

Stabilization of Beach Sand by Vibrations

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• **STABILIZATION** of sands has been achieved by many methods, such as mechanical, chemical, addition of admixtures, grouting, and compaction. Of these methods, the most economical has been compaction, which can be achieved in many ways; for example, rollers, vibrotampers, and vibroflotation.

It has been reported that heavy duty pneumatic rollers imposing a pressure of about 150 psi have compacted sand to a depth of 6 ft below the ground surface. Vibrotampers, weighing 435 lb, operating at 2,100 cpm and producing a compacting force of 10,000 lb are reported to cause compaction of over 95 percent of modified AASHO on lifts up to 15 in. in one pass or two. The vibroflotation process, which imparts a centrifugal force of 10 tons at 1,800 rpm, is reported to compact sand up to a radial distance of 5 ft giving densities of 90 percent of optimum to depths in the range of piling.

Much laboratory research has been done on compaction of sands. One project conducted at the California Institute of Technology (1) by placing on the surface of a sand pit 10 ft square and 6 ft deep, an oscillator weighing 61 lb and driven at frequencies from 170 to 3,450 rpm led to the conclusion that the maximum compaction was obtained at resonant frequency involving several variables such as elastic constant of soil, vibrator dimensions, weight of vibrator, dynamic force, and base plate dimensions. Maximum density from 90 to 95 percent of Modified AASHO was obtained in a few seconds to a depth of twice the width of the oscillator.

The authors felt, after reviewing the field practice and laboratory research on the subject, that it would be profitable to investigate the compaction of sand with almost weightless tampers having several base plate dimensions and operated mechanically at the surface of dry sand at varying frequencies including the supersonic range. It was also decided to include some evaluation of the maximum possible laboratory sand density in view of the fact that though several methods have been suggested, none has been accepted so far as a standard.

APPARATUS

The compaction apparatus was constructed by attaching three aluminum plates 3 by 2 $\frac{3}{4}$ in., 4 by 2 $\frac{3}{4}$ in., and 5 by 2 $\frac{3}{4}$ in. of $\frac{1}{8}$ -in. thickness one at a time to the cone of a heavy duty loud speaker, as seen in Figure 1.

The speaker and plate were made to vibrate by an audio-oscillator augmented by an amplifier. A voltmeter across the supply line controlled the input voltage to prevent overloading the speaker. A cathode-ray oscillograph helped in the calibration of the audio-oscillator and also in the regulation of the precise frequency during the tests.

The sand to be compacted was contained in a glass-sided tank with a grid of 1-in. squares painted on one side. This tank was placed on a three-legged jack to permit raising and lowering of the tank during the compaction process. The complete apparatus is shown in Figure 2.

The dry sand chosen for the investigation has a uniformity coefficient of 4.35 and a grain-size distribution as shown in Figure 3. According to Hough (2), "an ordinary beach sand 'processed' to some extent by wave wash would have a (uniformity) coefficient of about 2 to 6." The selected grading thus has the uniformity coefficient of beach sand and in addition it fits within the grading limits for a well graded sand as specified by AASHO, M6-51, (3) as shown in Figure 3.

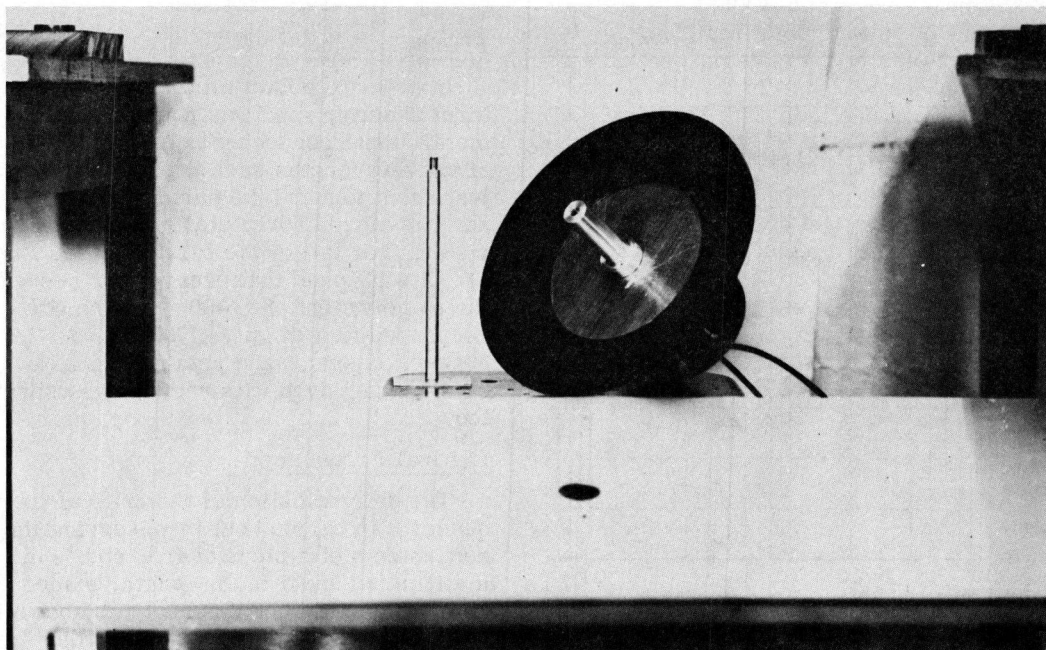


Figure 1. Details of speaker and tamper.

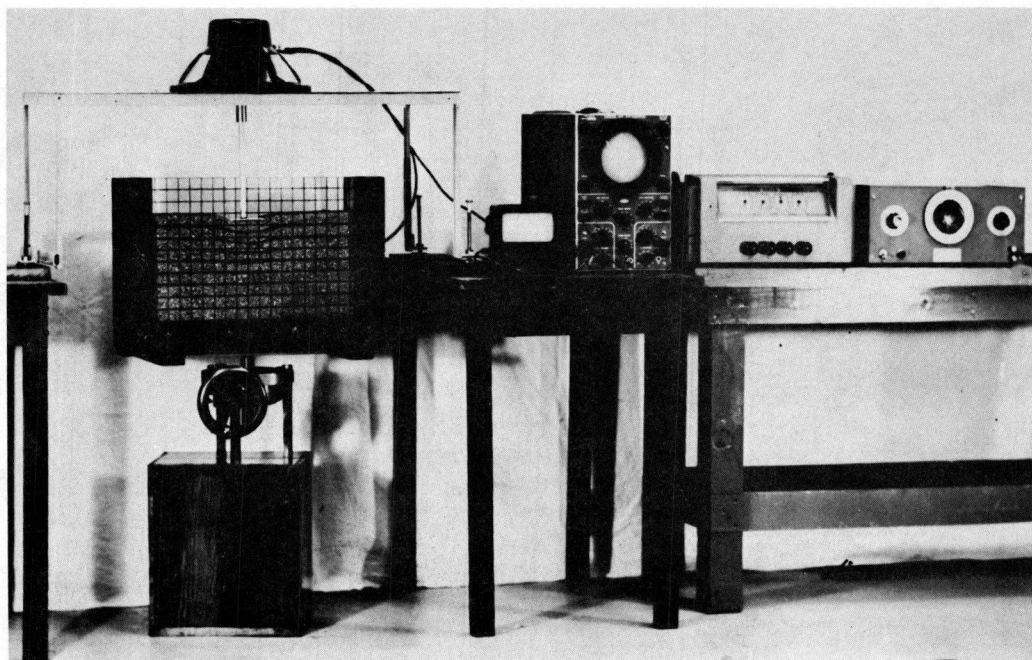


Figure 2. General view of apparatus.

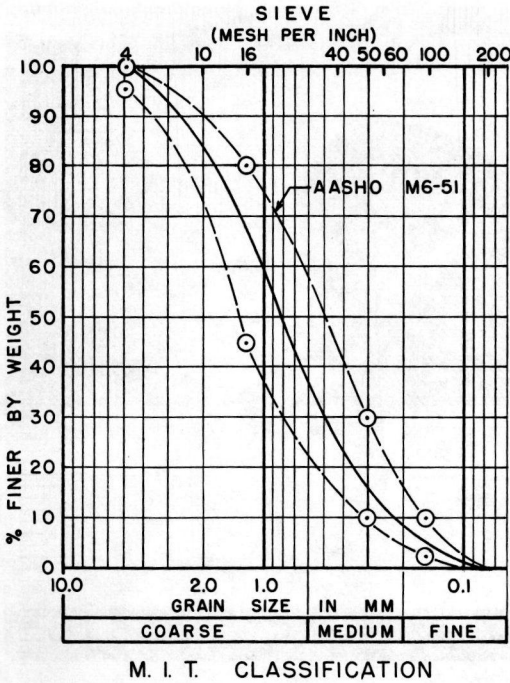


Figure 3. Mechanical analysis of sand.

PROCEDURE

Placing of Sand

In order to obtain minimum and uniform density, sand was poured through a metal funnel connected to extension tubes of varying lengths such that the extension just about touched the surface. The funnel was moved horizontally without giving rise to free fall of the particles (see Fig. 4). It was found that every layer needed the same weight of 1,400 g, which corresponded to a density of 102.5 pcf. In between layers, sand retained on a No. 60 sieve and dyed with red tint was sprinkled.

Critical Frequency

The determination of the critical frequency was carried out by observing the settlements of a piece of iron rod $\frac{1}{2}$ in. in diameter and 7 in. in length, placed vertically on the sand surface as shown in Figure 5. A dial gage measured the settlement. The entire range of frequencies from 18 to 20,000 cps was tried with a duration of $\frac{1}{2}$ min each time, taking care to see that the sand density was 102.5 pcf before each trial. Because the process

of placing the oven-dried sand without segregation of sizes and with uniform minimum density was laborious and time consuming the entire range from 18 to 20,000 cps was investigated by using a 3-in. tamper only. However, within the range that gave

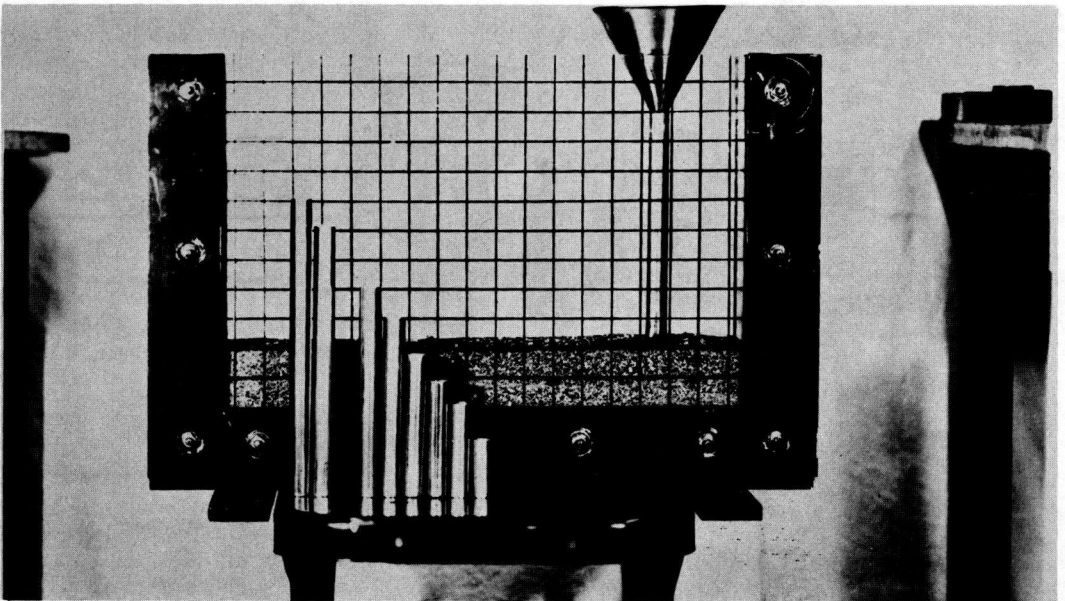


Figure 4. Apparatus for placing sand.

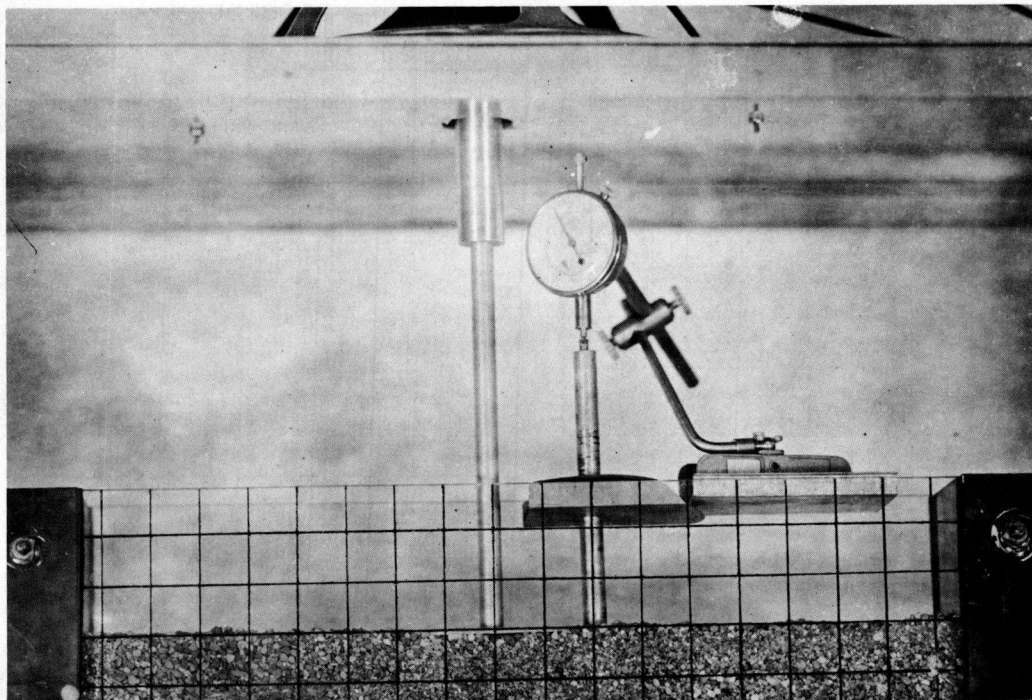


Figure 5. Apparatus for critical frequency.

appreciable settlements (for example, 18 to 30 cps), tests were carried out with all three tampers.

Evaluation of In-Place Density

Each tamper was operated at the critical frequency of 25 cps, during 5 min. Before starting each experiment and at the end of each minute photographs were taken to record the change in the thickness of layers. Examples are shown in Figures 6 through 11.

The reduction in the thickness of the layers is inversely proportional to the increase of the density of sand. Thus the change of the thickness of layers is a measure of their in-place density. On tracing each photograph, the in-place density at every point was calculated and lines drawn connecting equal densities, as shown in Figures 12 through 16.

Evaluation of the Tamping Force

To evaluate the load on the soil from the tamper a proving ring was placed under the tamping rod, as shown in Figure 17. When the tamping rod was vibrated at 25 cps a force of 0.375 lb resulted. Thus the pressures exerted by the 3-, 4-, and 5-in. tampers were 0.045, 0.034, and 0.027 psi respectively.

STANDARD FOR FIELD COMPACTION

Knowing that Proctor curves for sands are erratic and often not sharply defined as to maximum density, relative density was adopted as a standard for the study. The minimum density of the sand was found to be 96.2 pcf by following the funnel method with no circular motion and no free fall, as suggested by D'Appolonia (4). The maximum laboratory density was obtained by the concrete flow table surcharge method of D'Appolonia which resulted in a maximum density of 117 pcf.

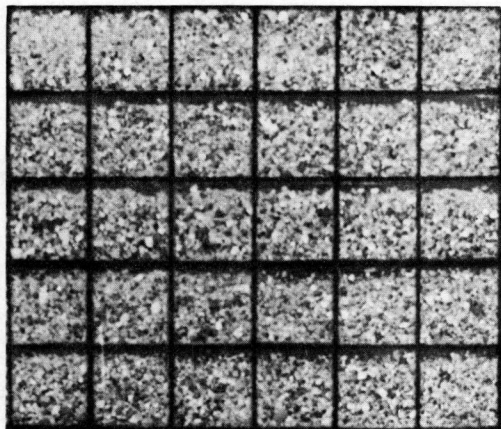


Figure 6. Settlement of 5-in. tamper at 0 min.

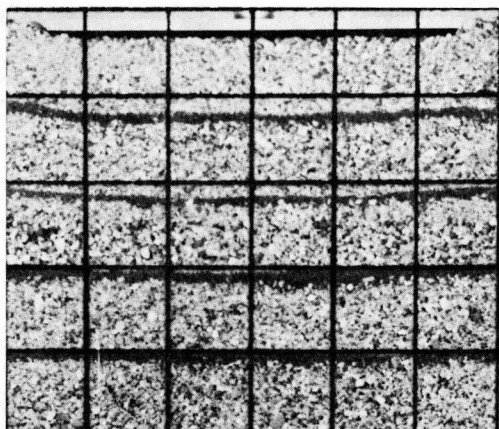


Figure 7. Settlement of 5-in. tamper at 1 min.

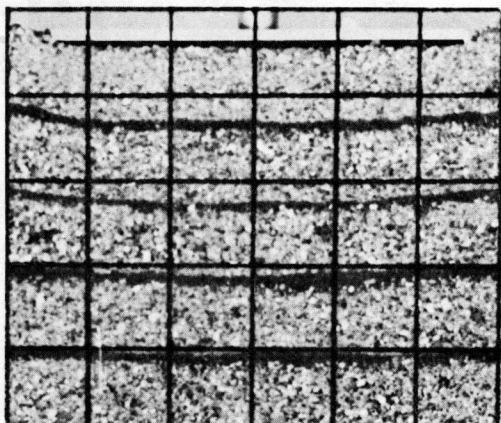


Figure 8. Settlement of 5-in. tamper at 2 min.

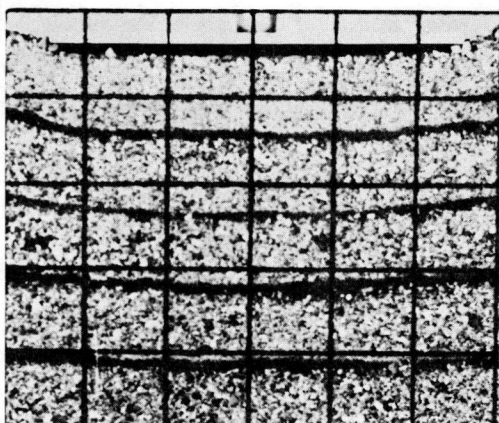


Figure 9. Settlement of 5-in. tamper at 3 min.

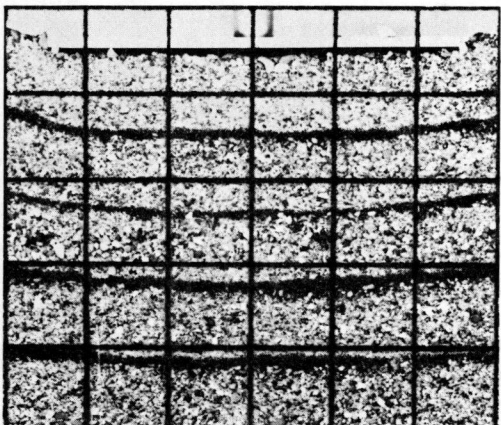


Figure 10. Settlement of 5-in. tamper at 4 min.



Figure 11. Settlement of 5-in. tamper at 5 min.

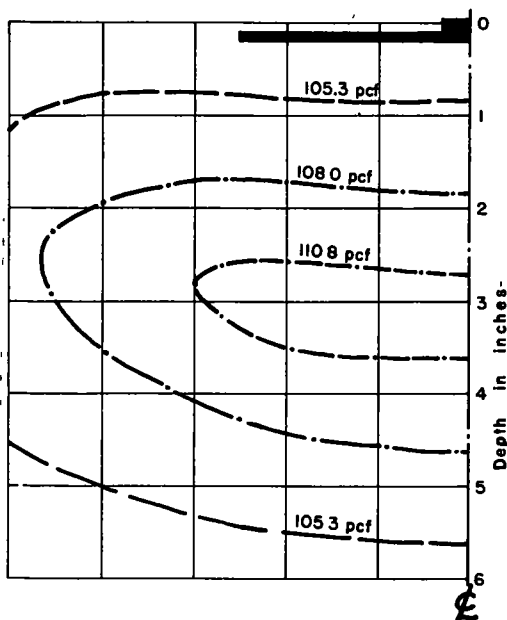


Figure 12. Curves of equal density for 5-in. tamper at 1 min.

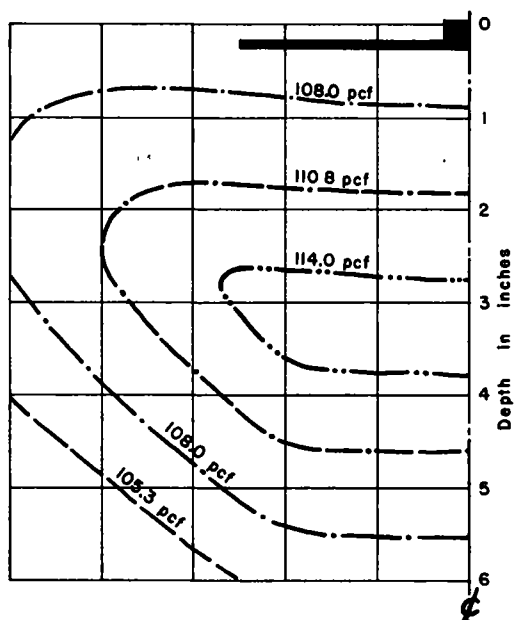


Figure 13. Curves of equal density for 5-in. tamper at 2 min.

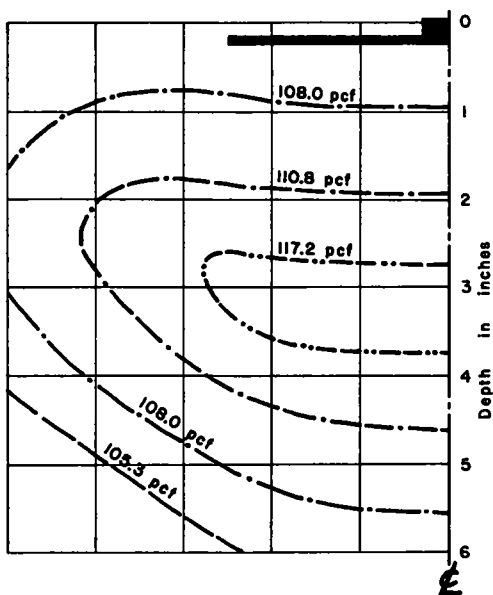


Figure 14. Curves of equal density for 5-in. tamper at 3 min.

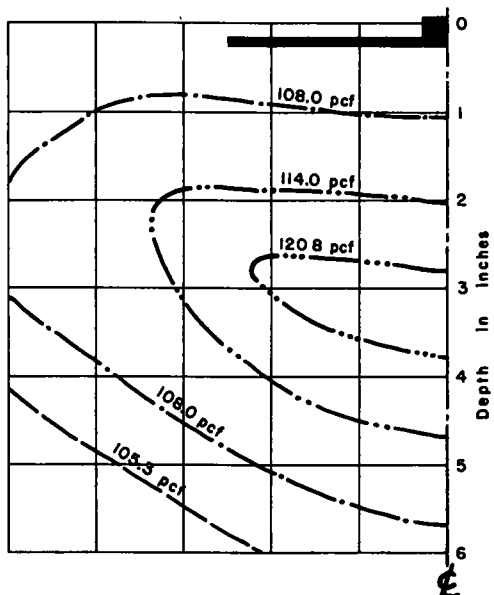


Figure 15. Curves of equal density for 5-in. tamper at 4 min.

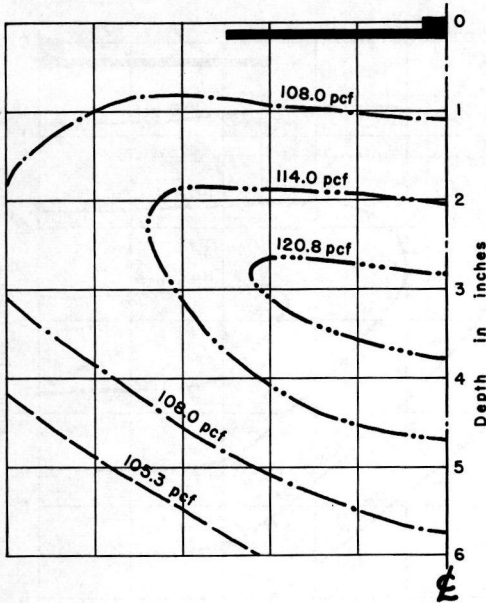


Figure 16. Curves of equal density for 5-in. tamper at 5 min.

RESULTS

The effect on sand settlement and thus density of varying the vibration frequency is shown in Figure 18 and 19. The greatest increase of density was obtained at 25 cps though vibrations above 800 cps did not increase the density at all.

The effect of duration of the vibrations is shown in Figure 20 where it can be seen that 100 percent relative density is reached in 5 or 6 min when the critical frequency of 25 cps is used. The maximum density reached was 120.8 pcf which is larger than the 117 pcf reached by the D'Appolonia method and, therefore, was adopted as the maximum for computing relative density. Also, the area referred to is the region of greatest compaction and not the over-all space beneath the vibrating plates.

Figure 21 shows that this region of greatest compaction moves down from the vibrating plate as the duration increases up to 5 or 6 min but as the plates get larger the ratio of the depth of maximum compaction to the plate width reduces.

The change with time in the depth above which there is 45 or more percent relative

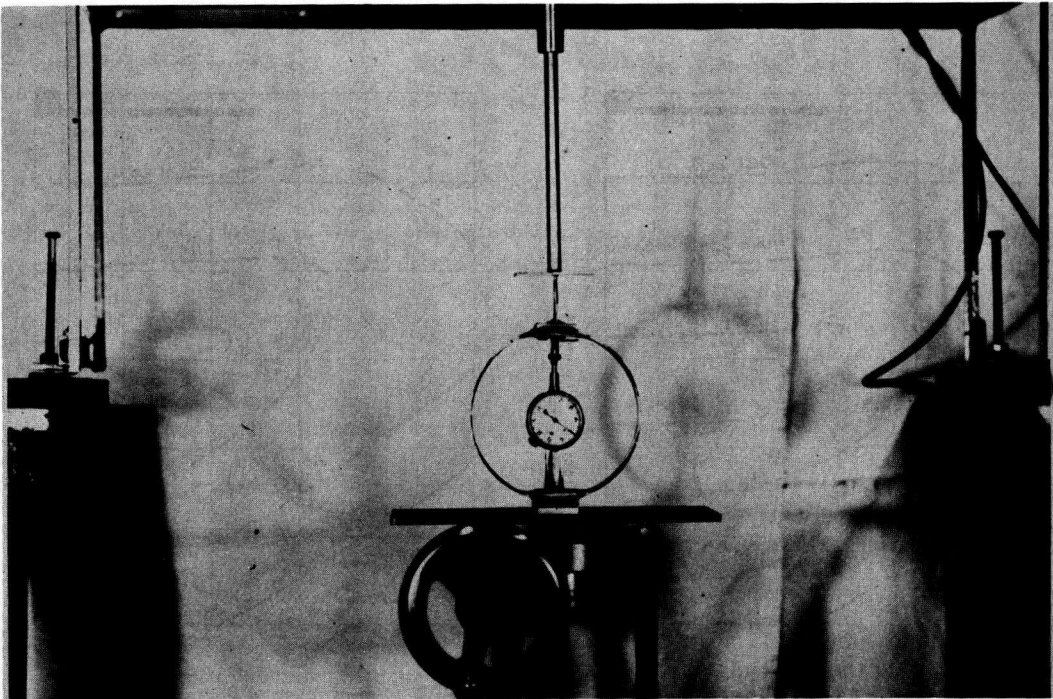


Figure 17. Apparatus for evaluating tamping force.

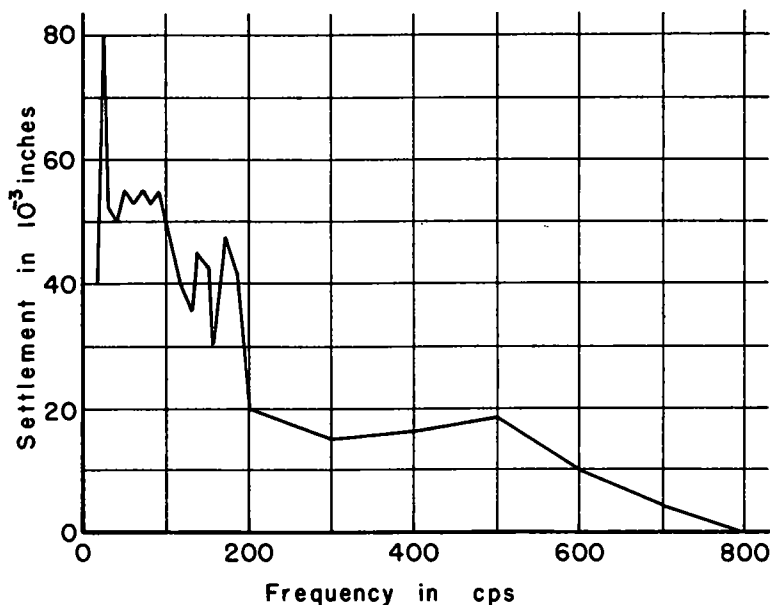


Figure 18. Settlement vs frequency for 3-in. tamper.

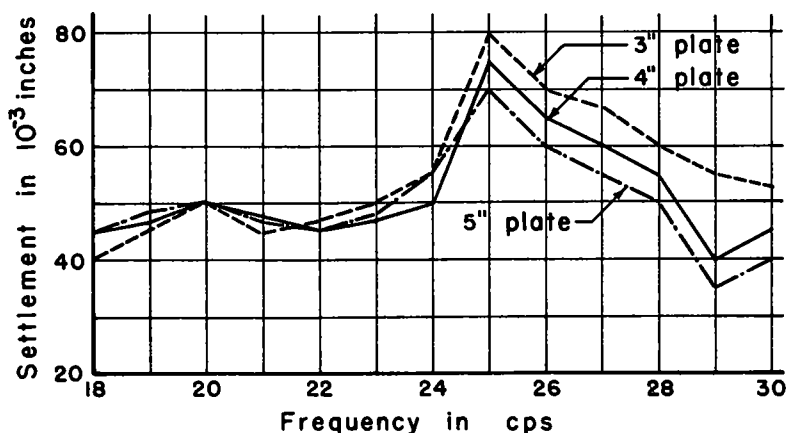


Figure 19. Settlement vs frequency.

density is shown in Figure 22. Here again the ratio of depth of compaction to plate width reduces as the plate size increases.

The change with time in the width within which there is 45 or more percent relative density is shown in Figure 23. Here again the ratio of compacted area to plate width decreases as the plate width increases.

CONCLUSIONS

The results obtained indicate that 25 cps is the most efficient vibration frequency for compacting the dry sand used in the investigation over the tamper-size range used. The efficiency of higher and lower frequencies drops sharply from this optimum indicating that vibrations should not be applied at random frequencies but closely controlled

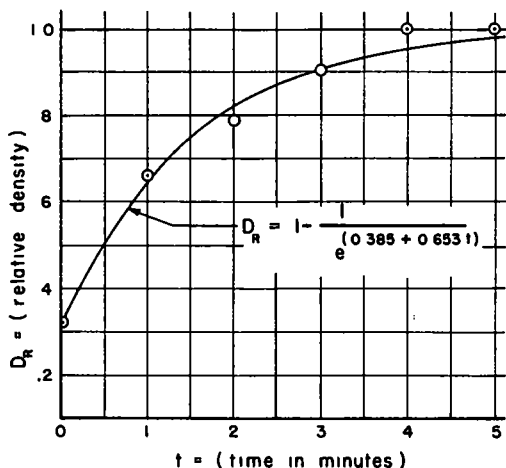


Figure 20. Maximum compaction vs time.

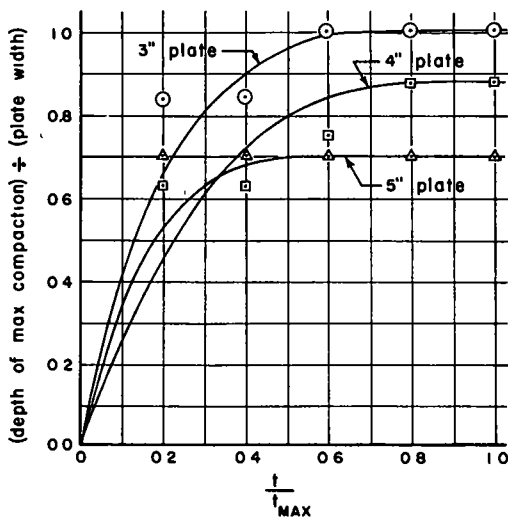
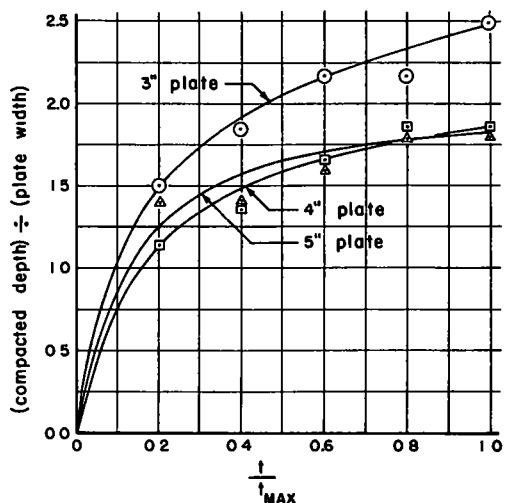
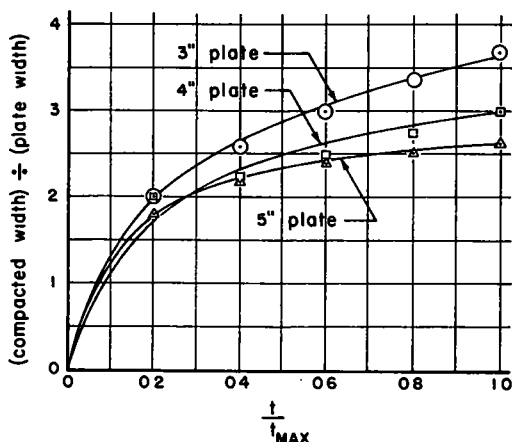


Figure 21. Depth of maximum compaction vs time.

Figure 22. Compacted depth along center-line ($D_R = 0.45$ or greater) vs time.Figure 23. Compacted width at surface ($D_R = 0.45$ or greater) vs time.

for best results. Comparison of these results with those of other investigators indicates that the optimum frequency may have to be determined for each soil. Even at optimum frequency the vibrations must be applied for an appreciable length of time to obtain reasonable densities.

Maximum compaction is not attained immediately below the tamper but at some distance below the vibrating plate. The ratio of this distance to the plate width decreased as the plate width became larger but not in a straight line variation. There is some evidence that this ratio varied with the tamping force because the tamping force also decreased as the plate size increased.

The following conclusions may be derived from the experiments:

1. Compaction of dry sand by vibration is controlled by the frequency of vibration and is the greatest at the critical frequency.

2. The critical frequency is the one that gives the greatest settlement of surcharge load. For the sand used, the critical frequency was 25 cps.
3. Maximum compaction is not obtained immediately below the tamper but at a certain depth below the surface.
4. No compaction was obtained at supersonic frequencies.
5. The degree of compaction is a function of time and is represented by the equation:

$$D_r = 1 - \frac{1}{e^{(0.358 + 0.653t)}}$$

6. Almost 100 percent compaction is obtained at the end of 6 min at the point of maximum compaction.
7. Surcharge is effective in transmitting the maximum compaction to lower depths.
8. The maximum depth and maximum width to which compaction is effective is an exponential function of tamper dimensions.
9. In evaluating the relative density the minimum laboratory density can be determined by using D'Appolonia's funnel method with no circular motion and no free fall, and the maximum laboratory density can be obtained by vibratory equipment used in this experiment run at critical frequency.

FUTURE SUGGESTED RESEARCH

1. Laboratory maximum density might be determined by using a circular tamper of about a 4-in. diameter with the vibrator used in this experiment. The sand could be contained in a plastic cylinder about 4 in. high with a collar like a Proctor mold. The sand could be placed in four layers. The first layer should be 3 in. thick and the other three layers should be 1 in. thick. Each layer could be compacted at critical frequency for 6 min. The collar could be removed and the excess sand trimmed off as in the Proctor test. The first layer is to permit room for the maximum compaction which would occur in the third inch below the surface with a 4-in. tamper. As the other layers are added, the point of maximum density would move up and the procedure should result in 4 in. of maximum density material.
2. Field compaction by vibrotampers should be run at critical frequencies which could be estimated in situ or determined in the laboratory for each soil.
3. The experiment on dry sand should be repeated with more variety of tamper dimensions to permit correlating the depth of maximum compaction with tamper dimensions.
4. The effect of moisture on the compaction of sand by vibration should be investigated.

REFERENCES

1. Converse, J., "Compaction of Sand at Resonance Frequency." Symposium on Dynamic Testing of Soils, ASTM (July 1953).
2. Hough, B. K., "Basic Soils Engineering." Roland Press, New York (1957).
3. AASHO, "Standard Specifications for Highway Materials and Methods of Sampling and Testing." (1955).
4. D'Appolonia, E., "Loose Sand — Their Compaction by Vibroflotation," Symposium on Dynamic Testing of Soils, ASTM (July 1953).
5. Casagrande, A., "Discussion." Conf. on Soil Stabilization, Mass. Inst. of Technol. (June 1952).
6. Proctor, R. R., "Fundamental Principles of Soil Compaction." Engineering News Record, Vol. 3 (Sept. 1933).
7. Housel, W. S., "Principles of Soil Stabilization." Civil Engineering, 7: No. 5 (May 1937).
8. Carpenter, C. A., and Willis, E. A., "A Study of Sand-Clay Gravel Materials for Base-Course Construction." Public Roads, 20: No. 1 (March 1939).
9. Dolch, W. L., "The Lime Stabilization of Soil." Unpublished report, National Lime Assoc. (March 1951).

10. Whitehurst, E. A., and Yoder, E. J., "Durability Tests on Lime-Stabilized Soils." HRB Proc., 31: 529-540 (1952).
11. Zube, E., "Experimental Use of Lime for Treatment of Highway Base Courses." Committee on Lime-Soil Stabilization, American Road Builder's Assoc., paper (March 1950).
12. Minnick, L. J., and Miller, R. H., "Lime-Fly Ash Composition for Use in Highway Construction." HRB Proc., 30: 489-496 (1950).
13. Smith, J. C., "The Chrome-Lignin Process and Ion Exchange Studies." Conf. on Soil Stabilization, Mass. Inst. of Technol. (June 1952).
14. Woodring, P. W., "Requirements and Experience in Expeditions Military Soil Solidification." Conf. on Soil Stabilization, Mass. Inst. of Technol. (June 1952).
15. Winterkorn, H. F., "A Laboratory Study of the Soil Stabilizing Effectiveness of Artificial Resins with Special Emphasis on the Aniline-Furfural Resins." U.S. Department of Commerce, CAA Tech. Development Note 43 (Jan. 1947).
16. Lowance, F. E., McKennis, H., and Bishop, J. A., "Navy Requirements and Experience with Soil Stabilization." Conf. on Soil Stabilization, Mass. Inst. of Technol. (June 1952).
17. Yoder, E. J., "The Effects of Calcium Chloride on the Compactive Effort and Water Retention Characteristics of Soils." HRB Proc. 27: 490-504 (1947).
18. Hardy, R. M., Discussion on "Stabilization with Soil, Lime, or Calcium Chloride as an Admixture." Conf. on Soil Stabilization, Mass. Inst. of Technol. (June 1952).
19. Hicks, L. D., "Soil Stabilization for Highways." Conf. on Soil Stabilization, Mass. Inst. of Technol. (June 1952).
20. American Cyanamid Company, "AM-9 Chemical Grout." New York.
21. Casagrande, L., "Electric Stabilization in Earth-Work and Foundation Engineering." Conf. on Soil Stabilization, Mass. Inst. of Technol. (June 1952).
22. Halton, J. E., and Holden, E. R., "Beach Sand Stabilization - Thermite Method." Tech. Memo M-011.
23. Soil Compactors, Inc., "A Unique and Exclusive Controlled Blasting Process Tailored to Individual Conditions by Experienced Engineers." Tampa, Fla.
24. Philippe, R. R., "Field Compaction." Conf. on Soil Stabilization, Mass. Inst. of Technol. (June 1952).
25. Burmister, D. M., "Method Suggested for Test for Maximum and Minimum Densities of Granular Soils." Procedures for Soil Testing, ASTM (April 1958).
26. Yemington, E. G., "Suggested Method for Test for Minimum Density of Noncohesive Soils and Aggregates." Procedures for Soil Testing, ASTM (April 1958).
27. U.S. Department of the Interior, Bureau of Reclamation, "Earth Manual." (July 1960).
28. Housel, W. S., "Suggested Method of Test for Maximum Density of Granular Materials by the Cone Test." Procedures for Soil Testing, ASTM (April 1958).
29. Pauls, J. T., and Goode, J. F., "Suggested Method for Maximum Density of Noncohesive Soils and Aggregates." Procedures for Soil Testing, ASTM (April 1958).
30. Jones, C. W., "Suggested Method for Test for Relative Density of Cohesionless Soils." Procedures for Soil Testing, ASTM (April 1958).