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Model studies on the influence of gradation of sand in free field liquefaction

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ABSTRACT: The present study was conducted to find the influence of gradation of sand on initiation of liquefaction in free field conditions. Sands with two different gradations were subjected to dynamic loading and the development of pore water pressure at different locations was monitored. Acceleration and frequency of base shaking were varied and the results showed that fine graded sands were more susceptible to liquefaction at higher frequencies compared to coarse grained sands. The accelerometer response at different depths showed that acceleration amplifications were more prominent in case of coarse-grained sands due to flow liquefaction. In case of fine-grained sands, liquefaction was associated with higher initial settlements and acceleration amplifications were less because the sand beds got densified during initial shaking cycles. It was also observed that the liquefaction response of finer sand was found to be depended on the input frequency to a large extent compared to the coarser sand.

1 INTRODUCTION

Liquefaction of sands has remained as a research area of potential interest to geotechnical engineers since many years. The phenomenon of liquefaction and its initiation in sands during seismic events is being continuously investigated by several researchers (Fiegel & Kutter, 1994, Kokusho, 1999, Vaid et al., 1990, Vaid & Thomas, 1995). However, it is very important to understand the liquefaction behaviour of sands under different dynamic as well as in-situ conditions. Most of the studies on liquefaction were focused on clean sand because it is believed that fine grained soils are resistant to liquefaction. Many studies were focused on understanding the factors that affect the liquefaction behaviour of sand but studies related to the influence of gradation of sand on its liquefaction response are

Seed et al. (1975) developed correlations between the $(N_1)_{60}$ values obtained from field Standard Penetration Tests and the resistance of soil to the liquefaction. According to that liquefaction potential of soil decreases with increase in its fines content for a specific range of grain size distributions. Hence gravely soils will have more liquefaction resistance than silty soils which contradicted with the studies done by Tsuchida (1970), in which it is observed that the liquefaction potential may not reduce when the soil contains non-plastic fines. According to Xenaki and Athanasopoulos (2003), intergranular and interfine void ratios govern the variation of liquefaction potential with fines content, rather than just the percentage fine content. Vaid (1990) had conducted researches on liquefaction characteristics of clean sand with same mean size and different grain size distribution. The results showed contractive deformations for poorly graded sand and the well graded sand had shown strain development through cyclic mobility. Microstructural studies done by Thevanayagam et al. (2000) proved the relationship between the intergranular and interfine void ratios and the liquefaction characteristics of soils. Recent undrained cyclic triaxial tests on sands with various grain size distribution had showed a reduction the liquefaction potential of sand-silt mixture with increase in mean size and effective size (Xenaki & Athanasopoulos, 2003). Hsiao et al. (2015) has made studies with various grain size distributions by changing the amount of non-plastic fines and found that the increase in silt content has decreased the cyclic resistance ratio with a silt content up to 40 to 50% which was a contrary to the previous researches. Recent studies on the effect of fines content on liquefaction potential had showed that the behavior of sand mixed with fines during dynamic loading was significantly influenced by the plasticity of fines that contained in the mixture (Huang & Zhao 2018; Papadopoulou & Tika 2016; Wei & Yang 2018). Studies showing the effect of gradation of sand on its liquefaction potential under different seismic loading conditions are very few in literature. Present study is aimed at providing some insights into the influence of gradation of sand on its liquefaction response under different seismic shaking conditions. While understanding the influence of gradation, fines were not just mixed with the sand as done in many studies in this area, but sands of two different gradations were used so that the complete grain size distribution curve was reconstituted and the practical application of results is enhanced.

2 MATERIALS USED

Two types of sands (Sand 1 and Sand 2) were used in this study. Figure 1. shows that the grain size distribution curves of both these sands are falling within the range of liquefiable sands given by Tsuchida (1970). Table 1. gives the properties of both the sands used in this study and both were classified as poorly graded sand (SP) but the fines content is more in Sand 2. It is also observed that, the permeability of Sand 2 was 38% lower than Sand 1.

3 EXPERIMENTAL SET-UP

Uniaxial shaking table tests on saturated sand beds of size 1200 mm × 500 mm × 600 mm (length × width × height) were conducted in this study. Saturated sand beds were prepared in a perspex box by wet pluviation technique. Sand was poured loosely into the water using a

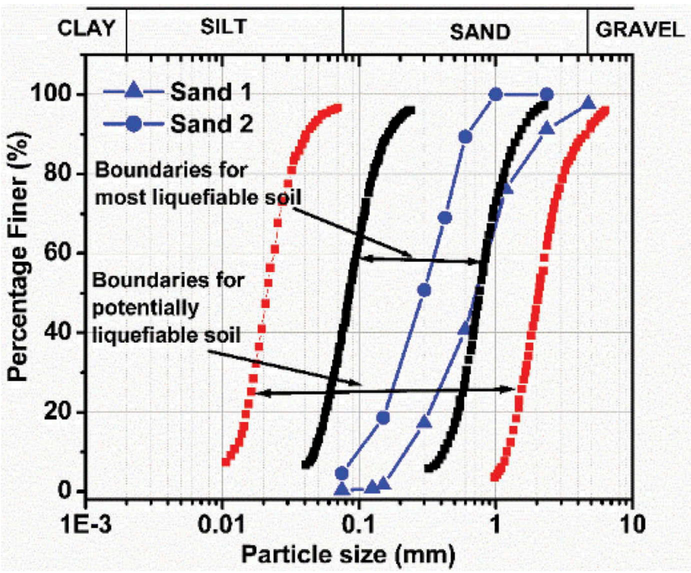

Figure 1. Grain size distribution of test soils.

Table 1. Properties of Sands used in the Study.

Property	Sand 1	Sand 2
Maximum dry unit weight (kN/m^3)	17.67	17. 94
Minimum dry unit weight (kN/m^3)	14.23	13.98
Specific gravity	2.65	2.65
Maximum void ratio	0.862	0.859
Minimum void ratio	0.500	0.449
Coefficient of uniformity, C_u	2.857	3.578
Coefficient of curvature, C_c	1.35	1.11
D_{10}(mm)	0.23	0.095
Permeability (cm/sec)	5.078×10^{-3}	3.12×10^{-3}

conical hopper. An inverted solid cone with a 60° angle was attached at the end of the funnel to get the uniform distribution of loose soil. Vaid and Negussey (1988) proved that the sample prepared by pluviation under water will be homogeneous, and it is almost independent of height of fall. Relativedensity of sand beds prepared using this method varied for the two sands used in the study. Relative density of sand bed of Sand 1 was 43% with initial void ratio of 0.706, whereas the relative density of sand bed of Sand 2 was 15% with initial void ratio of 0.798. Miniature pore water pressure sensors which could measure pressures in the range 0-20 kPa and MEMS based triaxial submersible accelerometers (Bhattacharya et al. 2012) were used to measure the pore water pressures and accelerations at different locations of sand beds. The natural frequency of the sand bed with Sand 1 was found as 30 Hz and Sand 2 was 23 Hz. These natural frequencies were calculated based on the shear wave velocities estimated using initial void ratio and initial mean effective confining pressure (Hardin & Richart Jr, 1963, Varghese & Latha, 2014). Variations in acceleration amplification were measured at different depths in the sand beds. Shaking table tests were carried out at different sinusoidal accelerations and frequencies to understand the input ground motion parameters that could initiate liquefaction.

Table 2. represents the parameters varied in different shaking table tests. Test code used for each test is also given in this table. First two letters of the code indicate the sand type used in the test. Next three letters of the code indicate the input acceleration of shaking. Sixth and seventh letters of the code indicate the input frequency. Figure 2. shows the schematic diagram of the test set-up showing the positions of sensors in the tests. Pore water pressure sensors were kept exactly at the center of the sand layer at different depths. The accelerometers were placed at various locations in the sand bed as shown in Figure 2 to measure the response of

Table 2. Test matrix.

Sand type	Acceleration (g)	Frequency (Hz)	Test Code
Sand 1	0.1	1	S1A01F01
Sand 1	0.12	1	S1A12F01
Sand 1	0.13	1	S1A13F01
Sand 1	0.14	1	S1A14F01
Sand 1	0.15	1	S1A15F01
Sand 1	0.1	4	S1A01F04
Sand 2	0.1	1	S2A01F01
Sand 2	0.15	1	S2A15F01
Sand 2	0.15	4	S2A15F04
Sand 2	0.1	4	S2A01F04
Sand 2	0.11	1	S2A11F04
Sand 2	0.12	1	S2A12F04

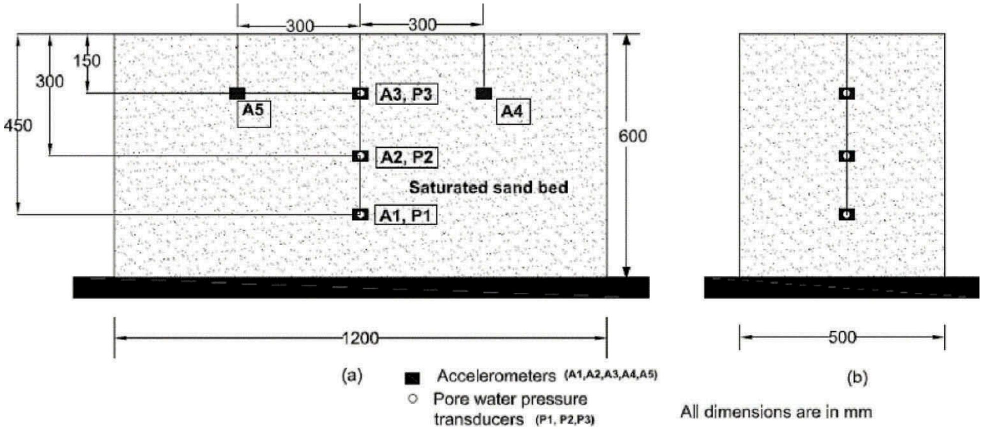

Figure 2. Schematic sketch of the experimental set-up.

soil during dynamic loading conditions. Sufficient clearance from the boundary was maintained to minimize the boundary effects.

4 RESULTS AND DISCUSSIONS

The miniature pore water pressure sensors give the pore water pressure developments in the saturated sand bed during cyclic loadings. Initiation of liquefaction was defined in terms of pore water pressure ratio. It is the ratio between the excess pore water pressure developed during excitation to the initial vertical effective stress. The accelerometers were the indicators of the amplification/deamplification of the sand bed under dynamic loading conditions.

4.1 *Response of Sand 1*

A series of shaking table tests were carried out to find out the initiation of liquefaction in beds of Sand 1, varying accelerations between 0.1g and 0.15g at a frequency of 1 Hz (Figure 3). It can be observed that with increase in acceleration of shaking, pore water pressure ratio

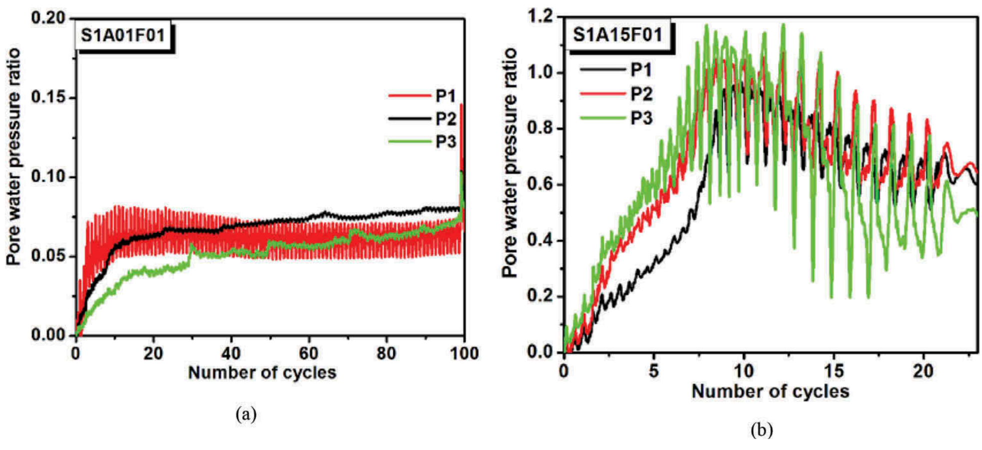

Figure 3. Influence of accelerations on liquefaction potential of Sand 1.

increased. However, the increase was marginal up to the acceleration level of 0.14g. When the acceleration was increased from 0.14g to 0.15g, pore water pressure increased dramatically, initiating liquefaction in the sand bed.

Figure 4 compares the pore water pressure ratios at three different depths of the sand bed for 0.1g and 0.15 g accelerations at a frequency of 1 Hz. As observed from the figure, the pore water pressure ratios were less than 0.1 at all depths when the acceleration was 0.1g and with the increase in acceleration to 0.15g, pore water pressure ratios increased drastically and reached a value of 1, indicating complete liquefaction of sand bed. Next set of studies were intended to find the influence of shaking frequency on the liquefaction potential of sand beds. In this series of tests, acceleration of shaking was kept constant as 0.1g and two different shaking frequencies, 1 Hz and 4 Hz were used. In trial tests, it was observed that the lateral variation of pore water pressure is insignificant. Hence lateral variation of pore water pressure was not measured in the tests.

Figure 5 shows the variation of pore water pressure ratio with respect to depth for frequencies 1 Hz and 4 Hz. Computed pore water pressure ratios were less than 0.1 at all depths for

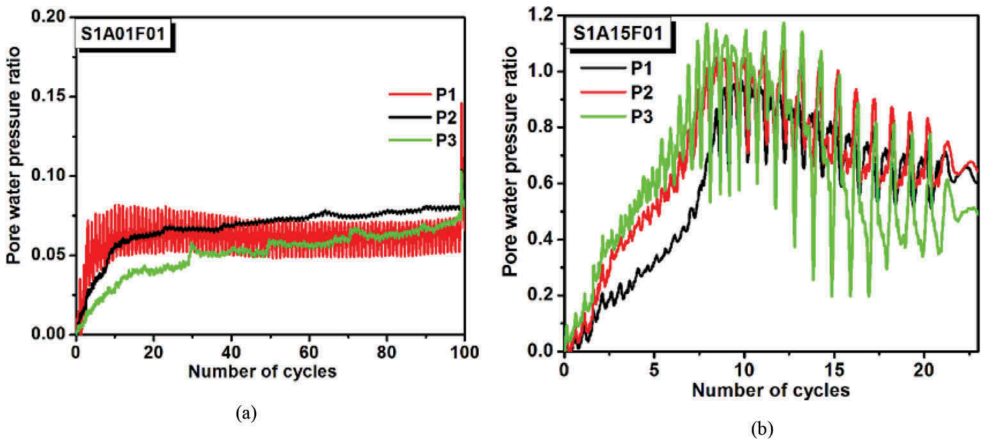

Figure 4. Variation of pore water pressure ratios in Sand 1 with (a) 0.1g and (b) 0.15g acceleration.

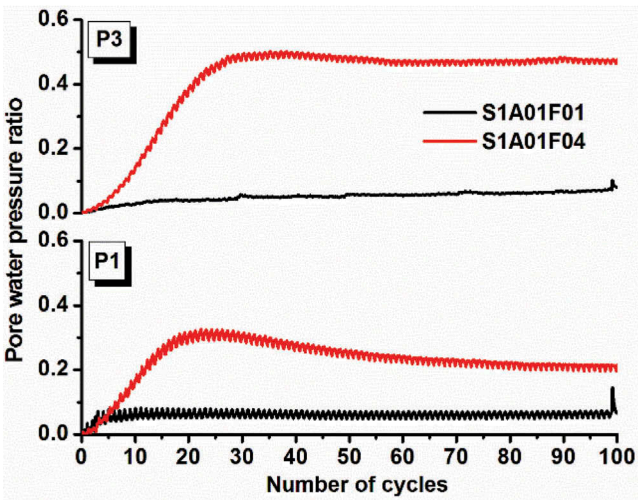

Figure 5. Vertical Variation of pore water pressure ratio with frequency for Sand 1 at 0.1g acceleration.

test with 0.1g acceleration and 1 Hz frequency. When the frequency was increased to 4 Hz, keeping the acceleration constant, maximum pore water pressure ratio of 0.5 was observed in this test at 0.15 m below the surface of the sand bed (P3). It was also observed that the vertical variation of pore water pressure was minimal for low frequency of 1 Hz and the variation became evident only at higher frequency of 4 Hz.

When the vertical variation of pore water pressures developed in these tests were compared, it was also observed that pore water pressure developed in top layers of sand is more, indicating that top layers of the sand bed are more susceptible to liquefaction compared to bottom layers. Increase in overburden with the increase in depth causes increase in the static shear stress of bottom layers and hence the resistance to the liquefaction increases. Measured accelerations at different locations in the sand bed at 0.1g acceleration with 1 Hz and 4 Hz frequencies were equal to the base acceleration. When the individual influence of acceleration and frequency of shaking are compared, it is obvious that acceleration of shaking has predominant influence on the liquefaction response of sands. With change in acceleration from 0.1g to 0.15g, the soil got liquefied but the increase in frequency from 1 Hz to 4 Hz could not initiate liquefaction in the sand.

4.2 *Response of Sand 2*

Shaking table tests on sand beds of Sand 2 were carried out at different accelerations and frequencies to understand the influence of these parameters on the liquefaction potential of Sand 2. Experiments were carried out at accelerations of 0.1g and 0.15g, keeping the frequency as 1 Hz (Figure 5). To initiate liquefaction in the sand bed and to understand the influence of acceleration of shaking on the pore water pressure development in Sand 2, a series of tests was planned at different accelerations of 0.1g, 0.11g, 0.12g and 0.15g, keeping the frequency as 4 Hz. Sand bed got liquefied even when the acceleration was increased from 0.1g to 0.11g. With further increase in the acceleration, development of pore water pressure was rapid and sand beds got liquefied at lesser number of shaking cycles as shown in Figure 6(b).

Acceleration amplifications observed in Sand 2 were not as significant as they were in case of Sand 1. Higher frequencies resulted in higher pore water pressures. However, at higher accelerations, the effect of frequency on the pore water pressure development is more pronounced. Development of pore water pressure was drastic and the difference in response at two different frequencies is more evident. It was also observed that the manifestation of liquefaction on the surface of the sand beds is different for different sands.

Liquefaction in Sand 1 can be classified as flow liquefaction, as the sand bed was flowing after the initiation of liquefaction. In case of Sand 2, the type of liquefaction observed can be associated with lateral spreading. As the relative density of sand beds made of Sand 2 was

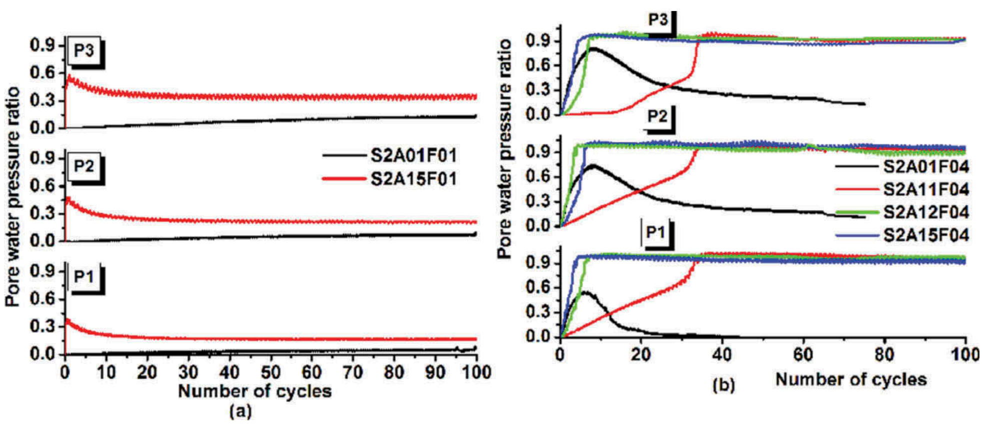

Figure 6. Variation of pore water pressure ratio with acceleration at different depths for Sand 2 at (a) 1 Hz frequency and (b) 4Hz frequency.

only 15%, flow liquefaction is expected in this case. But high amount of settlements was observed in Sand 2 during initial shaking and by the time the liquefaction was initiated, the density of sand bed was increased considerably, leading to lateral spreading type of liquefaction. Liquefaction was observed gradually on the surface in case of Sand 2, whereas it was sudden in case of Sand 1, with complete movement of sand bed. But when the development of pore water pressures was compared, it was seen that the pore water pressure development in Sand 2 was immediate and in Sand 1, it was gradual. The measurement of acceleration at different elevations depicts the profile of acceleration amplification/de-amplification occurred during the initiation of liquefaction and the response was explained in terms of acceleration amplification factor. Acceleration amplification factor is defined as the ratio of measured acceleration at any location within the sand bed and the base acceleration. When the shaking frequency was 1 Hz, at all base acceleration levels less than 0.15g, no amplification was occurred at any location within the sand bed and the measured accelerations at different depths were same as that of the induced base acceleration. However, when the base acceleration was 0.15g, accelerations were amplified and Figure 7(a) shows the acceleration amplification factors for Sand 1 and Sand 2. The alterations in the base accelerations occurs due to the stiffness reduction of the soil during liquefaction (Ueng et al. 2005). The acceleration measured in the saturated sand bed at different depths had concluded that there were no alterations happened in the base input accelerations at different depths of sand bed when the initiation of liquefaction was not visible. Computed acceleration amplification factors at different locations for the test with 0.15g base acceleration are shown in Figure 7(b). It can be observed from the figure that the top layers of the sand bed amplified more than the bottom layers. As observed from the figure, accelerations were amplified more in case of Sand 1. Acceleration amplifications measured during liquefaction in beds of Sand 1 at all locations were higher than those measured in beds of Sand 2. The reason for this difference could be attributed to the difference in the process of initiation of liquefaction in these two types of sands. Rapid transmission of pore water pressure to the top layers in case of Sand 1 due to its high permeability caused drastic changes to the acceleration of the seismic wave travelling from the base to the top. Finer particles in Sand 2 obstructed channel formation as seen in Sand 1and hence the liquefaction appeared to be gradual at the surface. Permeability of Sand 2 is about 38% less than that of Sand 1 and hence pore water pressure transmission was gradual and its interference with the seismic wave was limited. Acceleration amplifications in Sand 1 were more than those in Sand 2, to a maximum of 60% and amplifications were higher close to the surface of the sand bed (A3) and decreased with depth. Accelerations in a test remained almost uniform at a specific depth as shown in Figure 7, irrespective of the gradation.

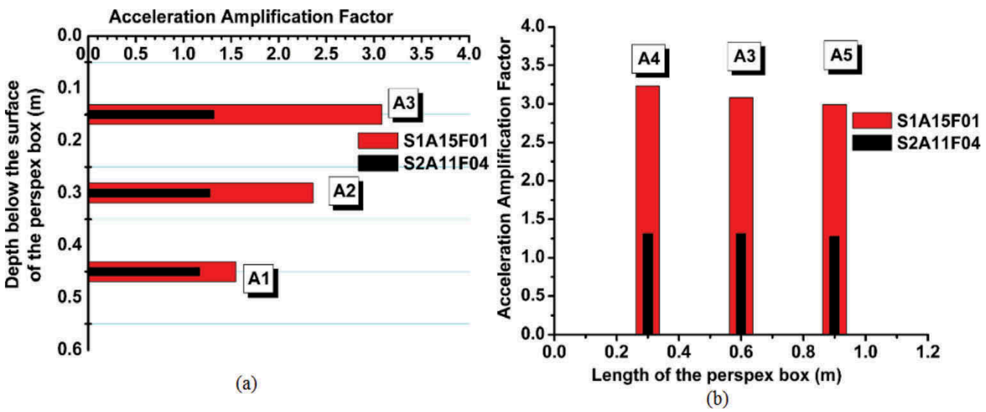

Figure 7. Amplification of acceleration during liquefaction (a) Vertical variations (b) Lateral Variations.

5 CONCLUSIONS

Following major conclusions are drawn from the shaking table tests on sands with two different gradations.

1. The pore water pressure ratio decreases with increase in depth from the surface of the sand bed for all types of sands and accelerations at different locations of sand beds remain same as the base acceleration for sand beds in which liquefaction is not initiated. During liquefaction, sand beds amplify the input accelerations.
2. Acceleration amplifications are less and relatively uniform with depth for Sand 2, which has higher fines content, whereas acceleration amplifications reduced with depth for Sand 1, which has lesser fines content. For finer sand, liquefaction was associated with higher initial settlements and development of a central crack along the direction of shaking with no visible flow of the sand bed.
3. For tests in which liquefaction was initiated in the sand beds, development of pore water pressure was relatively gradual for coarser sand and for finer sand, it was sudden.
4. Liquefaction response of coarser sand is governed by the acceleration of shaking, whereas in case of sand with more fines, liquefaction is governed by the frequency of shaking.

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