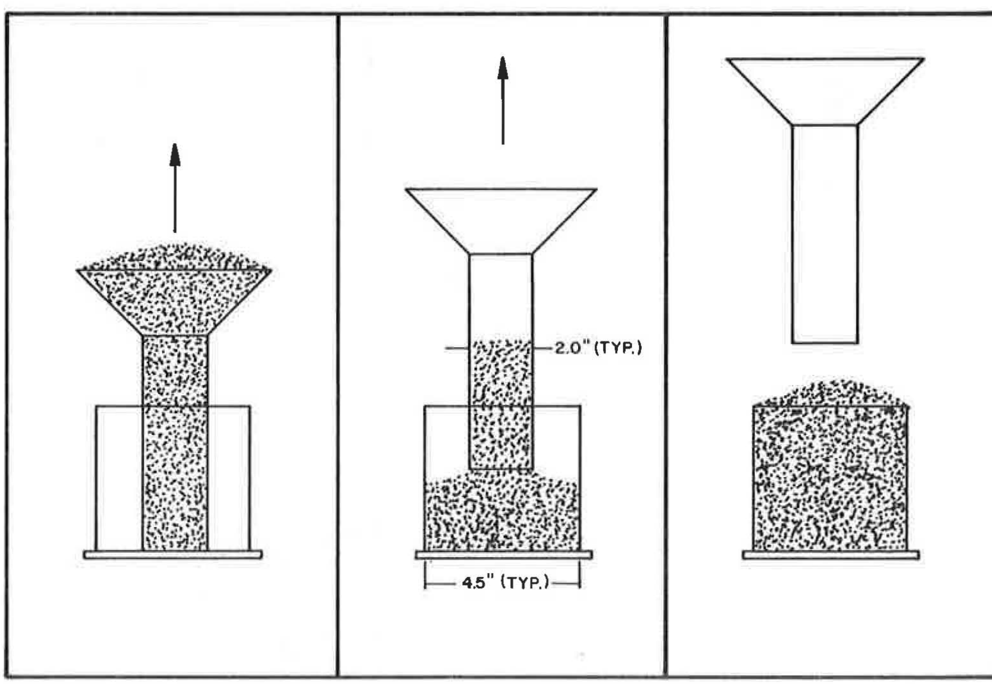


Figure 3. Schematic of tube method.



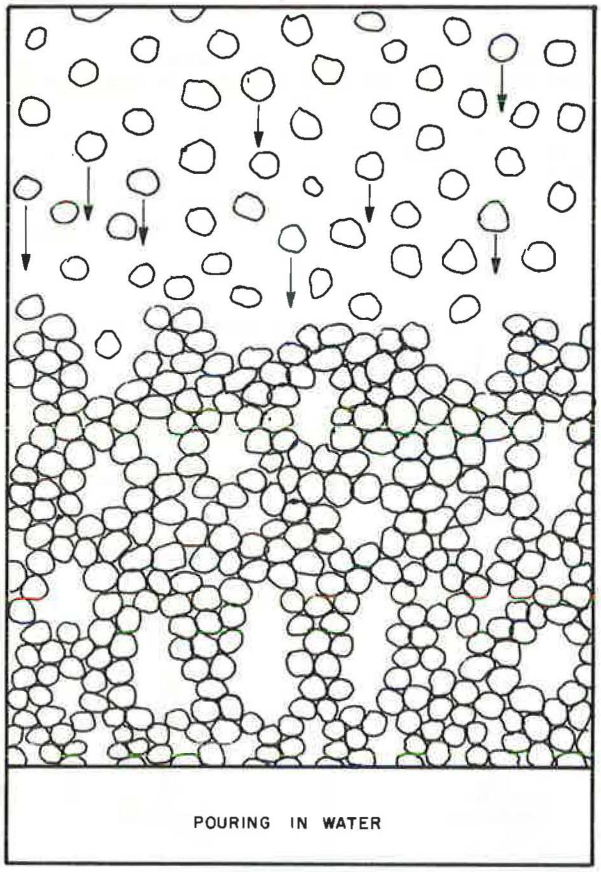


Figure 4. Honeycomb structure developed when water is used as the medium in Kolbuszewski method.

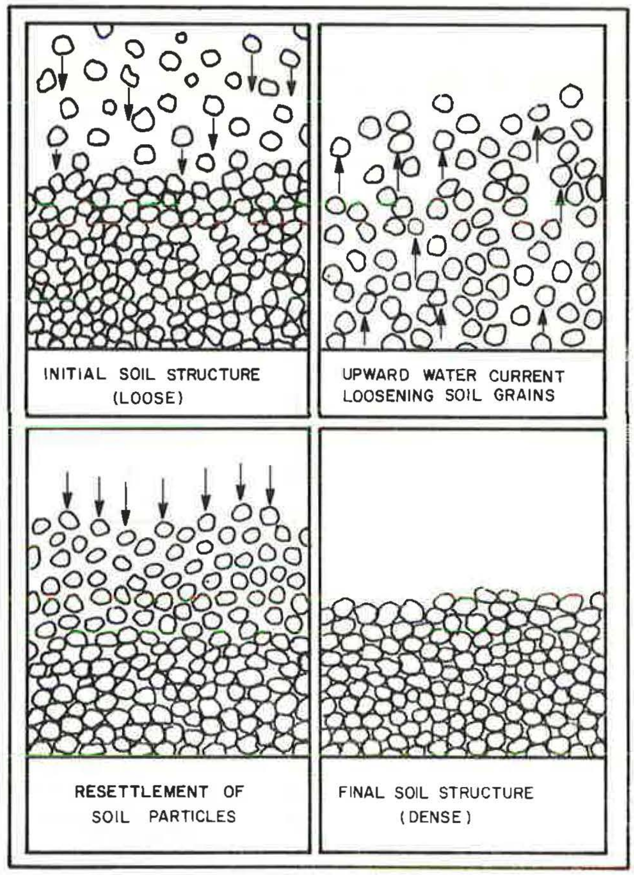


Figure 5. Soil structure from vertical channel currents when water is used as the medium in Kolbuszewski method.

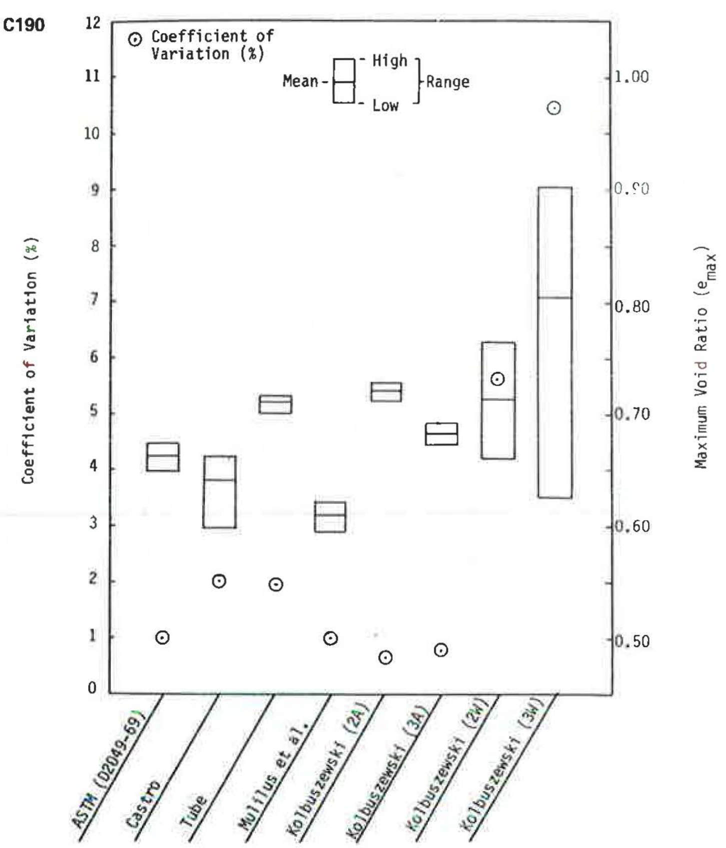


Figure 6. Range, mean, and coefficient of variation of e_{max} for C190 sand from eight test methods.

by the effect of water flowing upward on the settling soil particles. The vertical water currents caused a disturbance of the soil particles during pluviation, which forced the grains upward and caused them to resettle in columns (Figure 5). Kolbuszewski noted that the number of water channels increased for a given soil as the cylinder diameter decreased in size.

Air entrapment and soil arching result in wide scatter in the data obtained from tests that use these methods. This is shown in Figure 6. Because of the problems associated with the Kolbuszewski 2W and 3W methods, these procedures were not reported in the evaluation of methods for determining maximum void ratio. Results obtained from these methods are given by Walter (14).

The results from the six other test procedures were analyzed statistically to determine if the differences among mean e_{max} values obtained for each method were statistically significant. The statistical analysis examined the null hypothesis that there was no significant difference between the mean values of the maximum void ratio values obtained from any two test procedures. Rejection of the null hypothesis indicated that there existed a statistically significant difference between the mean values at a given level of confidence (95 percent was used). If the null hypothesis could not be rejected, then the analysis indicated there was no statistically significant difference between the mean values and, therefore, both methods gave the same mean e_{max}.

Banding Sand

Test results for the banding sand (subangular grains) are given in Table 3 arranged by method from the highest to the lowest mean value of maximum void ratio. The tube method gave the highest mean value of e_{max} and had the lowest standard deviation and coefficient of variation, which indicates that the method allowed the operator to reproduce results very closely. All methods had coefficients of variation of less than 2 percent.

Table 3 gives mean e_{max} values ranged from 0.836 for the tube method to 0.763 for the Kolbuszewski 3A method. Figure 7 shows the results of the statistical analysis to test the null hypothesis that the mean e_{max} from each method is not significantly different. The tube method gave a significantly higher mean e_{max} value than did each of the other methods (the null hypothesis that the means were the same was rejected).

C109 Sand

The results of the tests for this sand with subrounded grains are tabulated in Table 4. Once again the tube method gave the highest value of maximum mean void ratio and had the lowest coefficient of variation. The Castro method gave the second highest results for the C109 sand but had the largest coefficient of variation. Results for the statistical test on the mean e_{max} values for this sand are given in Figure 8. The mean value of maximum void ratio obtained from the tube method was statistically different (greater than) the mean values obtained from each of the other methods.

C190 Sand

A summary of the results of the six methods for the C190 sand that has rounded particles is given in Table 5 and Figure 6. The Kolbuszewski 2A method, which uses a 2-in diameter cylinder and pluviates the grains through air, gave the highest value of maximum void ratio. It was followed by the tube method. Statistical tests on the null hypothesis were carried out for each pair of data and in all cases the null hypothesis that the means were not statistically significantly different was rejected. Data from the Kolbuszewski 2W and 3W methods are included in Figure 6, which illustrates the effects of soil arching and air entrapment on the mean and range of the e_{max} values obtained in the 30 trials. Visual observation of the soil structures in the laboratory indicated the high mean value of e_{max} was mostly due to arching. The wide range of e_{max} values obtained in the tests and the high coefficient of variation indicate that arching did not occur in all of the 30 trials.

Mine Tailings

The mean maximum void ratio for each method for mine tailings with angular particles is given in Table 6. The mean e_{max} values ranged from a low of 0.966 (Kolbuszewski 3A) to a high of 1.044 (tube method). The coefficients of variation for all methods were less than 1.5 percent. The results of the statistical tests for significant differences between means are given in Figure 9. The mean of e_{max} obtained from the tube method is statistically significantly different from the mean of e_{max} obtained from the other five methods. However, the mean values of e_{max} obtained from the second and third ranking methods for the mine tailings, Kolbuszewski 2A method, and Castro method, respectively, were not significantly different.

Comments on the Test Methods

The tube method required no special preparation and was easy to perform. Visual inspection of the soil after deposition indicated a homogeneous structure if the tube was raised steadily. Soil layering resulted if the tube was extracted with a jerky stop and go motion. The tube method gave highly consistent results.

The Kolbuszewski method that used pluviation through air was easy to perform and gave consistent results. The soil structure was homogeneous. Special equipment was needed to measure the volume occupied by the soil so that the void ratio could be calculated accurately. For each soil tested the e_{max} obtained was higher for the 2-in diameter cylinder than for the 3 in and the means were statistically significantly different. This effect of cylinder diameter was also observed by Kolbuszewski (4).

Objections with the Kolbuszewski method that used water as a pluviation median were discussed previously. The soil structure obtained was heterogeneous and coefficients of variation obtained from the data for the four soils ranged from 10.8 to 13.9 percent compared with a maximum of 2.6 percent for any of the other methods (14).

Of the three pluviation methods employed in this study that used a funnel, controlling the height of fall while maintaining a continuous spiral motion was easiest by using the modified ASTM D2049 method. No special preparation was needed and the results were consistent.

It was difficult to duplicate test results by using the Castro method. This was because the dispersion plate, located just below the funnel, made it difficult to maintain the height of free fall (0.1 in) suggested by Castro (12). Even with special care, this invited operator error.

The 6-in pluviation height was difficult to maintain by using the Mulilus, Chan, and Seed method. Comparatively low values of e_{max} were obtained

Table 3. Results for F-70 banding sand.

Method	Mean ($\bar{x}$)	SD[a] (S)	Coefficient of Variation[b] [V (%)]
Tube	0.836	0.003 12	0.37
Castro	0.818	0.008 77	1.07
ASTM D2049-69	0.810	0.010 21	1.26
Mulilus, Chan, and Seed	0.800	0.006 50	0.81
Kolbuszewski, 2A	0.799	0.005 18	0.65
Kolbuszewski, 3A	0.770	0.010 89	1.41

Note: For each method, 30 tests were run.

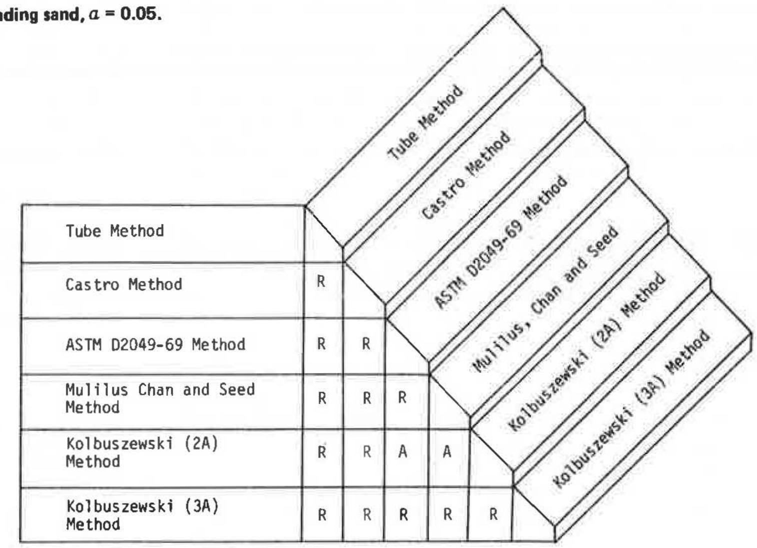
[a] $S = \sum_{i=1}^{N} (x_i - \bar{x})^2/(N-1)$. [b] $V = (S/\bar{x})(100\%)$.

Table 4. Results for C109 sand.

Method	Mean ($\bar{x}$)	SD (S)	Coefficient of Variation [V (%)]
Tube	0.737	0.001 88	0.26
Kolbuszewski, 2A	0.709	0.003 97	0.56
ASTM D2049-69	0.696	0.006 20	0.89
Mulilus, Chan, and Seed	0.683	0.006 54	0.96
Kolbuszewski, 3A	0.681	0.006 12	0.90
Castro	0.677	0.017 76	2.62

Note: For each method, 30 tests were run.

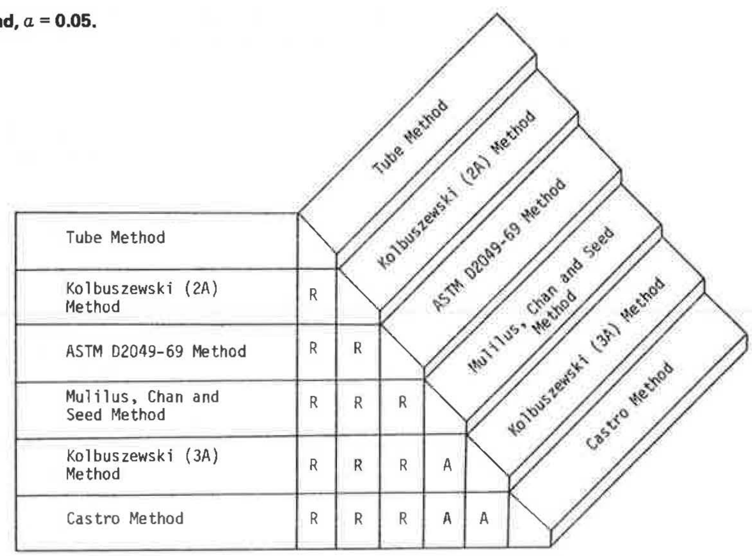
Figure 7. Results of null hypothesis on mean values for F-70 banding sand, α = 0.05.



R-Rejection of the null hypothesis that the e_{max} means are equal

A-Acceptance of the null hypothesis that the e_{max} means are equal

Figure 8. Results of null hypothesis on mean values for C109 sand, α = 0.05.



R-Rejection of the null hypothesis that the e_{max} means are equal

A-Acceptance of the null hypothesis that the e_{max} means are equal because of compaction of the material already in the mold by the impingement of particles that dropped through a relatively large (6 in) pluviation height.

Operator Effect of Using the Tube Method

All the test results reported to this point were obtained by a single operator. Because of the encouraging results obtained with the tube method, the results of several operators were compared. After having 15 min of instruction that described the tube method and a demonstration, nine undergraduate students each ran 25 trials that used C109 sand. Each student was asked to complete the 25 trials without interruption within a 10-day period. Unreduced data were collected as soon as each student had finished 25 trials. Data reduction was not performed until all results were in and the students were asked not to discuss their data with others during the 10-day period.

The results of this study are given in Table 7. Students are differentiated by the order in which they completed their trials. Each student was able to reproduce his or her results extremely well. Coefficient of variation of all nine students was less than 0.5 percent and, with two exceptions, the range in data for each of the 25 trials was less than 1 lb•f/ft³.

Even though each student's mean of 25 trials was within 0.8 lb•f/ft³ of one another's, because of

Table 5. Results for C190 sand.

Method	Mean ($\bar{x}$)	SD (S)	Coefficient of Variation [V (%)]
Kolbuszewski, 2A	0.721	0.004 54	0.63
Tube	0.710	0.013 87	1.95
Kolbuszewski, 3A	0.682	0.005 61	0.82
ASTM D2049-69	0.662	0.006 66	1.01
Castro	0.640	0.013 22	2.07
Mulilus, Chan, and Seed	0.610	0.006 20	1.02

Note: For each method, 30 tests were run.

Table 6. Results for mine tailings.

Method	Mean ($\bar{x}$)	SD (S)	Coefficient of Variation [V (%)]
Tube	1.044	0.006 44	0.62
Kolbuszewski, 2A	1.013	0.005 71	0.56
Castro	1.012	0.012 85	1.27
ASTM D2049-69	0.995	0.010 66	1.07
Mulilus, Chan, and Seed	0.982	0.013 26	1.35
Kolbuszewski, 3A	0.968	0.003 60	0.37

Note: For each method, 30 tests were run.

Figure 9. Results of null hypothesis on mean values for mine tailings α = 0.05.

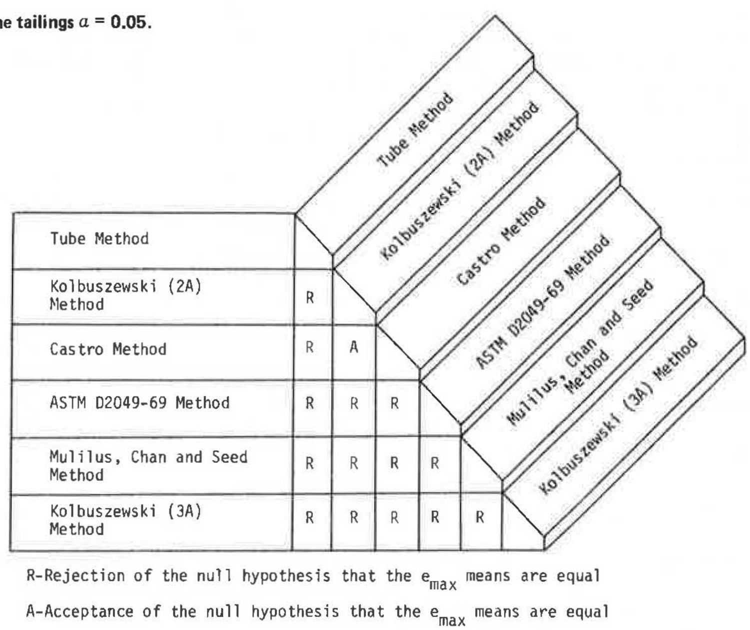


Table 7. Results for student operators using C109 sand.

Operator	Mean (lb·f/ft³)	SD (lb·f/ft³)	Coefficient of Variation (%)	Maximum (lb·f/ft³)	Minimum (lb·f/ft³)	Range (lb·f/ft³)
Student S5	95.5	0.16	0.17	96.0	95.2	0.8
Student S7	95.4	0.16	0.17	95.9	95.2	0.7
Student S1	95.3	0.22	0.23	95.5	94.4	1.1
Student S8	95.3	0.13	0.14	95.5	95.1	0.4
Student S6	95.1	0.16	0.17	95.4	94.8	0.6
Student S3	94.9	0.41	0.43	96.1	94.4	1.7
Student S9	94.7	0.14	0.15	95.1	94.5	0.6
Student S4	94.7	0.13	0.14	95.0	94.5	0.5
Student S2	94.7	0.10	0.11	94.9	94.5	0.4
Overall[a]	95.1	0.36	0.38	96.1	94.7	1.7

[a] 225 trial runs.

Figure 10. Value of σ required so that null hypothesis on mean values for different operators cannot be rejected, $\alpha = 0.05$.

	Student S5	Student S7	Student S1	Student S8	Student S6	Student S3	Student S9	Student S4	Student S2
Student S5									
Student S7	0.03								
Student S1	0.11	0.01							
Student S8	0.13	0.03	0.0						
Student S6	0.32	0.22	0.11	0.13					
Student S3	0.45	0.35	0.24	0.26	0.05				
Student S9	0.73	0.63	0.51	0.54	0.33	0.05			
Student S4	0.73	0.63	0.51	0.54	0.33	0.06	0.0		
Student S2	0.74	0.64	0.52	0.54	0.34	0.06	0.0	0.0	

each student's ability to reproduce his or her own results so closely, statistical analysis indicated that in most cases each student's mean value was statistically significantly different from others (at the 95 percent level of confidence).

To get a clearer idea of the magnitude of the numbers involved, a statistical analysis was carried out to see how much smaller the difference in mean values of dry unit weight of two students need be so that the difference between them was not statistically significant. The results of the analysis, for the 36 combinations of nine students, is given in Figure 10. This figure shows, for example, that if students S1 and S9 had obtained means 0.51 lb•f/ft³ closer to one another the means would not have been statistically signficantly different.

The magnitude of the differences in means of the nine students is not believed to be of practical significance. The maximum difference that a change in $\gamma_{d_{min}}$ of 0.8 lb•f/ft³ makes in the density index (Equation 1) is about 8 percent.

SUMMARY AND CONCLUSIONS

The following observations and conclusions can be made as a result of this study, which used eight methods of determining the maximum void ratio of four soils.

1. In a preliminary series of tests where soil pluviation was used, larger values of maximum void ratio were obtained by decreasing the free fall height. An intermediate funnel diameter yielded the largest void ratios. Mold diameter was not found to be important.
2. In a preliminary series of tests that used tube extraction as a means of determining e_{max}, the highest void ratios were achieved when the tube was extracted slowly and a tube-mold radius ratio equal to 0.44 was used. This was the smallest radius ratio used in this study.
3. The Kolbuszewski method that used water as a pluviation medium resulted in a heterogeneous soil structure with some soil arching. This method is not recommended for obtaining e_{max} values.
4. The Kolbuszewski method that used air as a pluviation median in a 2-in diameter cylinder gave high, consistent values of e_{max}. The only drawback of this procedure is the difficulty and care that must be taken to measure the volume of the soil. Special equipment is needed for this purpose.
5. The method that gave the highest values of e_{max} for three of the four soils tested and the second highest for the fourth soil is the tube method. A 2-in diameter tube extracted slowly from a 4.5-in diameter mold gave consistent values of e_{max} in successive trials. Coefficients of variation of less than 0.7 percent were calculated from data from three of four soils; a value of 1.95 percent was obtained from the fourth.
6. The tube method of determining e_{max} produces very similar results for different operators. The range in γ_d for nine operators running 25 trials was 1.7 lb•f/ft³; the overall coefficient of variation was less than 0.5 percent.
7. For the soils tested in this study, the tube method is an excellent method of determining maximum void ratio of granular material.

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Compressibility of Field-Compacted Clay

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This study investigates the compressibility of a plastic Indiana clay (St. Croix) compacted in the field. Correlation among compaction variables and compacted properties was a prime objective. The clay was compacted to three levels of effort and five levels of water content by two kinds of rollers. As-compacted compressibilities were assessed in the laboratory oedometer, and compaction prestress values were interpreted from the e-log p curves. These values were always less than the nominal roller pressures previously applied to the soil. A regression model was written in terms of the compaction pressure and an interaction between pressure and compaction water content. Other compacted samples were saturated under three levels of confinement, with the aid of vacuum and backpressure. The subsequent volume changes depended on the compaction variables as well as on the confinement during saturation. A correlation was developed among the volumetric strain, the initial void ratio, the compaction water content, and the confinement during saturation. Soaked compressibilities were also measured and compared with the as-compacted values. The variability of the field samples is large. Comparable studies with samples of laboratory-compacted clay had been previously made and reported. Coupling of the relations for field compaction with those previously established for laboratory compaction is also reported here.

Compacted soils are used in large quantities in the construction of roadway embankments and other fills. The stability of these structures against a slope failure is always of major concern, and in most cases it is the only criterion taken into consideration in the design. However, as the construction of higher embankments becomes more common, specification of compaction procedures so that embankment settlement can be predicted and controlled for both the short- and long-term conditions is increasingly more important.

During an embankment design, the geotechnical engineer quantitatively predicts and controls the overall performance of field-compacted soil. One method is to construct a special fill section by using a range of compaction processes and then testing samples from the soil mass after each process. Such a test pad with the associated costs of field sampling, laboratory testing, and analysis is not economically feasible for most projects. Therefore, the design engineer must infer the compressibility behavior of field-compacted soils from relations developed in the laboratory. Because this inference process may not be the most desirable, this paper presents a rational method of predicting the field-compaction response from laboratory tests.

This study investigates the compressibility behavior of a field-compacted soil in the as-compacted and soaked conditions. The soil used was plastic residual clay, and field compaction was achieved by using a Caterpillar model 825 tamping roller and a RayGo Rascal model 420C vibratory roller. Three energy levels and five molding water contents were used for each roller type to study their effects on compressibility behavior. To examine the as-compacted compressibility characteristics, the compacted samples were trimmed to appropriate size and loaded incrementally in the oedometer. Of particular interest was the value of compactive prestress. During the service life of an earthen embankment, environmental changes may affect an increase or decrease in the volume of the mass.

In order to simulate the changes in the mass that may occur in service, compacted samples were saturated by a back-pressure technique in the oedometer under an equivalent embankment load. Of major interest was the percentage of volume change on wetting under loading. Saturated compressibility was also measured.

A similar study of the compressibility characteristics of laboratory-compacted samples from the same area soil was made by DiBernardo (1). Combined, the results of both studies will allow the engineer to predict the field response from laboratory-compacted samples.

BACKGROUND

The concept of compactive prestress is generally defined as analogous to the preconsolidation pressure, where the pressure effect is caused by the compaction process (2). Lambe (3) agreed with this definition, but added that the value of the compactive prestress was sensitive to chemical and physical changes in the soil with time.

The process of compaction of a soil involves transmittal of the external compaction energy to the soil skeleton and pore fluids. On completion of the process, an induced prestress in the soil that may or may not be equal to the compaction pressure is produced. Abeyesekera (4) observed that this value of compactive prestress is important with respect to compacted shale behavior.

In order to determine the compactive prestress, Woodsum (2) statically compacted soil directly in oedometer rings, allowed the soil to come to equilibrium with water under an applied load, and performed the consolidation test. He found that, as the confining pressure remained constant and as the compaction pressure (P_{cp}) increased or void ratio decreased, the value of prestress (P_s) increased. Moreover, he found that, although the value of prestress increased with increasing compaction pressure, the prestress ratio (P_s/P_{cp}), which was similar to the overconsolidation ratio for saturated soils, varied but slightly. This prestress ratio reflects the effective transmittal of external compaction energy to the soil skeleton. On completion of the compaction process, the induced prestress in the soil may or may not be equal to the compaction