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THE EFFECTS OF WATER-SATURATED SAND-FRACTIONS ON THE SAND-BOILING PHENOMENON

*Rina Yuliet[1], Abdul Hakam[2], Mas Mera[3] and Fauzan[4]

[1,2,3,4]Engineering Faculty, University of Andalas, Indonesia

*Corresponding Author, Received: 13 March 2021, Revised: 20 April 2021, Accepted: 12 June 2021

ABSTRACT: Understanding the stress distribution behaviors along a soil cross-section have been the challenging topics in geotechnical engineering for the last two decades. Stress analysis by considering saturated sand without upward flow of water has been well studied. However, stress analysis in saturated sand-fraction with upward flow of water, which causes the sand-boiling phenomenon still needs a better understanding. In this paper, the relative density is used to indicate the denseness and looseness of sand fraction. The sand-boiling behaviors are then investigated through two scenarios. The first scenario uses a fine sand-fraction, called the FS scenario. The second scenario uses a mixture of coarse and medium sand-fractions, called the CS-MS scenario. For the FS scenario, the fine sand-fraction only consists of one layer, while for the CS-MS scenario, it consists of two layers where the coarse sand-fraction is above the medium one. The use of the relative density values of the fine sand, medium sand, and coarse sand in both scenarios are 7.6%, 12.4%, and 5%, respectively. As a result, all sand fractions used are categorized as very loose sand because their relative densities are less than 15%. The FS scenario shows that the effective stress is equal to zero obtained within 10 seconds at a depth of 0.12 m under the ground surface. This indicates that the sand boiling has occurred in the FS scenario. Whereas in the CS-MS scenario, the variation of effective stress with depth for a soil layer with upward seepage has a value greater than zero. This indicates that the sand boiling never occurred in the CS-MS scenario. Furthermore, both scenarios also show that the addition of coarse sand-fraction above medium sand-fraction could prevent the sand-boiling phenomenon.

Keywords: Relative density, Sand fraction, Very loose sand, Upward flow, Effective stress

1. INTRODUCTION

The upward flow of water in the very loose and water-saturated sand fraction can increase pore-water pressure and decrease effective stress. When the flow velocity increases slowly, a boundary state is reached, that is, when the effective stress is zero. Because of this, soil stability will be lost and will behave similarly to fluids, and large deformations will occur [1-6]. Loss of soil stability due to the upward flow of water is commonly known as boiling [1-3, 7]. The sand boiling occurs when the soil experiences a seepage force greater than the weight of the holding soil [8]. The phenomenon associated with the sand boiling is called liquefaction [9, 10]. In the case of the sand boiling, the sand particles move upward due to the water flow while in the case of liquefaction, the sand particles tend to stay below due to vibrations [9]. The parameters that affect soil stability are the size of the sand particles (sand fraction), the relative density, and the maximum hydraulic-gradient of the soil [7, 11, 12].

The results of observation of Yuliet *et al*. (2020) show that the upward flow of water in the saturated fine sand-fraction causes boiling so that the foundation above it collapses. On the other hand, boiling does not occur in coarse sand-fraction above medium sand-fraction, so that the foundation might not collapse [13]. The upward flow of water can reduce the bearing capacity of the foundation and cause the building to fall and slope [2, 13, 14]. The results of observation from the model test conducted by Ueng *et al*. show that upward flow and vibrations that occur in the saturated fine sand-fraction increase the excess pore water pressure (EPWP) and reduce the effective stress [6].

Based on the problems mentioned above, it is necessary to conduct a research on the effect of the saturated sand-fraction against the sand boiling. This study is carried out to determine the effect of the sand fraction with upward flow of water on the in situ stresses, which causes the sand-boiling phenomenon. In this study, a laboratory work is carried out to simulate boiling phenomena. There are two scenarios made in this study. The first scenario uses a fraction of fine sand, called the fine-sand scenario, abbreviated as FS Scenario. The second scenario uses two layers of sand fraction. The coarse sand-fraction above the medium sand-fraction is called the scenario for coarse sand and the medium sand, and is abbreviated as CS-MS Scenario. The fine sand-fraction (FS) is the sand that passes through sieve number 40 but is held back by sieve number 200.

The medium sand-fraction (MS) is the sand that passes through sieve number 10 and but is held back by sieve number 40. Coarse sand-fraction (CS) is the sand that passes through sieve number 4 but is held back by sieve number 10. Total stress, pore-water pressure, and effective stress at each depth due to upward flow are plotted and then analyzed to determine the occurrence of boiling in each saturated sand-fraction. From the both scenarios, it is hoped that the most appropriate way can be found to prevent the boiling of saturated sand due to upward flow of water.

2. EXPERIMENTAL DETAIL

2.1 Apparatus

The present laboratory work uses an experimental tank as shown in Fig. 1. It consists of a tank made of acrylic with a length of 100 cm and a width of 15 cm. Four piezometers are installed to measure the rise in water level due to the upward flow of water. A pump is used to supply water to the tank, and a flow meter is used to adjust the flow of water entering the tank.

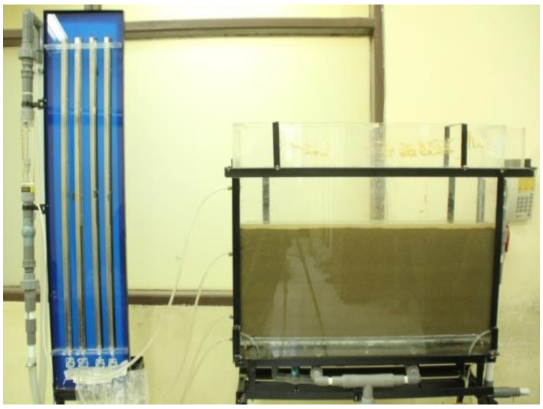

Fig. 1 Experimental tank

2.2 Materials and Preparation of Specimens

The sand used for the specimens in the present test is sand taken from the beach of Muaro Baru and from the Batang Kuranji river. Both areas are located in Padang city. The sand is then washed using distilled water to remove clay particles and dirt adhering to coarse particles. The sand is then dried using an electrical oven, then separated into fine fraction, medium fraction, and coarse fraction using a sieve system (often called sieve analysis). The physical and mechanical properties of the three sand fractions can be seen in Table 1.

Table 1. The physical properties of sand fractions

Soil Properties	Fine Sand (FS)	Medium Sand (MS)	Coarse Sand (CS)
Permeability, k (m/sec.)	0.666×10^{-2}	0.095×10^{-2}	0.809×10^{-2}
Dry unit weight, γ_{dry} (gr/cm^3)	1.150	1.130	1.360
Maximum dry unit weight, $\gamma_{dry\,(max)}$ (gr/cm^3)	1.223	1.177	1.464
Minimum dry unit weight, $\gamma_{dry\,(min)}$ (gr/cm^3)	1.144	1.124	1.355
Relative Density, Dr (%)	7.6	12.4	5

Based on the permeability values shown in Table 1, it can be seen that all sand fractions are poorly graded or uniform sand. Based on the relative density (Dr) then, all sand fractions are very loose sand since their relative-density values are in the range of 0 to 15%.

2.3 Experimental Procedures

In the FS Scenario, the experimental tank is filled with only one layer of fine sand-fraction (FS). In the initial conditions (Fig. 2), the tank is first filled with water to a certain height. The water level in the experimental tank equal to the water level in the piezometer. After that, fine sand is put into the tank to a height of 37 cm from the bottom of the tank. Adjust the water level in the tank and piezometer. In this FS scenario, the initial water level (IWL) is 1.7 cm above the ground surface. The water level in each piezometer will also be the same height as the water level in the experimental tank. Then, turn on the pump, the valve located near the flow meter is gradually opened so that the water will flow upward from the bottom of the tank towards the bottom soil mass and continue to the ground (Fig. 3). The pressure head on the piezometer at point A will be equal to point 1. Meanwhile, the pressure head on the piezometer at point D will be the same as the height of the pressure at points 2, point 3 and, point 4.

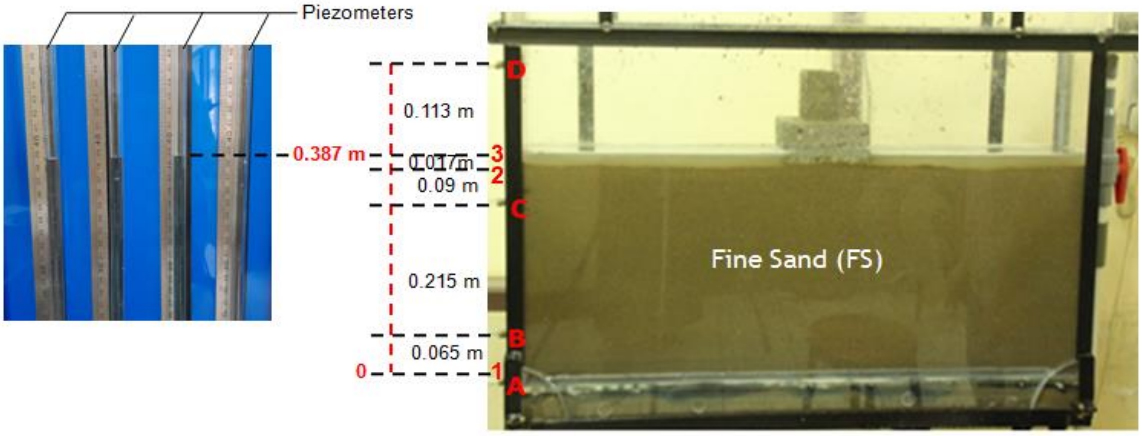

Fig. 2 FS scenario (without the upward flow) [13]

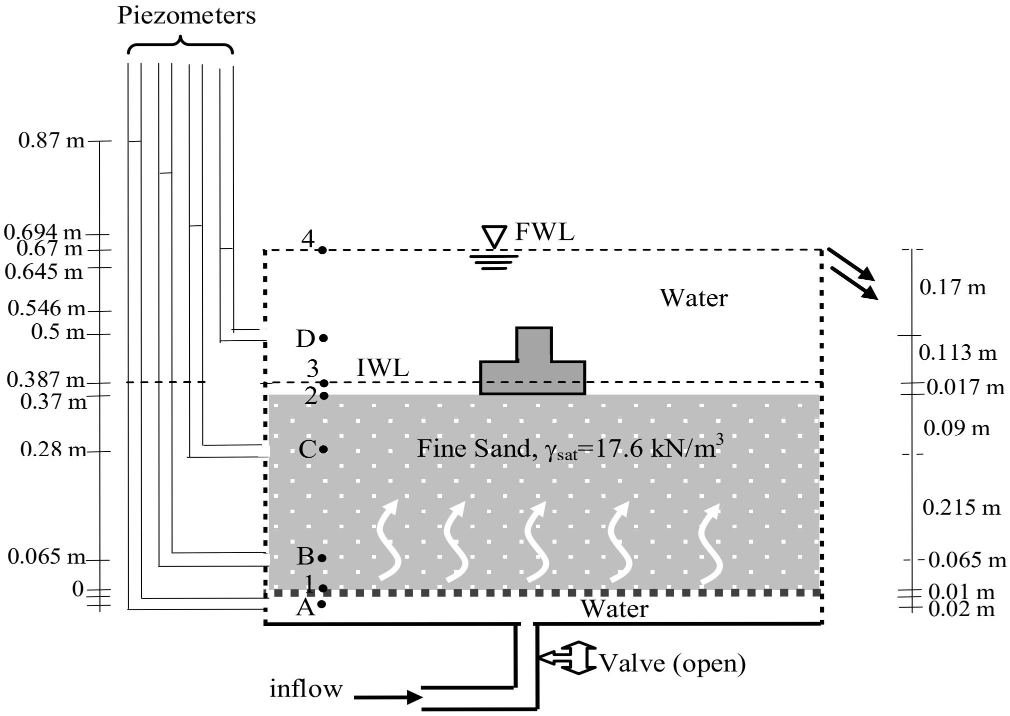

Fig. 3 FS scenario (with the upward flow)

In the CS-MS scenario, the tank is filled with two layers of sand fraction, namely coarse sand (CS), which is above the medium sand-fraction (MS), as shown in Fig. 4. Similar to the FS Scenario, the tank is first filled with water to a certain height. Set the water level for each piezometer to equal the water level in the tank. Then put medium sand with a height of 29 cm and coarse sand with a height of 10 cm into the tank. Set the initial water level to 2 cm above the ground level or 41 cm from the bottom of the experimental tank. Then, open the flow meter valve gradually and adjust the water flow until it flows upward (Fig.5). Like the FS scenario, the water level in the piezometer at point A will be the same height as the water level at point 1 because there are no porous media (in this sand) at both points, so there is no head loss. To get the pressure head at point 2 which is in the interface area (slightly below the coarse sand), linear regression is used. The pressure head on the piezometer D will be the same as the pressure heads at point 3, point 4, and point 5.

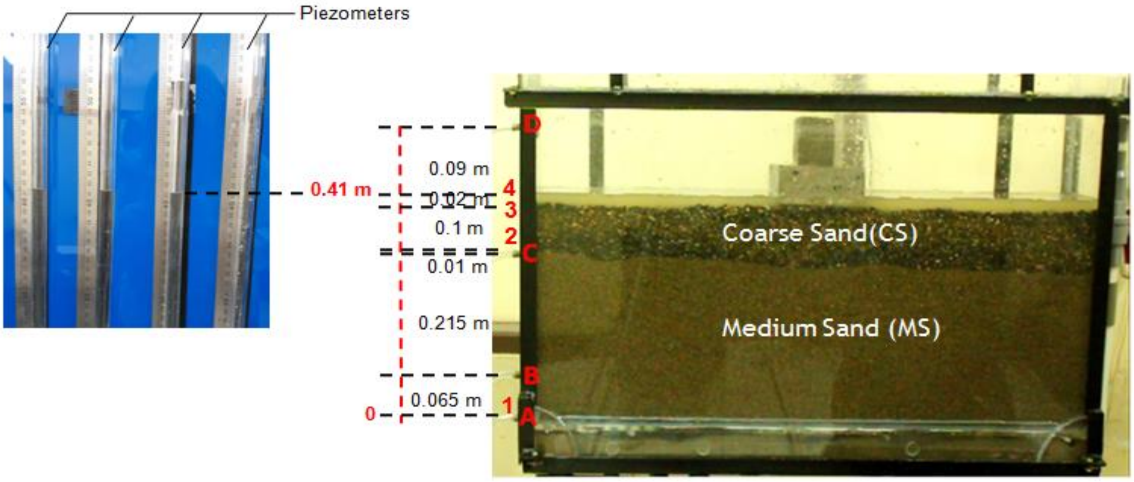

Fig. 4 CS-MS scenario (without the upward flow) [13]

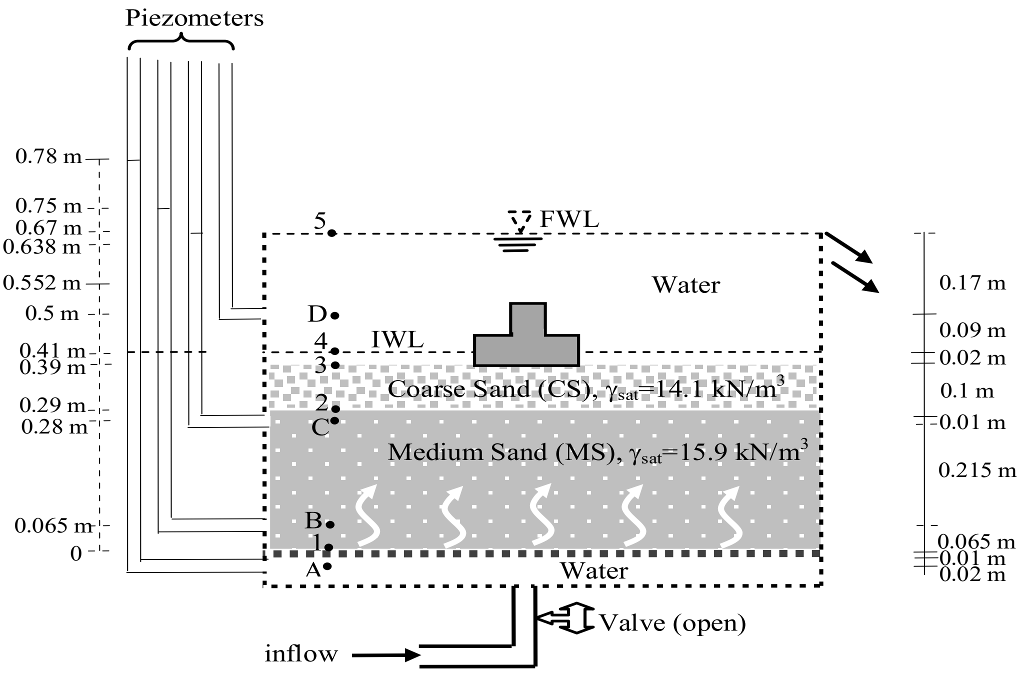

Fig. 5 CS-MS scenario (with the upward flow)

Record the increase of pressure head in the piezometer measuring point A, the piezometer measuring point B, and the piezometer measuring point C every 10 seconds. Then, calculate and plot the total stress, pore-water pressure, and effective stress to the depth of upward infiltration of the soil layer.

3. RESULTS AND DISCUSSION

The total stress, pore-water pressure, and effective stress at each depth due to the upward flow of water can be seen in Figs. 6-9, respectively. The results of observations during the test in the FS scenario show that the upward flow of water carries sand particles moving up so that boiling happens. The occurrence of boiling can also be demonstrated by increasing the pore-water pressure continuously over the total stress value at each depth (Fig. 6). Consequently, the effective stress decreases (Fig. 7). In the FS scenario, the sand boiling occurs very quickly, where the effective stress reaches zero in 10 seconds at a depth of 0.12 m. The effective stress decreases and becomes zero because the flow velocity has reached a critical value to lift the sand particles.

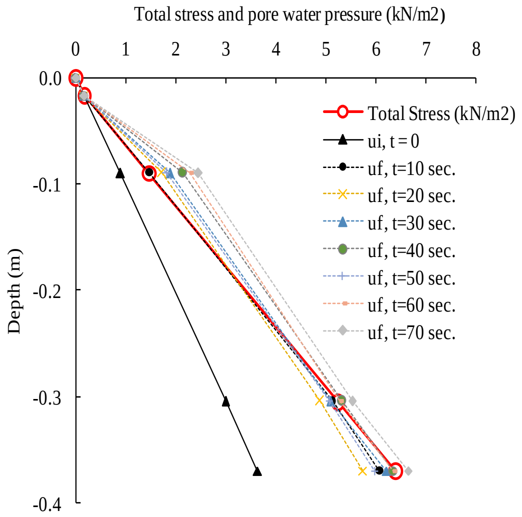

Fig. 6 The total stresses and pore-water pressures each depth due to the upward flow on FS scenario

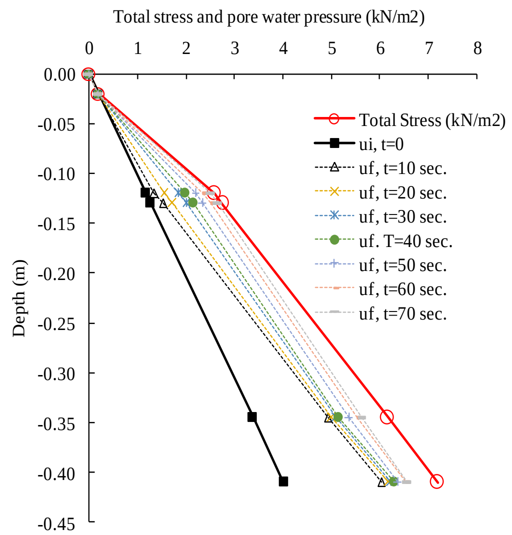

Fig. 8 The total stresses and pore-water pressures each depth due to the upward flow on CS-MS scenario

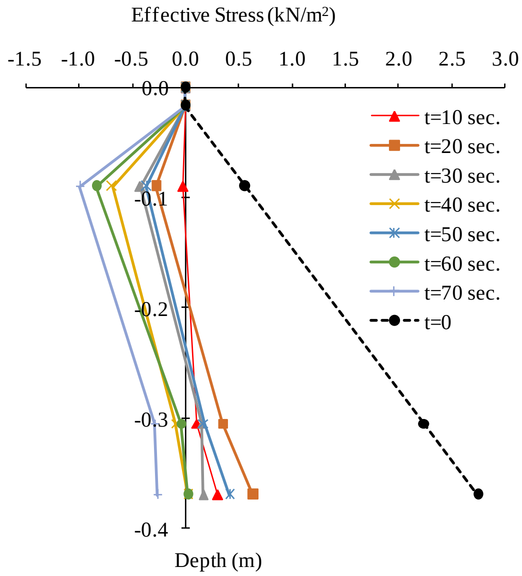

Fig. 7 The effective stresses of each depth due to the upward flow on FS scenario

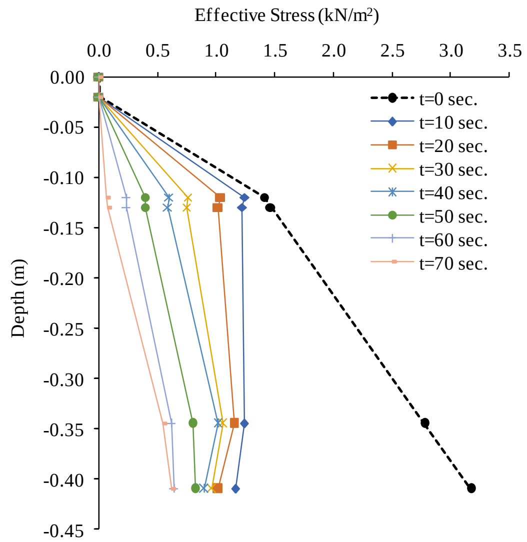

Fig. 9 The effective stresses of each depth due to the upward flow on CS-MS scenario.

The observations based on the CS-MS scenario show that there is no boiling due to the upward flow. Figure 8 shows that the upward flow of water causes an increase in pore-water pressure but does not exceed the total stress value, so the effective stress will never reach zero (Fig. 9). This is because the net weight of the coarse particles is greater than the seepage force of water. The upward flow of water does not carry sand particles that come from under coarse sand. This proves that adding coarse sand to medium sand can prevent boiling.

Figs. 10 and 11 show the relationship between time and pore-water pressure at t = 0 (without the upward water-flow) and t > 0 (with the upward water-flow), respectively. For the FS scenario (Figure 10), when t = 0, the pore pressure at point 3 is equal to zero and continues to increase linearly up to point 1 with the pore-pressure value equal to 3.63 kN/m^2. For the CS-MS scenario (Fig. 11), when t = 0, the pore-pressure value at point 4 is also zero and increases linearly up to point 1 with a pore-pressure value equal to 4,022 kN/m^2. The difference in pore-pressure value at point 1 in the two scenarios is due to the difference in depth under review. The pore-water pressure that occurs in the absence of an upward flow of water is called hydrostatic pressure. When t > 0, the upward flow of water is given, the pore-water pressures increase at point 1, point B, and point C for FS scenario, and an increase in pore pressure also occurs at the point 1, point B, point C and point 2 for CS-MS scenario. While at the points 2 and 3 (FS scenario) and points 3 and 4 (CS-MS scenario), the pore pressure is constant. In the FS scenario, the increase in pore-water curve from t = 0 to t = 70 seconds at the point 1, point B, and point C shows the value that increases irregularly. In contrast to the CS-MS scenario, at the point 1, point B, and point C (medium sand), there is a significant increase in pore-water pressure from t = 0 to t = 10 seconds, then at t = 10 seconds to t = 70 seconds of increase. Pore-water pressure is not too large, where the curve is more gentle and linear. At point C and point 2 (coarse sand), the curve is more stable and tends to be linear, starting from t = 0 to t = 70 seconds. From Fig. 11, it can be seen that the addition of coarse sand significantly affects the pore pressure value.

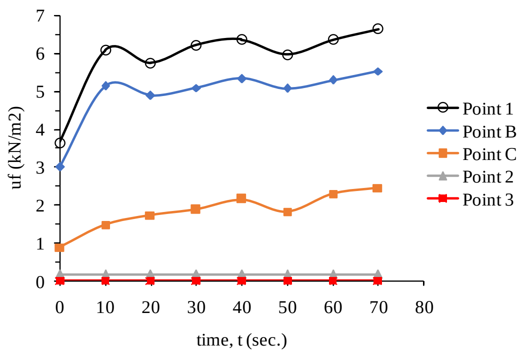

Fig. 10 Variation in time versus pore pressure in the FS scenario

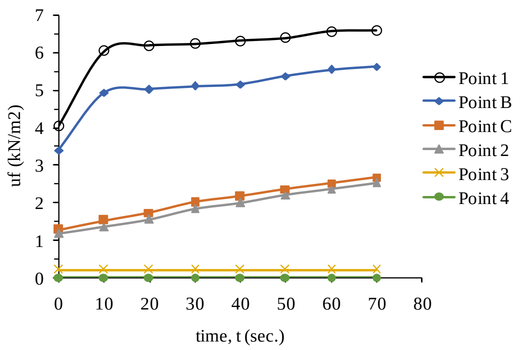

Fig. 11 Variation on time versus pore-water pressure in CS-MS scenario

Effective stress in the FS scenario (Fig. 12) decreased faster than in the CS-MS scenario. From Fig. 12, it can be seen that the effective stress is equal to zero occurring at the 10th second. This indicates that boiling has occurred. Meanwhile, in the CS-MS scenario (Fig. 13), the effective stress is never zero from t = 0 to t = 70 seconds. This is because the addition of coarse sand causes the seepage force to be smaller.

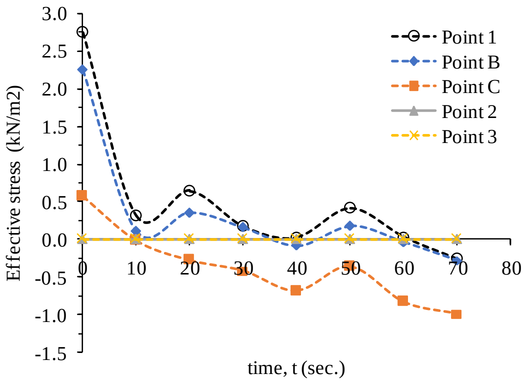

Fig. 12 Variation in time versus effective stress in FS scenario

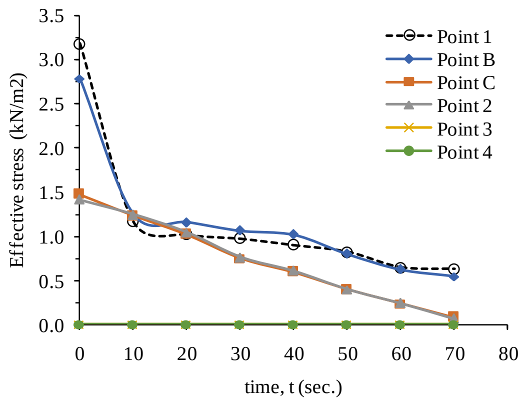

Fig. 13 Variation in time versus effective stress in CS-MS scenario

4. CONCLUSIONS

In this study, it can be concluded that the sand fraction is very influential on the occurrence of the boiling phenomenon. In the saturated fine sand-fraction, boiling occurs faster, where the upward flow of water causes pore water increase and the effective stress decreases to zero in 10 seconds at a depth of 0.12 m. Meanwhile, the combination of the saturated coarse sand-fraction above saturated medium sand-fraction with the upward flow of water, the boiling does not occur. The addition of a coarse sand-fraction can reduce pore-water pressure and increase the effective stress so that the soil remains stable and can prevent the boiling phenomenon at a specific flow rate.

5. ACKNOWLEDGMENTS

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