Seepage Test on Liquefiable Sand

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Abstract: ***This paper presents a series of seepage test on potentially liquefiable sand in the laboratory. Both downward and upward seepage direction were applied during the tests. These tests were conducted to investigate the influence of soil grain size and its distribution on hydraulic conductivity k, critical hydraulic gradient i_{cr} and piping failure mode of liquefiable sand. The seepage test results revealed that the hydraulic conductivity from upward seepage test is greater than the downward seepage test. The upward seepage test revealed that during liquefaction or piping failure/boiling, the hydraulic conductivity increased significantly, depending on the soil grain size, its ranging from 83% to 321%. The greater the size of soil grains the lesser potential of liquefaction or piping failure to occur. Because the pores space of the soil grain sufficient enough to dissipate the excess pore water pressure. The results and discussion in this study provide insightful information for the behavior of liquefiable sand when subjected to excess pore water pressure with different seepage force direction.***

Keywords: Sand, Permeability, Liquefaction, Downward and Upward Seepage test, Critical Hydarulic Gradient

1. Introduction

Liquefaction can occur when a site with saturated relatively loose soils (usually sands or silts) experience strong earthquake ground motion. When seismic forces excite the saturated loose soil structure tends to contract generating excess pore water pressure, accompanied by a reduction in soils' strength. This causes the soil to behave as a viscous liquid rather than soil.

The consequences of liquefaction for shallow foundations include the reduction in foundation support through the loss of bearing capacity, excessive settlement, lateral spreading, and flow failures. In deep foundations, liquefaction can cause reduction in lateral capacity, additional down drag forces.

In order to examine the behavior of liquefiable sand when subjected to excess pore water pressure, a static liquefaction is introduced to the soil column by subjecting to gradually increase its static pore water pressure until piping or soil boiling occurred in the liquefiable sand.

The preceding discussion is the basis of this study, which involved conducting a series of upward seepage tests on the liquefiable sands. The objective of this study is to evaluate the influence of grain size and distribution on the hydraulic response such as piping failure mode, hydraulic conductivity, and critical hydraulic gradient of the liquefiable sand. The results and discussion in this experiment provide insightful information for the behavior of the liquefiable sand during earthquake.

2. Experimental Program

2.1 Test System

A series of seepage tests were conducted to evaluate grain size and grain distribution on the hydraulic conductivity and critical hydraulic gradient of the liquefiable sands. For this purpose, a seepage test system (Fig. 1), consisting of a constant head device, a permeameter, and measuring systems, was developed in this study and is described in this section.

The permeameter consists of a cylindrical cell (7.4 cm in diameter and 25 cm in height) and a bottom pedestal. To avoid a scale effect, the ratios of the specimen diameter to the mean grain diameter of sand in this test were 90, which is larger than the values (8–12) specified in ASTM (D2434). The interface is layered with porous screens was used to distribute the water seepage evenly across the soil specimen. The porous screens comprised two perforated metal plates and a nonwoven geotextile. The perforated metal plates, with numerous punched holes, were used to support the overburden pressure from soil specimens. The non-woven geotextile was placed between the two perforated metal plates and served as a filter to prevent the loss of soil.

The water flow from the top of the specimen was measured and then discharged to the barrel. Discharge velocity v at a given hydraulic gradient was calculated by dividing the collected volume of discharge at a certain time period by the cross-sectional area of the soil specimen. The hydraulic gradient i can be calculated at each stage of the test using the following equation:

$$i = \frac{\Delta h}{L}$$

where Δh is the various head difference between the permeameter and the water reservoir and L (=25 cm) is the length of tested sample.

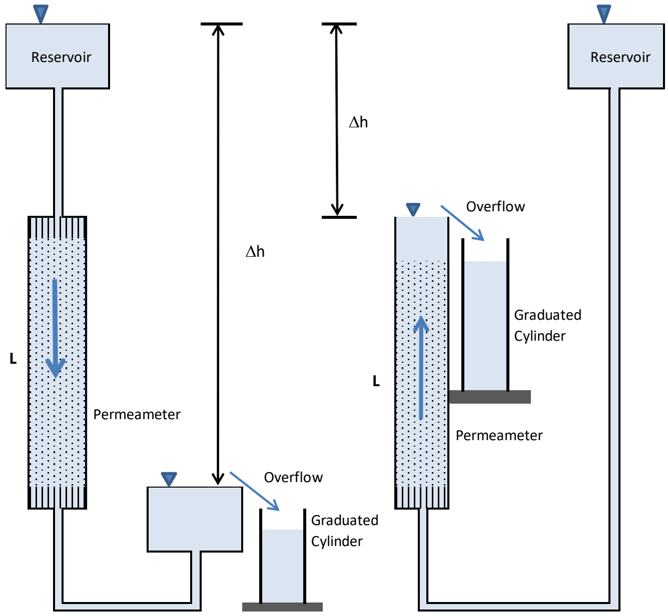

Figure 1: Constant Head seepage test system, Downward and Upward

2.2 Test Material and Test Program

Quartz sand (QS) originated from Bangka island was used in this study. Table 1, summarizes its property and Figure 2 presents the grain size distribution curve of the tested soil. The graph has shown that the tested soil sample was fall in the Tsuchida's envelope for the most liquefiable soil.

Table 1: Summary of soil property of quartz sand (QS)

Soil properties	Value
Specific gravity G_s	2.69
Effective particle size d_{10} (mm)	0.28
Mean particle size d_{50} (mm)	0.55
Uniformity coefficient C_u	2.39
Coefficient of curvature C_c	0.85
Soil classification (USCS)	SP

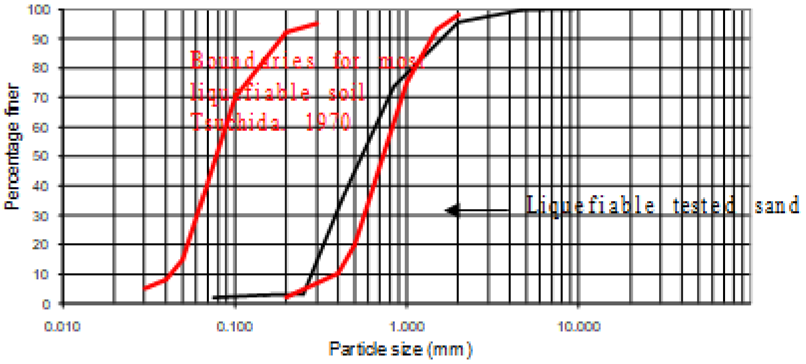

Figure 2: Grain size distribution curve of the tested sand, QS

In order to obtain specific uniformly graded specimen, the quartz sand (QS) from Bangka island was sieved. A total of 5 specimens were prepared from the quartz sand sample, and those soil specimens are summarizes in the Table 1. And then 10 seepage tests both downward and upward seepage direction were conducted on the following soil specimens. The following are the soil properties of the specimens during their tests.

Table 2: Summary of soil specimens for the seepage test

No.	Specimen Name	Soil Type	Remarks
1	QS	Fine to medium Quartz Sand	Sample with original grain size distribution
2	QS 2 mm	Uniform Medium Quartz Sand	Passing # 10 sieve & retained # 20 sieve
3	QS 0.85 mm	Uniform Medium Quartz Sand	Passing # 20 sieve & retained # 40 sieve
4	QS 0.42 mm	Uniform Fine Quartz Sand	Passing # 40 sieve & retained # 60 sieve
5	QS 0.25 mm	Uniform Fine Quartz Sand	Passing # 60 sieve & retained # 100 sieve

Table 3: Summary of soil properties of the tested specimen

No.	Specimen Name	Dry Density kN/m3	Porosity	Void Ratio
1	QS	15.73	0.42	0.71
2	QS 2 mm	14.43	0.67	0.88
3	QS 0.85 mm	14.50	0.46	0.85
4	QS 0.42 mm	14.70	0.45	0.83
5	QS 0.25 mm	15.11	0.44	0.78

2.3 Specimen Preparation and Test Procedure

The specimens were prepared at certain and constant conditions, approximately having soil relative density D_r = 60% to 70%. Each specimen was carefully prepared to ensure that its soil had a uniform density and full saturation.

A known quantity of soil was carefully placed by hand. The hand placed method has been commonly adopted by various researchers (Yetimoglu and Salbas 2003; Das et al. 2009; Estabragh et al. 2014). The permeameter was carefully filled with the wet soil in five layers (5-cm thick for each layer). Each layer was slightly compacted using a metal rod to control its height. This procedure was repeated until the desired specimen height (H = 25 cm) was reached. Visual inspection showed that good uniformity was achieved. The repeatability and consistency of the test results were verified by examining test results performed under the same conditions.

After specimen preparation, the specimen was submerged in water and subjected to a constant seepage flow under a low hydraulic head that did not affect the specimen stability for 24 h to ensure the full saturation of specimens. Afterward, the seepage test began by applying a series of incrementally increased hydraulic heads to the soil specimen until maximum hydraulic gradient of 1.8 achieved. The applied hydraulic head was increased by 5 cm (approximately $\Delta i = 0.2$) for each increment and maintained for at least 10 min until the hydraulic discharge in the graduated cylinder having stabilized measurement, indicating that equilibrium was reached. Both downward and upward seepage direction were conducted for each soil specimen. The hydraulic gradient i and corresponding discharge velocity v were recorded in each stage of the test.

3. Results and Discussion

In this section, the influence of seepage direction and hydraulic gradient on the hydraulic responses of liquefiable sand is qualitatively evaluated and discussed.

3.1 Downward Seepage Test

The hydraulic conductivity or coefficient permeability obtained from the seepage test with downward water flow direction is summarized in the Table 4 and graphed in Figure 3.

Table 4: Summary of downward seepage test results

No.	Specimen Name	Permeabity, cm/sec.		Permeability Changes
		i = 0.2	i = 1.8	
1	QS 2 mm	0.7188	0.3235	- 45%
2	QS 0.85 mm	0.5086	0.2720	- 53%
3	QS 0.42 mm	0.1929	0.1561	- 81%
4	QS 0.25 mm	0.0683	0.0681	- 100%
5	QS	0.1199	0.1030	- 86%

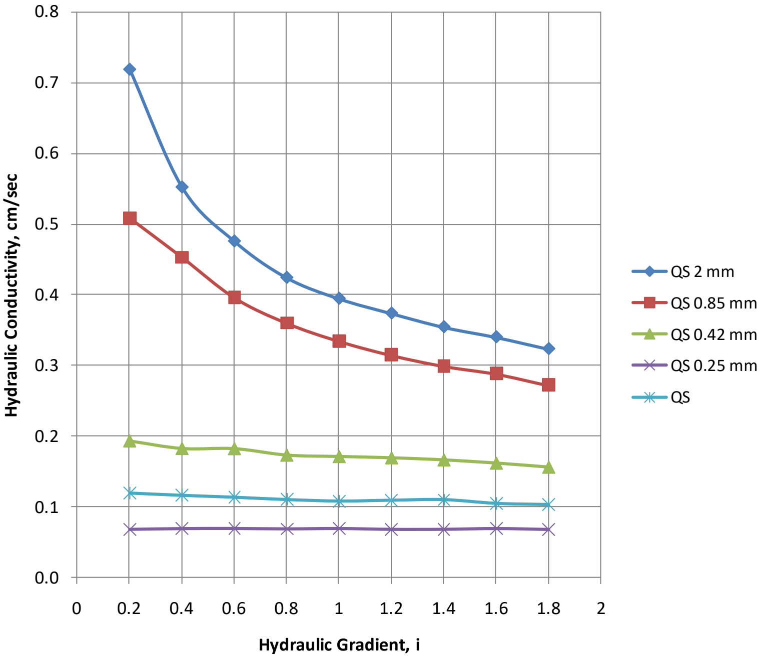

Figure 3: Downward direction seepage test results

Based on the above results the following phenomena can be observed;

- The smaller the soil grain size or the porosity the smaller the hydraulic conductivity
- There is reduction of hydraulic conductivity as the hydraulic gradient increases, the effect is more pronounced on the bigger grain size which has greater porosity
- There is no hydraulic conductivity changes on the QS 0.25 mm

3.2 Upward Seepage Test

The hydraulic conductivity or coefficient permeability obtained from the seepage test with upward water flow direction is summarized in the Table 5 and graphed in Figure 4. The main differences between the downward and upward seepage test is the seepage force direction. In the upward seepage test the seepage force acting against the soil effective stress, so that when the hydraulic gradient reach the critical gradient, the effective stress become zero, and the soil start to behave as a viscous liquid. When the next hydraulic head increment after i_{cr} was applied, the specimen showed a sudden and notable heave, following by the sand piping/boiling phenomenon. The soil lost it overall stability. The heave and boiling phenomenon are strong evidence of soil failure subjected to seepage. The soil boiling happened globally within the soil specimen in which soil particles were forced to migrate with the upward seepage. Vigorous soil boiling on top of the specimen can also be clearly observed.

Table 5: Summary of upward seepage test results

No.	Specimen Name	Permeabity, cm/sec.		Permeability Changes
		i = 0.2	i = 1.8	
1	QS 2 mm	0.9292	0.4198	- 45%
2	QS 0.85 mm	0.5962	0.2991	- 50%
3	QS 0.42 mm	0.2503	0.3645	+ 146%
4	QS 0.25 mm	0.1183	0.3802	+321%
5	QS	0.1980	0.3626	+ 83%

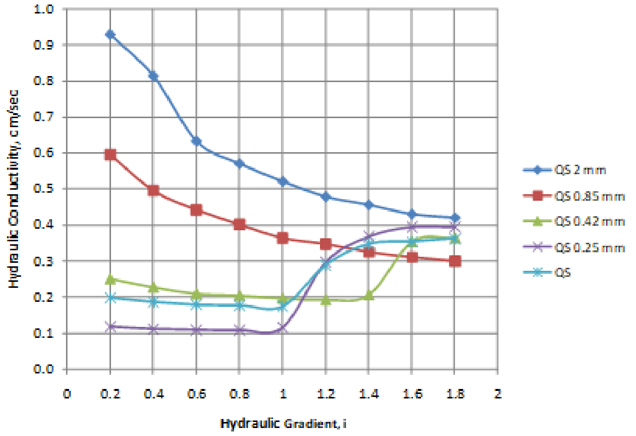

Figure 4: Upward direction seepage test results

QS, QS 0.42 mm and QS 0.25 mm at Figure 4 shows the typical failure modes of soil specimens at and after the critical hydraulic gradient i_{cr}. At this stage, the soil seemed to have liquefied (the author's finger can easily penetrate into the specimen without feeling much resistance). Failure mode of soil specimens observed for QS at $i_{cr} = 1.0$; QS 0.42 mm at $i_{cr} = 1.4$; and QS 0.25 mm at $i_{cr} = 1$.

4. Conclusion

In this study, experimental seepage tests with downward and upward water flow direction were conducted to investigate the hydraulic responses (i.e., piping failure mode, hydraulic conductivity, and critical hydraulic gradient) of liquefiable sand subject to seepage. Based on the test results, the following conclusions can be drawn:

1) The results of hydraulic conductivity from upward seepage test are greater than the hydraulic conductivity from the downward seepage test for the same soil specimen. This is due to the direction of the seepage force in the upward seepage test is reducing the effective stress and cause opening of the pores of the tested soil. Whilst in the downward seepage test the seepage force somehow increases the density of the tested specimen.
2) Both at downward and upward seepage tests, there is hydraulic conductivity reduction as the hydraulic gradient increases, the effect is more pronounced on the bigger grain size which has greater porosity. The effect unobservable at QS 0.25 mm.
3) The greater the size of soil grains the lesser potential of liquefaction or piping failure to occur. Because the pores space of the soil grain sufficient enough to dissipate the excess pore water pressure.
4) In the upward seepage test, the liquefiable soil specimens had a failure mode associated with a soil heave and vigorous soil piping/boiling,
5) Seepage test results revealed that critical gradient i_{cr} certain grain size (Qs and QS 0.25 mm) equal to unity, which indicate maximum effective diameter for soil which potentially subjected to liquefaction.
6) The upward seepage test on the aforementioned soil specimen revealed that during liquefaction or piping failure/boiling, the hydraulic conductivity increased significantly, depending on the soil grain size, it's ranging 83% to 321%.

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