Particle packing of granular soils as affected by vibration

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ABSTRACT

The effect of vibration on packing of particles, which determines volume change and density of granular soils, is studied.

The laboratory tests were performed to study the variation of particle packing as affected by duration time, acceleration, and frequency for the vibration system; and surcharge, moisture content, and initial density for granular soils. An ideally-graded sand and a uniformly-graded sand were used in the tests. Vibration strongly affects particle packing of granular soils. An attempt is made to explain the mechanism of volume change in dry sands in terms of "air lubrication," analogous to liquefaction. Significant pore air pressure may develop during vibration which is attributable to a volume change following the vibration. Changes in packing of particles result in large inhomogeneity within specimen due to shift in particle gradation.

INTRODUCTION

The effect of vibration on granular soils is to change the density and the state of pore pressure in the material. The use of a vibratory method, therefore, is an
effective means of compacting sand. On the other hand, ground vibration may become a source of foundation settlement or even of bearing capacity failure. The mechanisms which control the behavior of granular materials during vibration have not been completely understood, especially the effects of various parameters affecting vibratory densification and their influence on packing of particles.

In most of the significant tests relating to vibration of sand, the volume change is assumed to be uniform throughout the material before and after vibration. Because of the insufficient studies relating to density variation, misinterpretation of the behavior of a sand may have occurred in the past. Studies relating to density variation are important for such tests as cyclic loading triaxial or simple shear test, and shake table test. The present investigation relates to various parametric effects on vibration of sand as characterized by changes in particle packing.

THEORETICAL CONSIDERATION

The densest packing condition of particles if formed when larger voids are filled with smaller particles, and these voids are in turn filled with smaller particles, and so on. It can be shown that neither the specific gravity of the material nor a difference in size significantly affect the ultimate void ratio (White [8]). However, volume composites of each grain size should be controlled to obtain the maximum density when vibrated. Fig. 1 shows a convenient form to explain the mechanisms of packing of particles of two sizes (Westman [5]). The relative bulk volume \( V_a \), as defined by \( V_a = 1/1-e \), is related to the percentage fraction of fine particles as shown in this figure. Points C and F in the figure are the experimentally determined maximum density with a single size of coarse or fine sands, respectively. The distance from the line segment CF to the \( V_a \) curve shows the amount of densification after vibration.

The sagging of the \( V_a \) curve is a function of the diameter ratio, \( m \), which is defined as the ratio between the diameter of the large and small particles. As the
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diameter ratio, \( m \) approaches to 1.0, the \( V_a \) curve will approach to the line segment CF; as it increases to infinity, the \( V_a \) curve will approach the line segment CRF. The point P in the figure shows the combination ratio of given particle sizes which produces the possible maximum density. Westman [5] gives an empirical equation for the \( V_a \) curve as:

\[
\left[ \frac{V_a - Cx}{F} \right]^2 + 2m \left[ \frac{V_a - Cx}{F} \right] \left[ \frac{V_a - x - Fz}{C - 1} \right] + \left[ \frac{V_a - x - Fz}{C - 1} \right]^2 = 1.0 \quad (1)
\]

where \( x \) and \( z \) are the compositions of the coarse and fine particles, respectively. \( C \) and \( F \) represent the experimentally determined relative bulk volume of the coarse and fine particles, respectively. Westman's experimental data which are represented by the data points in Fig. 1 gave a reasonably good fit to the values computed by this equation.

EXPERIMENTAL INVESTIGATION

A series of laboratory tests was conducted on a uniform sand and an ideally-graded sand. The ideally graded sand was artificially mixed with a definite amount for each size of particles based on Weymouth's theory of particles interference [7]. The uniform sand used in the tests passed sieve No. 40 and was retained all on the sieve No. 60. The uniformity coefficients were 8.9 for the ideally graded sand and 1.4 for the uniform sand. Fig. 2 shows the grain size distribution of the sands tested.

An overall experimental set-up is shown in Fig. 3. A special mold was built and was fastened to the vibration table of a MTS Model 840 Servohydraulic Vibration Test System. An upper plate served to hold the mold to the vibration table in addition to serving as a mount for single ended air cylinder. This air cylinder was used to apply confining pressure through a rod connected to the piston. A Model 308A quartz accelerometer was mounted upright on the modified base of the mold for the response measurement.
Fig. 4 is a close-up schematic diagram of the sample mold together with the device used to apply the surcharge on the specimen surface. The Lucite mold is 19.05 cm in height and 12.7 cm in diameter, and is made up of five tiered sections of equal height and held together by vertical screws. The mold can be dismantled tier by tier by unscrewing to make possible the measurement of density at each tier.

After the mold was filled with prepared sand under the preestablished procedure to obtain a loose initial condition, vibration of the system was started and readings of settlement using the Ame's dial were taken at prescribed time intervals.

After a series of initial pilot tests to determine the effect of duration of vibration, tests were conducted with confining pressures of 0.0, 6.9 and 13.8 kPa. In addition to the three different states of confining pressures, sands were tested at different moisture contents. All the samples were vibrated at five acceleration levels - 1.0, 2.0, 3.0, 4.0, and 5.0 g; and at frequencies of 10, 15, 20, 25, 30 and 35 cps.

PRESENTATION AND DISCUSSION OF TEST RESULTS

Ideally graded sand

Effect of acceleration and frequency

Fig. 5 shows the variation of density across height of the specimen at a frequency of 20 Hz, a surcharge of 6.89 KPa and at various acceleration levels. It can be seen that the density varies significantly throughout the specimen at any acceleration level. It is of interest to note that the degree of density variation becomes more pronounced as acceleration increases up to the 3 g level, beyond which the effect seems to start diminishing as acceleration is further increased. The density near the surface is not high for two reasons: first, due to the surcharge, the particles near the surface are not allowed to relocate to their favorable position, and secondly, grain size distribution changes from an ideal (which produces a high density) to relatively uniform (which produces a low density) as fine particles fall downward into the voids.
Another observation to be made of Fig. 5 is that the lowest density occurs at bottom of the specimen, which may be explained by the fact that particles in the lowest tier are subjected to the greatest amount of confining pressure. Secondly, this behavior may be explained in terms of the limit of packing of particles described previously. As can be seen in Fig. 6 there is shift in grain size distribution after vibration. The grain size distribution curve for the top tier (tier 1) now includes a greater percentage of coarse particles and lesser fine particles compared to the original grain size distribution curve (loss of fines). A reverse change in grain size distribution occurs at bottom tier of the mold: it now includes a smaller percentage of coarse particles and a greater percentage of fine particles compared to the original grain size distribution (grain of fines). In either case, there is a shift in grain size distribution from the ideal to a more uniform distribution. However, the grain size distribution curves from the midsections of the mold show only small changes in grain size distribution compared to the original graduation. Based on the theory of packing of particles developed by Westman [5] and others, one can expect an ideally graded sand to be compacted to a maximum terminal density. Therefore, the maximum terminal density is expected to occur at midsection of the mold because there is no significant change in grain size distribution here after the vibration. The terminal density of the top and bottom sections would be lower than that of the midsection because of the shift in gradation from that of ideal to relatively uniform. The terminal density is the lowest at bottom of the mold because of the additional effect of confining pressure.

It is interesting to compare the above-described results to the field vibratory compaction study by D'Appolonia [2]. The field compaction showed, as shown in Fig. 7, a similar pattern of density variation with depth.

Effect of saturation

Fig. 8 shows the variation of density for three acceleration levels at a frequency of 20 Hz and a surcharge of 6.89 KPa. The dotted lines in the figures illustrate the variation of water content within the specimen and solid...
lines represent dry density change. The variation of density at the 1 g acceleration level is not as prominent as that at the 3 and 5 g levels. It is of interest to note that the maximum density is obtained in the fourth tier from top of the mold for the saturated sand as opposed to dry sand for which the maximum density was obtained in the second or third tier (see Fig. 5). This may be explained by reasoning that fine particles, under saturation, are prevented from settling further down through the pores because of high pore water pressure developed during the vibration.

It can also readily be seen that the water content distribution is not uniform throughout the height of the specimen, and the specimen tends to lose more water toward the center. Again, the top tier has a high water content because of loosening or the loss of fine particles leading to more voids.

The role of the surcharge during the vibration of the saturated sand is depicted in Fig. 9. The dotted lines show the variation of water within the specimen. It is seen again that neither the density nor the water content distribution is uniform throughout height of the specimen. It should be pointed out that neither density nor water content is affected by an increase in surcharge.

Uniform sand

Effect of acceleration

Fig. 10 presents the results obtained by vibrating the uniform sand with a surcharge of 6.89 KPa at a frequency of 20 Hz and at five different acceleration levels. The location for the maximum density is, in general, lowered with an increase of acceleration. This phenomenon, again, can be explained by existence of confining pressure. For the uniform sand, there is no effect of shift in grain size distribution curve because the uniform sand has a single size of particles. Thus the lower terminal density obtained at the bottom of the specimen can only be explained in terms of the effect of confining pressure.
Effect of saturation

Fig. 11 presents the results for the saturated uniform sand subjected to three different levels of acceleration at a given frequency of 20 Hz and a surcharge of 6.89 KPa. The variation of density along specimen height is similar to that for the saturated ideally graded sand shown in Fig. 8. The variation of water content is shown by dotted lines in the figure. It is found that the change in relative density is quite uniform throughout the specimen at a high surcharge of 13.79 KPa. However, at low surcharge values the variation becomes quite significant. This is contrary to the behavior observed with the ideally graded saturated sand for which the surcharge had no effect at all.

CONCLUSION

1. Packing of particles, which determines volume change and density, is strongly affected by vibration.

2. Vibration of the ideally graded sand having a homogeneous initial density results in large inhomogeneities within the specimen due to shift in gradation from that of ideal to relatively uniform and the effect of confining pressure.

3. Density varies greatly throughout the specimen with the intensity of vibration. The degree of density variation becomes more pronounced as acceleration increases up to an optimum, beyond which the effect seems to start diminishing as acceleration is further increased.

4. Variation of relative density throughout the specimen for the ideally graded sand is not significantly affected by change in surcharge. The uniform sand is, however, moderately affected by change in surcharge.

5. Density within the specimen for the uniform sand varies with the intensity of vibration (acceleration) but the resulting degree of inhomogeneity is relatively small because the mechanism of density variation is only governed by confining pressure without a shift in gradation of particles.
REFERENCES


Fig. 1: Packing of particles in two-size system

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<th>GRAVEL</th>
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U.S. STANDARD SIEVES SIZES

Fig. 2: Gradation curves of materials tested

(A) UNIFORM SAND
(B) IDEALLY GRADED SAND
Fig. 3: Schematic diagram of experimental set-up

Fig. 4: Close-up schematic diagram of mold
Fig. 5: Density variation along height of specimen as affected by acceleration

![Graph showing density variation along height of specimen](image)

Table: Grain Diameter, mm

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Fig. 6: Gradation curve for each tier after vibration

![Gradation curve for each tier](image)
Fig. 7: Field compaction curve (Reference 2)

Fig. 8: Density and water content variation along height of specimen as affected by acceleration
Fig. 9: Density and water content variation along height of specimen as affected by surcharge.

Fig. 10: Relative density variation along height of specimen as affected by acceleration.
Fig. 11: Density and water content variation along height of specimen as affected by acceleration.