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# Liquefaction Behavior of Clean Sand for Various Sample Sizes Using Triaxial Tests

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***Abstract***
*A total of 54 isotropically consolidated un-drained triaxial compression tests on various sample sizes were conducted to study the effect of sample size on liquefaction behavior of clean sand. Specimens were prepared using moist placement and dry deposition methods with different initial relative densities and tested for different confining pressures. It was observed that as the sample size increases, deviator stress also increases. Peak value of deviator stress increased as the confining pressure and relative density increased for all sample sizes for moist placement method. After reaching peak, deviator stress remained constant for large percentage of axial strain for smaller sample size, while larger-size sample offered maximum resistance to liquefaction. However, for dry deposition method opposite trend was observed especially for smaller sample sizes. Unstable zone already established by authors has been studied for all sample sizes with these two sample preparation methods. The ratio of excess pore pressure to mean effective stress at the maximum pore pressure point has been defined. The threshold value of this ratio has been found to indicate the transition from contractive to dilative behavior.*

***Keywords:*** *Clean sand, triaxial compression, sample size, liquefaction, unstable zone, un-drained testing*

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## INTRODUCTION

Liquefaction is a phenomenon wherein soil drastically loses large percentage of its shear resistance when subjected to static, monotonic or cyclic loading. Liquefaction occurs due to an increase in the excess pore water pressure and the corresponding decrease in the effective overburden stress in a soil deposit. The generation of excess pore pressure under un-drained loading condition is a hallmark of all liquefaction phenomena. Various physical parameters affecting the liquefaction resistance of sands under monotonic and cyclic loading have been extensively studied [1–3, 5]. Effect of grain shape and angularity on un-drained behavior of sand has been studied by Tsomokos and Georgiannou [6].

Yamamuro and Lade [4, 7], Yamamuro and Covert [8] proclaimed that complete static liquefaction (zero effective confining pressure and zero effective stress difference) in laboratory testing is most easily achieved in silty sands at very low pressures. Kramer and Seed [9], Pathak and Dalvi [10] have reported that liquefaction resistance increases with increase in relative density and confining pressure. The un-drained behavior of Dabaa calcareous sand under monotonic loading was studied by Salem *et al.* [11] through monotonic and cyclic triaxial loading. They observed initial contractive behavior for loose and dense sand with maximum excess pore water pressure at the phase transformation points. Further, they found that phase transformation stress ratio (q/p') for loose and dense sand was independent of the relative density of sand. Igwe *et al.* [12] introduced dilative potential index, $r_f$ as a ratio of pore pressure at failure to shear resistance at failure for representing dilative and purely contractive conditions. Many researchers, especially Miura and Toki [13], Mulilis *et al.* [14], Vaid *et al.* [15], Yamamuro and Wood [16] and Della *et al.* [17], have deduced that the behavior of sand can be greatly influenced by sample reconstitution method. Sze and Yang [18] studied effect of sample reconstitutional method on cyclic loading behavior of saturated sand including deformation pattern, pore water pressure generation, stress-strain relationship and cyclic shear strength. They observed significantly different liquefaction resistance values for moist tamping and dry deposition sample preparation method when tested under similar conditions.

Abdulla and Kiousis [19] studied the behavior of cemented sand using pluvial deposition method to identify the effects of sample size on strength, stiffness, softening and dilation characteristics of cemented sand. They concluded that smaller specimen exhibits higher strength than the large-size specimens when tested under similar conditions. Hu *et al.* [20] developed a set of triaxial cells of various sizes to study the experimental behavior of granular soils containing particles of sizes up to 160 mm. They also conducted a series of drained triaxial compression tests on sand samples of different sizes to examine specimen scale effects. They have reported that the behavior of sand has not been affected by the sample size before peak deviator stress. Literature survey reveals a great deal of experimental investigation carried out by the researchers. Time and efforts required to conduct triaxial tests depend particularly on size of the sample. However, the effect of sample size on liquefaction behavior of clean sand using triaxial test particularly under monotonic loading has not been reported so far. In the present experimental work, an attempt has been made to study the behavior of clean sand by conducting isotropically consolidated un-drained triaxial tests on three different sample sizes, viz., $38 \times 76$, $50 \times 100$ and $75 \times 150$ mm ($l/d = 2$). The liquefaction behavior of each sample has been examined for different relative densities and confining pressures for two sample preparation methods. Experimental program and results are discussed in subsequent sections.

## EXPERIMENTAL INVESTIGATIONS

A total of fifty-four consolidated un-drained triaxial compression tests were performed on three different sample sizes, $38 \times 76$, $50 \times 100$ and $75 \times 150$ mm using moist placement and dry deposition method of sample preparation. While preparing the sample by dry deposition method, a measured quantity of dry sand for a particular density was placed in the split mold in layers, by tamping each layer with the help of specially designed hammer. In moist placement method, a measured quantity of sand corresponding to a particular relative density was mixed with 5% water content by weight and the mold was then filled with such soil in layers; again each layer was tamped to obtain the required density. All tests carried out in this study have been performed on uniformly graded clean sand with $D_{50} = 0.3$ mm. The clean sand selected for the tests was found to lie in potentially liquefiable zone as per Tsuchida [21]. The properties of soil and the details of sample preparation methods used in this work were same as those reported in Pathak and Dalvi [10] for 38 mm sample size. However, this work is extended for larger-sized samples such as $50 \times 100$ and $75 \times 150$ mm. The numbers of layers of sand to fill the triaxial mold for these two sizes were also correspondingly increased to 8 and 12 respectively for achieving the particular density. Tests conducted on all of these three sample sizes with both methods for different initial relative densities, 30, 40 and 48%, representing loose, medium and medium dense condition respectively are discussed in the present work. For each of the three densities, tests were performed with confining pressures 60, 120 and 240 kPa. Table 1 presents detailed test program.

## SATURATION AND CONSOLIDATION

After the specimens were prepared, porous stone and loading pad were placed and sealed with O-rings. Negative pressure of 25 kPa was applied to the specimens to reduce disturbance during removal of split mold and triaxial cell installation. When the cell was filled with water the negative pressure was removed and the confining pressure of 50 kPa was applied to the specimens. Saturation of the specimens was accomplished by flushing carbon dioxide for 20 min to replace the air in the voids of the specimen. The specimen was then saturated by back pressure technique and the Skempton's coefficient B ($\Delta u/\Delta\sigma_3$) was periodically monitored. B value of at least 0.97 was achieved for all the specimens indicating that the specimens were completely saturated. The cell pressure was then slowly increased to provide the desired effective confining pressure and then the specimens were isotropically consolidated.

***Table 1:*** *Test Program.*

| Size of sample in $mm^2$ | Sample preparation method | Relative density (%) | Confining Pressure (kPa) | Number of tests |
|---|---|---|---|---|
| 38 × 76 | MP | 30 | 60,120,240 | 09 |
| | | 40 | 60,120,240 | |
| | | 50 | 60,120,240 | |
| | DD | 30 | 60,120,240 | 09 |
| | | 40 | 60,120,240 | |
| | | 50 | 60,120,240 | |
| 50 × 100 | MP | 30 | 60,120,240 | 09 |
| | | 40 | 60,120,240 | |
| | | 48 | 60,120,240 | |
| | DD | 30 | 60,120,240 | 09 |
| | | 40 | 60,120,240 | |
| | | 48 | 60,120,240 | |
| 75 × 150 | MP | 30 | 60,120,240 | 09 |
| | | 40 | 60,120,240 | |
| | | 48 | 60,120,240 | |
| | DD | 30 | 60,120,240 | 09 |
| | | 40 | 60,120,240 | |
| | | 48 | 60,120,240 | |

*MP = Moist placement method, DD = Dry deposition method, Total no. of tests = 54*

## TESTING PROCEDURE

After ensuring full saturation and consolidation process, the drainage valve was closed and LVDT (linear variable displacement transformer) was initialized to zero. Then the conventional strain controlled un-drained monotonic shearing of the specimen was carried out.

During the test for each effective confining pressure, the load, deformation and pore pressure values were recorded using data acquisition system after every 5 s. The test was then continued till load-carrying capacity of sample was reduced. The data collected from the tests was then analyzed and the results are discussed in the following section.

## RESULTS AND DISCUSSION

For all the tests, effect of confining pressure and effect of relative density on each sample size was studied and is discussed subsequently for each method of sample preparation.

### Effect of Confining Pressure

#### *Moist Placement Method*

Figure 1 shows effect of confining pressure on peak deviator stress typically for medium dense sand at relative density of 48% using moist placement method for all sample sizes. It is noticed that as the confining pressure increased from 60 to 240 kPa, peak value of deviator stress also increased for all sample sizes. 75 mm sample size showed maximum peak deviator stress of 1014 kPa which was around 27 to 57% higher than that of 50 mm sample size and 38 mm sample size respectively at confining pressure 240 kPa.

During un-drained shearing, the volume of 75 mm sample size was increased and negative pore water pressure was developed; as a result, there was increase in monotonic strength. However, for small size sample, positive pore pressure remained constant up to large percentage of strain which reduced load-carrying capacity of the sample. Similar trend was observed for 40% relative density. However, for 30% relative density, significant difference (62%) in peak deviator stress was observed between 75 and 38 mm sample size than that of 50 mm sample size.

Thus, increase in peak value of deviator stress with corresponding increase in sample size indicated higher resistance to liquefaction or increase in load-carrying capacity of the soil with increase in confining pressure.

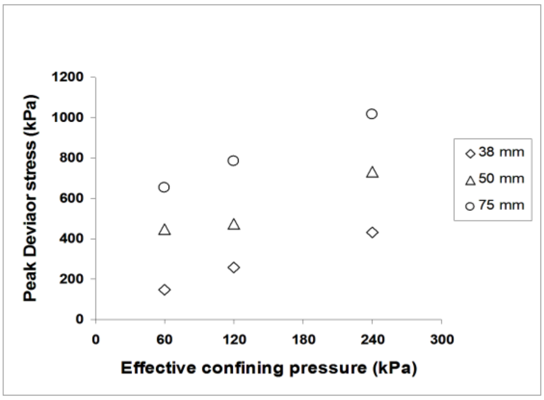


***Fig. 1:*** *Variation of Peak Deviator Stress with Effective Confining Pressure (Moist Placement Method) (RD = 48%).*

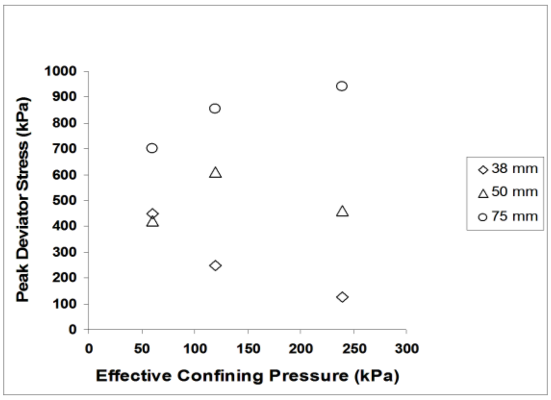


***Fig. 2:*** *Variation of Peak Deviator Stress with Effective Confining Pressure (Dry Deposition Method) (RD = 48%).*

***Dry Deposition Method***

Similarly, Figure 2 depicts the variation of peak deviator stress for three confining pressures for same relative density for all sample sizes but by dry deposition method. For 75 mm sample size, peak value of deviator stress increased as confining pressure was increased. Further, for 50 mm sample size, it increased for confining pressure of 60 and 120 kPa but decreased at confining pressure of 240 kPa. On the contrary, for all densities tested in the present work, peak deviator stress decreased with increase in confining pressure for 38 mm sample size. These results could be attributed to different soil fabric developed in dry deposition method of sample preparation; as dry sand is used at the time of sample preparation gets deposited under gravity, the long axis of grains orient primarily in the horizontal direction as the particles tend to deposit at the most stable position. Correspondingly, the contact tends to align along vertical direction.

This causes high degree of anisotropy in the specimen formed by dry deposition method [18, 22]. This anisotropy of the small size specimen might be reflected through fast generation of pore pressure than that of 75 mm sample size which resulted into reduced peak deviator stress for increased confining pressure. However, the trend of peak deviator stress for 75 mm sample has been similar to that observed in moist placement method (Figure 1). Thus, it could be inferred that for lower sample sizes due to anisotropy the load carrying capacity decreased in dry deposition method.

However, peak value of deviator stress for 75 mm sample size has been 51% higher than 50 mm sample size and 86% higher than 38 mm sample size for 240 kPa confining pressure for dry deposition method. Similar behavior has been observed for 40% relative density. However for 30% relative density, peak value of deviator stress increased with increase in confining pressure for 50 and 75 mm sample sizes.

Thus peak value of deviator stress increased with corresponding increase in confining pressure for all sample sizes in the moist placement method. Similar trend has been observed for larger-size sample using dry deposition method. But for small sample sizes, peak value of deviator stress decreased with the corresponding increase in confining pressure for dry deposition method. This difference in behavior could be attributed to the fact that moisture contained in the soil structures contributes a certain level of suction that holds particles together and thus the orientation of the individual grains is not controlled by gravity. As a result, the sample prepared using moist placement method has more isotropic initial fabric than that in dry deposition method. Furthermore, the effect of relative density on peak deviator stress for various sample sizes has been discussed in the next section.

**Effect of Relative Density**

**Moist Placement Method**

The values of peak deviator stress typically for effective confining pressure 240 kPa using moist placement method have been plotted for initial relative densities 30, 40 and 48% in Figure 3(i). It can be seen from the Figure that peak value of deviator stress increases as the relative density increases for all sample sizes. Peak value of deviator stress for 75 mm sample size has been 45% higher than 50 mm sample size and 71% higher than 38 mm sample size particularly at 40% relative density. Peak value of deviator stress has increased from 206 to 433 kPa for 38 mm sample size whereas more pronounced increase has been observed from 607 to 1014 kPa for 75 mm sample size for variation of density 30 to 48 %.

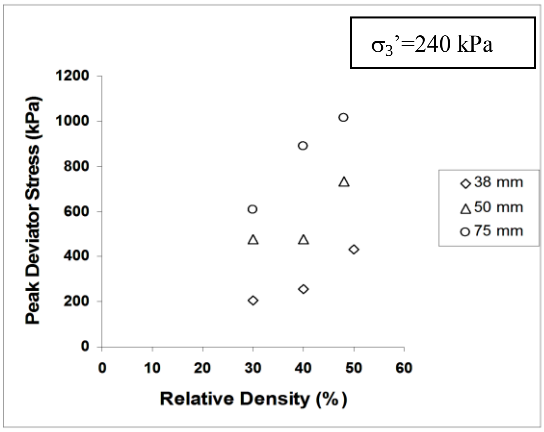


***Fig. 3(i):*** *Variation of Peak Deviator Stress with Relative Density (Moist Placement Method).*

The variation of peak pore pressure with density has been depicted in Figure 3(ii) typically for confining pressure of 240 kPa. It is observed that maximum pore pressure has been developed for 38 mm sample size for 30% relative density which is 50% higher than that of 50 mm sample size and 27% higher than that of 75 mm sample size. This could be because sample prepared at 30% relative density (loose state) exhibits larger contractive tendency compared to that prepared at 48% medium density. Also in loose sand, shearing disturbs the soil structure and soil particles tend to rearrange themselves into denser state of packing. But the initial state of sample prepared at relative density 48% is comparatively dense and hence changes its behavior. Similar trend has been observed for 60 and 120 kPa confining pressure.

Enhanced liquefaction resistance of sand is clearly discernible with increase in relative density for all sample sizes tested in the present work.

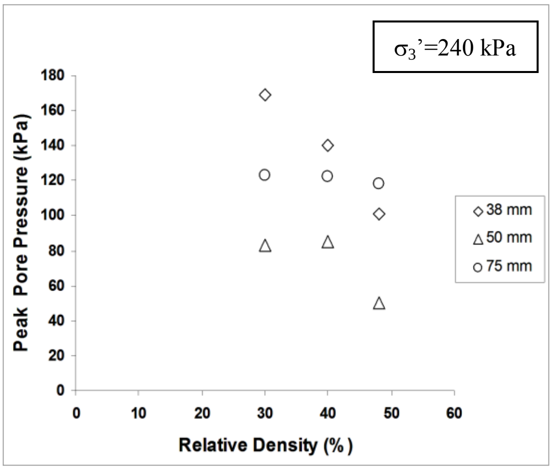


***Fig. 3(ii):*** *Variation of Peak Pore Pressure with Relative Density (Moist Placement Method).*

### *Dry Deposition Method*

Effect of relative density on peak deviator stress for dry deposition method typically for 240 kPa confining pressure has been presented in Figure 4(i). It has been seen that peak value of deviator stress for 38 mm sample size is decreased with increase in relative density. Peak value of deviator stress decreased from 203 to 125 kPa for 38 mm sample size and 638 to 460 kPa for 50 mm sample size as the density increased from 30 to 48% respectively. This could be the effect of method of sample preparation on sample size.

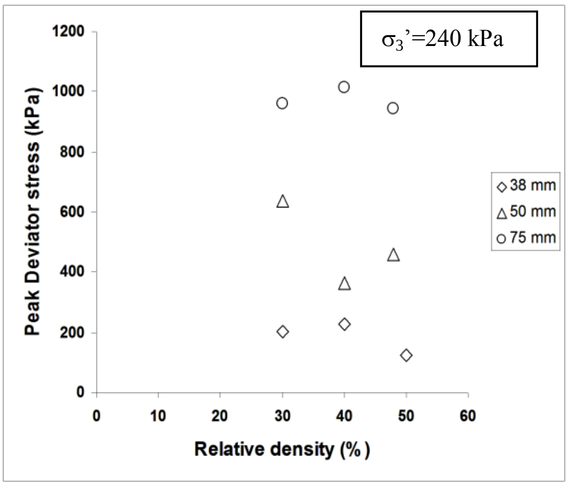


***Fig. 4(i):*** *Variation of Peak Deviator Stress with Relative Density (Dry Deposition Method).*

In dry deposition method, the dry soil particles freely fall under gravity with the formation of different soil fabric which might have resulted into the faster rate of generation of pore pressure. It is also seen from Figure 4(ii) that peak pore pressure generated for 38 mm sample size has been 26 and 73% higher than that of 50 and 75 mm sample size respectively particularly for 30% relative density. Thus the specimen gets easily compressed for 38 and 50 mm sample size. However, for 75 mm sample size, peak pore pressure almost remains constant with corresponding increase in relative density; hence, deviator stress also in turn almost remains constant.

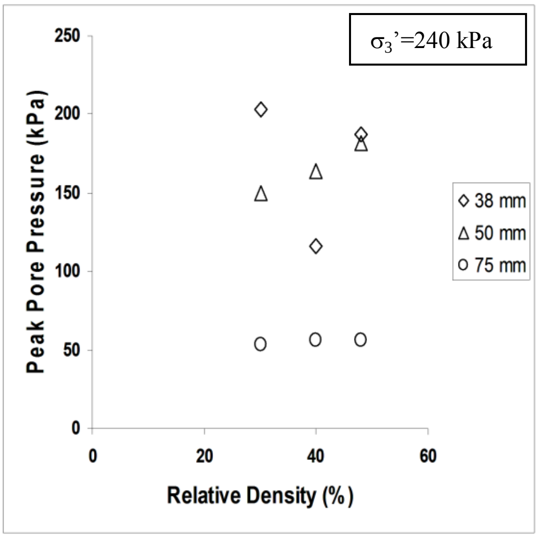


***Fig. 4(ii):*** *Variation of Peak Pore Pressure with Relative Density (Dry Deposition Method).*

Similar behavior has been observed for 60 and 120 kPa confining pressure. Opposite trend as observed in dry deposition method than that of moist placement method especially for 38 and 50 mm sample sizes can be explained by the fact that the molecules of water contained in the soil structures prepared by moist placement method prevent grain to grain contact; as a result the specimen does not have preferential particle orientation which might have resulted into opposite trend of pore pressure generation.

## UNSTABLE ZONE

In order to classify the liquefaction behavior of soil, the authors have already established unstable zone between $k_f$ line and peak pore pressure line [23]. This zone has been studied for 38 mm sample size using wet tamping, IS code method and moist placement method [10] for all relative densities. Unstable zone has been obtained by plotting effective stress path for all three confining pressures for each relative density for each sample preparation method. Present work necessarily incorporates unstable zone for all sample sizes for moist placement and dry deposition sample preparation methods as discussed below.

**Moist Placement Method**

Figure 5(i) shows a typical p'-q plot for $75 \times 150$ mm sample size under moist placement method for 30% relative density along with peak pore pressure and $k_f$ lines. It can be seen that the unstable zone is clearly visible (shaded portion). Figure 5(ii) also shows similar p'-q plot for 48% relative density. From these two figures, it could be observed that as the density increases unstable zone narrows down for $75 \times 150$ mm sample size.

It is also observed that for moist placement method as the size of sample increased from 38 to 75 mm unstable zone narrows down for all densities tested in the present work. Thus the cases where the $k_f$ line and peak pore pressure lines coincide with each other clear unstable zone could not be identified (Figure 5 (ii)). In such situations in order to study the liquefaction behavior, the authors have introduced the ratio of excess pore pressure to mean effective stress. As the liquefaction phenomena are associated with peak pore pressure generation, this ratio has been evaluated at maximum pore pressure point. The ratio at peak pore pressure for 75 mm sample size for 48% relative density has been observed to be 0.7 and 0.6 for higher confining pressures. The value of ratio greater than or equal to 0.4 with corresponding increase in confining pressure indicates the change in the behavior.

Interestingly this ratio when evaluated for all cases in the present work has been found to indicate the contractive or dilative behavior. For the value of this ratio less than or equal to 0.4, dilative behavior has been observed whereas for values greater than or equal to 0.4 the specimen initially contracts and then dilates.

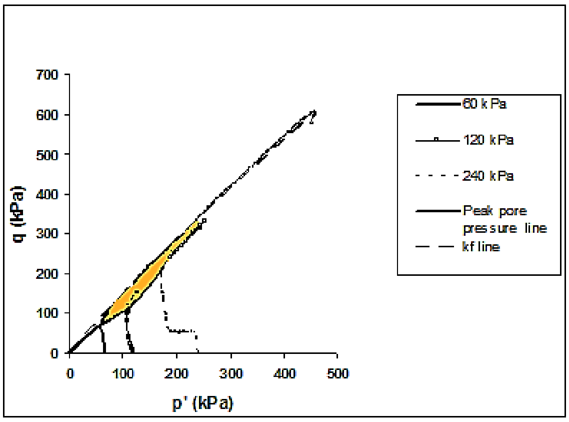


***Fig. 5(i):*** *Unstable Zone for Moist Placement Method (RD = 30%).*

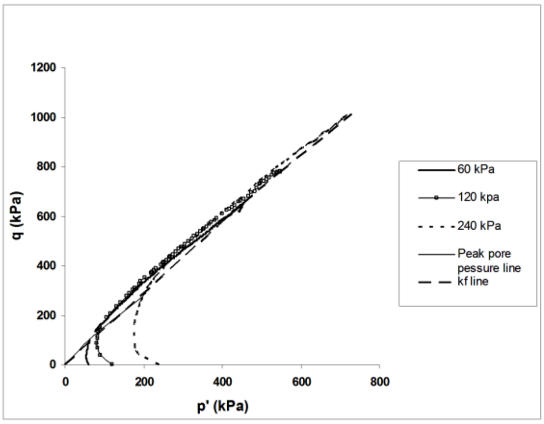


***Fig. 5(ii):*** *Unstable Zone for Moist Placement Method (RD = 48%).*

Thus, typically when this ratio is equal to 0.4, soil behavior changes from contractive to dilative. Hence, the value of ratio 0.4 has been considered as a threshold value indicating transition in the behavior of sample. From the preceding discussion, it becomes clear that the case wherein unstable zone is not identified ($k_f$ line and peak pore pressure line coincide) the value of threshold ratio can be effectively used to indicate contractive and dilative behavior. The threshold value of this ratio is observed to be 0.4.

### Dry Deposition Method

Figure 6(i) shows a typical p'-q plot for 75 × 150 mm sample size using dry deposition method for 30% relative density along with peak pore pressure and $k_f$ lines. It can be seen that the unstable zone is clearly visible (shaded portion). Similar p'-q plot for the same sample size Figure 6(ii) but for 48% relative density showed more widened unstable zone.

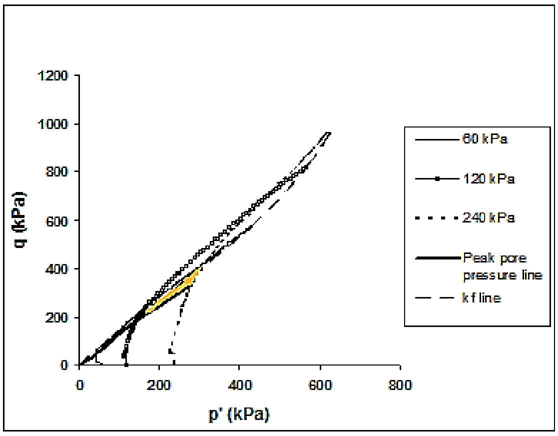


***Fig. 6(i):*** *Unstable Zone for Dry Deposition Method (RD = 30%).*

This could be due to typical behavior observed in case of 75 mm sample size as significant increase in the peak pore pressure value has not been observed for corresponding increase in relative density; the zone between $k_f$ line and peak pore pressure line has increased. For dry deposition method, it is also observed that for 30% relative density unstable zone gradually decreased as the sample size increased from 38 to 75 mm. However, for the same method, 40 and 48% relative densities, as the sample size increased unstable zone also increased.

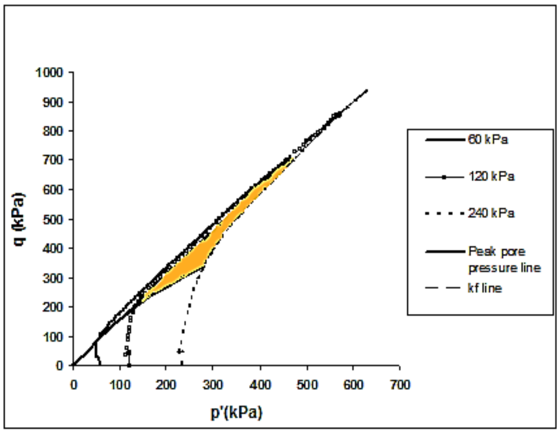


***Fig. 6(ii):*** *Unstable Zone for Dry Deposition Method (RD = 48%).*

## CONCLUSIONS

The following conclusions can be made based on the above study presented:

(1) For moist placement method peak value of deviator stress increased with corresponding increase in sample size indicated higher resistance to liquefaction

with increase in confining pressure. Similar trend has been observed for large sample size for dry deposition method. However, for same method for small sample sizes peak value of deviator stress decreased with corresponding increase in confining pressure.

(2) For moist placement method, liquefaction resistance increased with corresponding increase in sample size with increase in relative density. Similar trend has been observed for large sample size for dry deposition method; but small sample sizes showed opposite trend.

(3) For moist placement method as the size of sample increased from 38 to 75 mm, unstable zone narrows down for all densities tested in the present work.

(4) The case wherein unstable zone is not identified ($k_f$ line and peak pore pressure line coincide) the value of threshold ratio observed as 0.4 indicates the contractive to dilative behavior.

(5) For dry deposition method, unstable zone gradually decreased as the sample size increased from 38 to 75 mm for 30% relative density. However for 40 and 48% relative densities as the sample size increased unstable zone also increased.

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**List of Symbols**

| | |
|---|---|
| $D_{50}$ | Mean grain size |
| B | Skempton's pore pressure parameter |
| P' | Mean effective stress, $p' = (\sigma'_1 - 2\ \sigma'_3) / 3$ |
| q | Deviator stress $(\sigma'_1 - 2\sigma'_3)$ |
| $\Delta u$ | Excess pore pressure |
| $\sigma_3$ | Minor principal stress |

  