Foundation stability on sandy soil due to excessive pore water pressure: laboratory observations

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Abstract. Pore water pressure is a factor which contributes to foundation stability. The change in pore water pressure in soil mass may affect the bearing capacity of the foundation. Especially for sandy soil, the increased pore pressure may cause the foundation collapse. This study investigates the stability of soil-foundation system due to the increase of pore pressure using a scaled model in the laboratory. The sands were taken from Siteba Padang and sieved pass through sieve no. 40. The calculated relative density of sample in the box model is 51.76%, which indicated the medium sand density. The model was made up to obtain saturated condition. The increased pore water pressure was performed using upwards seepage method in several steps, which are monitored through piezometer pipes. The tests results show that at the last step, the sand boil happened on the soil surface that result the sink of foundation model. It also indicates the loss of bearing capacity due to the loss of effective stress in the soil mass. The Mohr-graphs is also performed to figures the stress in the soil mass. The graph also can show the collapse points in the soil mass during the test.

1. Introduction

One of the most dangerous phenomenon causes building damage is liquefaction in saturated sand deposit [1]. This kind of liquefaction happened in Niigata (1964) which becomes the icon of this phenomenon. An earthquake of 30 September 2009 in Padang also caused liquefaction in many areas, which are mostly at riverbank and in coastal areas [2]. Liquefaction generally occurs due to the increase of pore water in the soil mass in which there is no enough time to dissipate the water from pore of soil. The excessive pore pressure then causes the contact loss between grains of sand and also changes the mechanical behaviour of the soil. Al-Karni (2014) introduced a change in the Stress-Strain behaviour of sandy soil when quick positive building up of pore water pressure occurs [3]. At a certain condition, the soil will lost its shear strength due to the loss of its effective stress and thus behaves as dense liquid. This change behaviour of soil mass then will effect on the stability of foundation. This research was conducted to see changes in sandy soil mass behaviour due to increased pore pressure through changes in stress that occur and their impact on foundation stability through analysis of failure
under the foundation. It is expected to be useful for further research and as a consideration in the planning process in the construction industry.

2. The Principles of Effective Stress

The effective stress strictly applies only to fully saturated soils. When a saturated soil mass was given a sudden pressure load, it will cause compressive stresses of its. Some of the compressive stresses are covered by soil particles and partly covered by pore water pressure. The combination of these stresses is called total stress. Terzaghi (1923) explained the principle of effective stress acting on a soil mass with the following equation [4]:

\[ \sigma' = \sigma - u \]  

The pore water pressure \((u)\) is the stress in the water that fills the void between the soil grains. The total stress \((\sigma)\) is stress due to the total load including the weight of the soil and the water in the pore per unit area. The effective stress \((\sigma')\) is stress only at the soil grains. The effective stress plays an important role in mechanical problems such as settlement of the soil mass and shear strength of the soil mass.

3. Effective Stress with Upwards Seepage

To analyze the effective stresses of the soil carried out by several methods, one of them is upward seepage method. In this method the seepage is assumed from below against the direction of gravity that showed in Figure 1.

![Figure 1](image)

**Figure 1.** A layer of grain soil in the cylinder where there is a water secretion upwards caused by the addition of water to the pipeline [4]
If the seepage speed (and hydraulic gradient) increases slowly, a boundary condition will be achieved where [4]:

$$\sigma'_c = z \gamma - i_c z \gamma_w = 0$$

(2)

Under such circumstances, soil will be collapsed. This condition is usually known as boiling or quick condition which is part of the liquefaction phenomenon. Further, Terzaghi explained the calculation of bearing capacity of the shallow foundation which is known as Ultimate Bearing Capacity Theory which has an equation [4]:

$$q_u = c N_c (s_c) + q' N_q + \frac{1}{2} \gamma B N_y (s_y)$$

(3)

4. Grain Size Distribution

Based on the field case histories on evaluation of liquefaction potential, 78% of liquefaction happened on the soil with means grain size between 0.113 to 0.338 mm. These boundaries have been showed by Aydan [5]. In this test, the soil sample was taken from Siteba Padang and sieved pass through sieve No. 40 at the laboratory. The grain size distribution of the sample shows in Figure 3.
Figure 3. Grain size distribution Siteba sand

From the grain size distribution chart, the value of uniformity coefficient (CU) and coefficient of gradation (CC) are 1.423 and 0.928. These values indicate that the soil is poorly-graded. The soil properties were tested to identify the soil type. The direct shear test showed the value of the angle of internal friction, $\phi' = 32.280$ and cohesion, $c = 0.016$. Volume weight of the sample on a saturated condition ($\gamma_{sat}$) is 1.3168 g/cm$^3$. The relative density of sample 51.76% is obtained which indicated the medium sand criterion.

5. Laboratory Test Result

A series of laboratory tests has been done by arranging the soil sample in the box container as shows in Figure 4. In these tests, the pore water pressure ($u$) varies on the same relative density ($Dr$). The increased pore water pressure was performed in several steps by upwards seepage method. The water pressure is monitored through piezometer pipes. The piezometer tips are placed in some certain depths where becomes the point of view of the sample, i.e. at depth 50 cm, 30 cm, 10 cm and 0 cm from the surface. The sample was saturated before tests were performed. The model foundation dimensions are 15 cm x 15 cm x 6 cm and additional load 5723 gram is placed at the surface of the sample.
Data of increasing pore water pressure on each step are shown in Table 1. This data will be used to calculate the effective stress by the upward seepage method.

### Table 1. Data of increasing pore water pressure during testing

| point | depth | u (gram/cm²) | step 1 | step 2 | step 3 |
|-------|-------|--------------|--------|--------|--------|
|       |       | no seepage   | u (gram/cm²) | u (gram/cm²) | u (gram/cm²) |
| 0     | 0     | 0            | 0      | 0      | 0      |
| D     | -6    | 6            | 7      | 9      | 11.8   |
| C     | -16   | 16           | 17.8   | 24.3   | 27.5   |
| B     | -36   | 36           | 39.9   | 56.1   | 59.2   |
| A     | -56   | 56           | 61.8   | 88.5   | 99.2   |

The settlements of the foundation model based on visual observation were also recorded in this test as show in Table 2.

### Table 2. Settlement of foundation model during testing

| Step | Time (second) | Settlement (cm) |
|------|---------------|-----------------|
| Initial | 0            | 0               |
| 1     | 26            | 0.03            |
| 2     | 20            | 0.5             |
| 3     |               | collapse        |

### 5.1. The Effective Stress Analysis

The foundation stability depends on the strength of the soil, to investigate it effective stress analysis is required. The increased of pore water pressure induce the change in the effective stress as shown in Figure 5, Figure 6, and Figure 7.
Figure 7. Variation of effective vertical stresses ($\sigma'_v$)

From effective-stress charts are visible the initial condition of the soil is in a stable state. This is evidenced by the effective stress calculation in the positive value for all points of view. It proofs the foundation model at this stage in stable condition. The increase of pore water pressure at 1st step is caused the decrease of effective stress which is negative values (-1) gram/cm$^2$ occur at a point under the foundation meanwhile at another point of view still positive, the settlement of foundation 0.03 cm measured in testing. When the increase in pore water pressure continues, the effective stress value continues to decrease also. At 2nd and 3rd step, soil samples have changes in mechanical strength this indicated by the effective stress value that is negative thus triggering sand boil (boiling) in 3rd step. Sand boil (boiling) occurs indicates loss of bearing capacity due to loss of effective stress in soil mass, it proves that liquefaction conditions have happened. Liquefaction condition occurs because of the increase of pore water pressure can cause sand deposit to lose its contract, if soil has reached liquefaction condition then the effective stress in soil mass is decreased hence its shear strength can drop [6]. At that stage, the foundation model is already unstable; this is evidenced by a large decrease until it sinks the foundation model during testing.

5.2. Mohr-Coulomb Analysis

Mohr coulomb analysis was carried out to determine the condition of the collapse of a material. The stresses happened in the soil mass than can be explained using the Mohr graphs. The failure at the point of view occurs after increasing of pore water pressure which can be seen in Figure 8, Figure 9, and Figure 10. Figure 8 shows the Mohr Graphs at points of view in the initial condition, where there has been no failure in the soil mass because the graphs have not intersected the failure line.
Figure 8. Mohr-Coulomb at the initial condition for each point of view. The initial condition is a saturated condition with No Seepage. All of Mohr circles are still below the failure line.

Figure 9. Mohr-Coulomb at 1st step of the increase of pore water pressure. Failure occurs at points A, B, and C.

Figure 10. Mohr-Coulomb at 3rd step. This step is the last step of increasing pore water pressure during testing. All soil layers have a failure.
The failure of the soil layer occurs as the pore water pressure increase so that a large amount of pore water pressure greatly affects the level of soil failure. This is seen in Figure 9, the Mohr circle at points A and B has crossed the failure line which indicates that the points have failed before the increase in pore pressure reaches the peaks and point C failure at that moment. The failure continues to occur until it reaches the sample surface, where Mohr Circle at point D crossed the failure line.

When the failure reaches point D in the soil sample, behaviour of the soil changes to be liquid so that no solid particles support the load above, it causes a collapse in the foundation model as shown in Figure 11.

![Figure 11](image-url)  
**Figure 11.** The collapse of foundation at the 3rd step

Due to the pore water pressure that continues to increase in the sand soil to exceed the failure limit, causing the soil to appear to be liquid (liquefaction condition), bearing capacity of the soil continues to decline and even becomes lost, this triggers sand boil and causes the sinking of the foundation above the soil sample. The reduced bearing capacity of the soil due to the increase in pore water pressure will be followed by the large of foundation settlement. The relationship between bearing capacity and settlement in testing can be seen from Figure 12.

![Figure 12](image-url)  
**Figure 12.** Relationship of bearing capacity and settlement

The settlement at 1st step is 0.03 cm in 26 seconds, at 2nd step is 0.5 cm in 20 seconds, and at 3rd step, the settlement is kept on and the foundation was the collapse.
6. Conclusion

This paper presented that pore water pressure can affect the stability of foundations. The increase of pore water pressure can cause a decrease in effective stress in soil mass, even in some conditions becomes lost, and this causes a decrease in bearing capacity too. From the test result, at the 1st step of testing, the pore pressure read from each piezometer pipe is still on a low level, and the settlement measurably very small is 0.03 cm in 26 seconds. At the 2nd step, the pressure is increased so that the foundation settlement become more than before is 0.5 cm within 20 seconds. At the 3rd step, the increase of the pore water pressure is continued and the settlement is kept on. The 3rd step becomes the last step since the foundation settlement is never stopped and the sand boil has happened on the soil surface. It indicates the loss of bearing capacity due to the loss of effective stress in the soil mass, which causes the foundation to be unstable.

From Mohr, graphs can be analyzed the point of collapse under the foundation. Where are throughout the 1st step, failure occurs at point A, B, and C. And the last step the failure reach to the surface of the soil mass. So that magnitude of the increase in pore pressure will determine the level of soil failure which then has an impact to foundation stability. The settlement of foundation model is kept on during the test, until at critical point the foundation has collapsed. This is evidenced by changing behaviour of the sandy soil due to changes in stresses when the pore pressure increases. This paper can be used as a reference for further research using variations type of sand and variations of relative density (Dr).

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