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STABILITY OF UNDERGROUND CAVITY SUBJECTED TO SEISMIC MOTION

P. Pokhrel(1), J. Kuwano(2)

(1) *PhD Candidate, Saitama University, prpokhrelelx@gmal.com*
(2) *Professor, Saitama University, jkuwano@mail.saitama-u.ac.jp*

Abstract

Cave-in is often caused by hidden cavity in the subsurface of the ground, which is triggered by internal erosion of soil. In recent years, collapse of a sinkhole or a hidden cavity is widely observed on the road pavement in urban area due to the crack of buried pipe for example. Damage of buried pipe mainly occurs due to the aging effect of pipe or the ground motion caused by the large earthquake. In addition, the number of underground cavities in the road pavement in Tokyo area of Japan increased after the gigantic 2011 Tohoku earthquake. Limited researches have been made on the effect of ground motion on underground cavities. This kind of problem is found widely all over the world. In this study, a series of shaking table tests on a cavity in the model ground was carried out to investigate the effect of earthquake ground motion on the stability of subsurface hidden cavity. A soil chamber having an opening in a base was used to form a cavity in the model ground for the experiments. A subsurface cavity was formed above the opening at the base of a soil chamber by water supply and drain. Then, a stepwise increase in seismic motion was applied using a shaking table and the stability of the underground cavity was investigated. It was observed that the surrounding soil of the cavity subsided and was deformed by the earthquake motion after the partially drainage. Furthermore, with the increase in amplitude of the ground motion, shear cracks formed in the soil layer above the cavity and collapse of the arching action were observed.

Keywords: underground cavity; stability; earthquake; arching

1. Introduction

Cave-in is often caused by hidden cavity in the subsurface of the ground, which is triggered by internal erosion of soil. In recent years, collapse of a sinkhole or a hidden cavity is widely observed on the road pavement of the urban city. In most of the urban city, buried pipes are located in the subsurface of the road pavement. Damage of such deteriorated sewer pipe cause hidden cavity or cave-in and local subsidence of the road pavement [1]. Except aging, large earthquake also can cause the damage of buried pipes located in the subsurface of the road pavement. The number of the underground cavities in the road pavement in Tokyo area of Japan increased after the gigantic 2011 Tohoku earthquake [2, 3]. Although the mechanism of formation of cavity have been widely investigated, limited research has been made on the effect of ground motion on underground cavities. So that, it is important to understand the effect of seismic motion on the stability of underground cavity. In this study, the mechanism of subsurface cavity collapse in gap graded sand due to stepwise increase in seismic motion was studied.

2. Experimental Setup and Test Procedure

2.1 Apparatus

A model ground was prepared in a soil chamber of size 67 cm long, 10 cm wide and 30 cm high as shown in Fig.1. Water was supplied at constant water head from the bottom of the soil chamber to saturate the model ground. A small rectangular box having small holes covered with porous material was placed at the one side of the model ground to monitor the water level in the ground. Water level in the model ground was controlled by adjusting the height of the water tank. After maintaining the specified water level, a slit at the base of the soil chamber was opened where water and soil flowed out form the opening and cavity was formed. Then, a stepwise increase in seismic motion was applied using a shaking table. A video camera was connected to the soil chamber from the front side to observe the behavior of the cavity and surrounding soils. In addition, three accelerometers were used to measure the input acceleration applied.

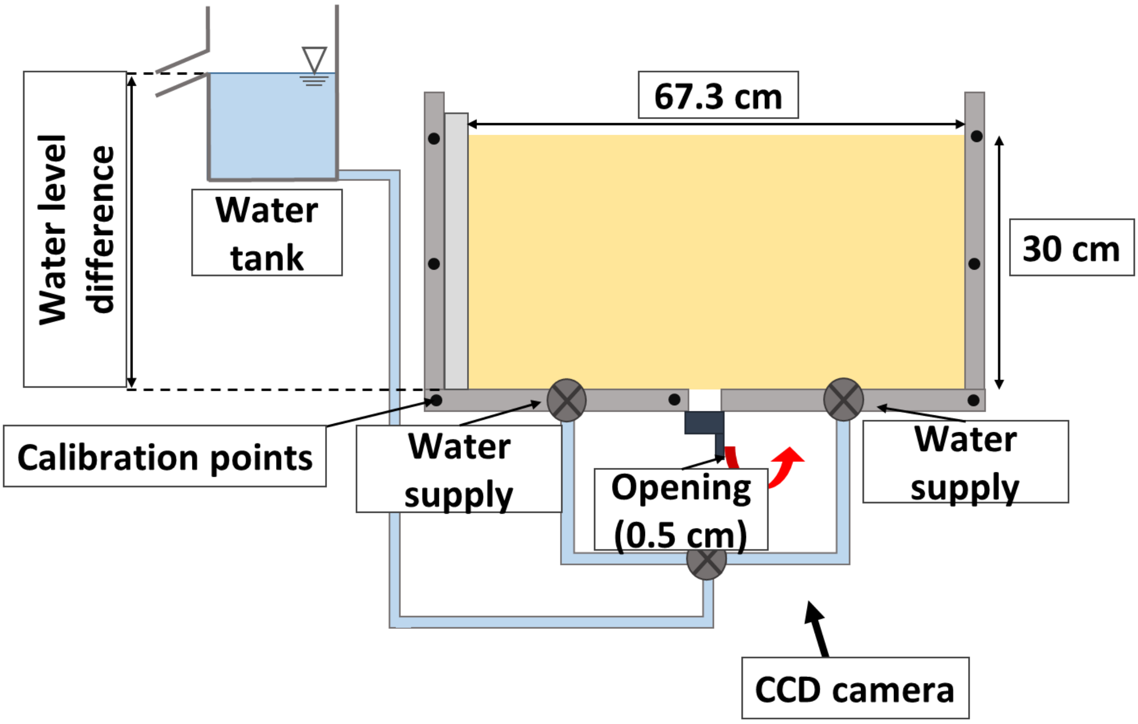


Fig. 1 – Schematic diagram of test apparatus.

2.2 Tested material

Uniform silica sand No.5 having median grain size (D_{50}) of 0.6 mm was used to prepare the model ground. The particle size distribution of the used material is shown in Fig.2. A layers of 2 cm thick dry sand were placed manually by a scoop in the soil chamber at a relative density of 50%. The corresponding dry density of soil at 50% relative density is 1.384 g/cm3. The maximum and minimum void ratios of the silica sand No. 5 are 1.04 and 0.67 respectively.

2.3 Test procedure and experiment case

A model ground of 67 cm long, 10 cm wide and 30 cm high was made in an acrylic soil chamber having an opening of 5 mm slit at the base. Model ground was saturated by supplying water from the bottom of the soil chamber at constant water head of 60 cm. When the model ground was fully saturated, the water level of the model ground was lowered to the specified level by adjusting the height of water supply tank. In this study, water level of the model ground was made 10 cm from the bottom of the model ground. A slit of the soil chamber was opened after maintaining the specified water level. Sand and water flowed out from the opening and a cavity was formed just above the opening at the base of a soil chamber. Then, a stepwise increase in seismic motion was applied on the model ground using a shaking table as shown in Fig.3.

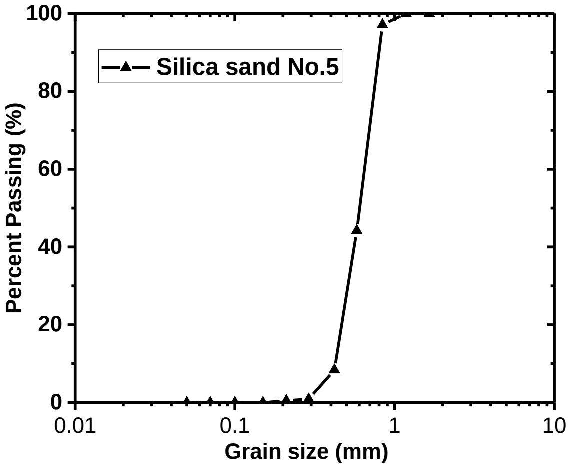


Fig. 2 – Particle size distribution of tested material.

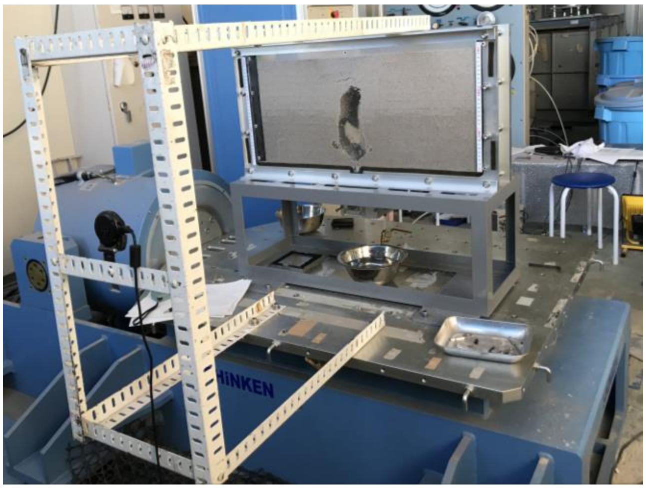


Fig. 3 – A soil chamber on the shaking table.

In this study, two experiments with different drainage conditions were conducted to observe the behavior of cavity under seismic motion. Partially and fully drained model grounds were made to model the possible ground water tables during shaking. The sand started to deform just after the opening of the slit and was flowed out very quickly within very short period. So that, the amounts of soil flowed out during the fully and partially drained condition were almost equal. In case of fully drained condition, shaking was applied after the 24 hours of drain of water from the model ground. But shaking was applied after the 10 minutes of drain in case of partially drained condition. The experiment case and conditions were presented in Table 1.

2.4 Seismic motion

In this study, a stepwise increase in sinusoidal wave seismic motion with frequency 5 Hz was applied using shaking table and the stability of underground cavity was investigated. The initial input acceleration was set to 100 gal and step wise increased with the increments of 100 gal after each step until the failure of cavity. The duration of shaking in each step was set to 10 sec. Fig. 4 shows the accelerometer data of the input base acceleration.

Table 1 – Experiment case

Test No.	Specified water level (cm)	Drain condition	Cavity size		Overburden Thickness (cm)
			Height (cm)	Width (cm)	
1	10	Full (24-hours)	20.22	8.29	9.78
2	10	Partial (10 minutes)	19.19	7.01	10.81

Table 2 – Specifications of seismic motion

Condition	Unit	Value
Direction	-	Horizontal
Frequency of sinusoidal motion	Hz	5
Minimum acceleration	gal	100
Step increment value of acceleration	gal	100
Duration of shaking per step	sec	10

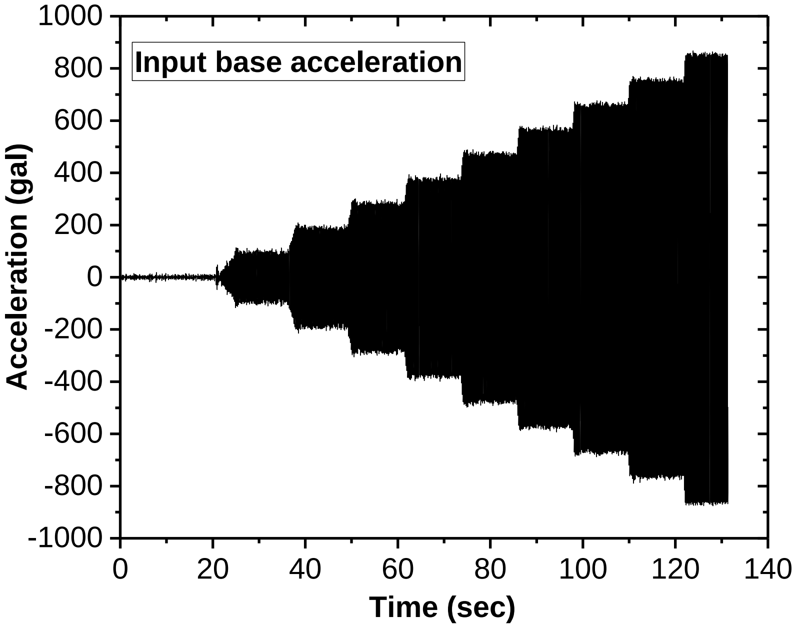


Fig. 4 – Input base acceleration measured from accelerometer.

3. Experimental results and discussion

3.1 Experiment case 1 (Fully drained condition)

A cavity was formed above the opening at the base of soil chamber after opening the slit as shown in Fig.5. An arch was formed at the top of cavity which supports the overburden sand layer. The cavity elongated along the vertical direction like a shape of vertical ellipse. The cavity height and width were about 20 cm and 8 cm respectively. The amount of soil and water flowed out from the model ground to form the cavity was around 2285 gm and 4715 gm respectively. The tentative volume of the cavity calculated from the drained soil was about 2240.65 cm^3. In this case, shaking was applied after the 24 hours of drainage of water from the model ground. So, assumed that there is no effect of water saturation on the stability of cavity.

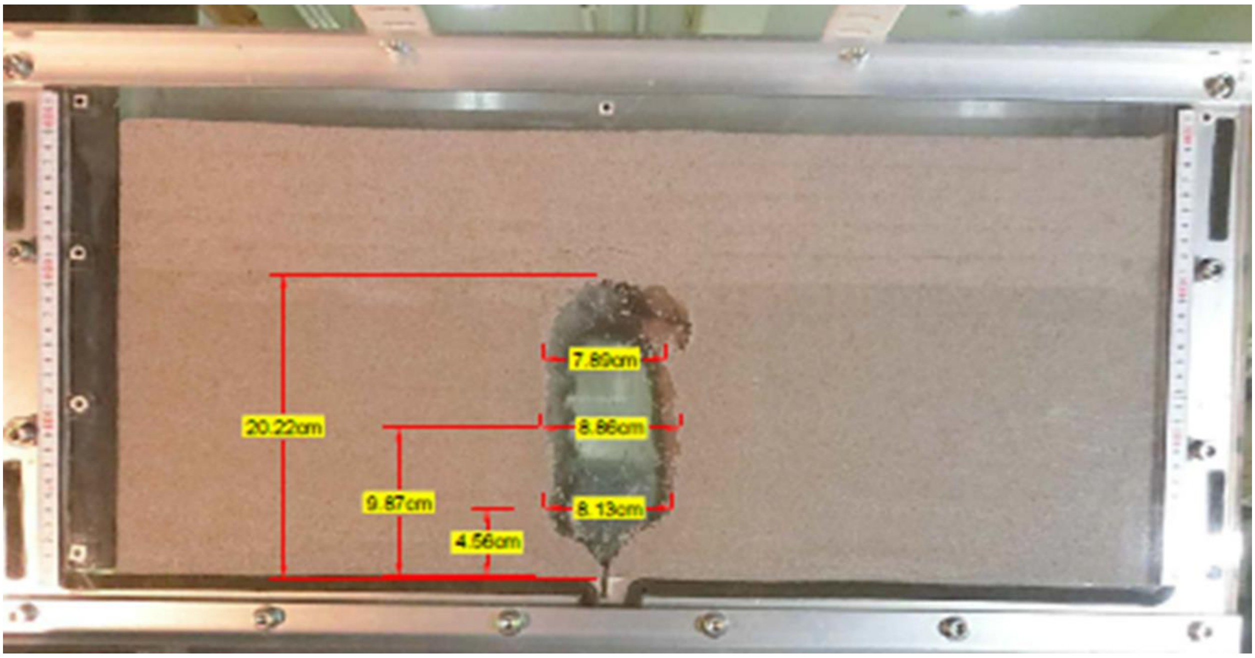
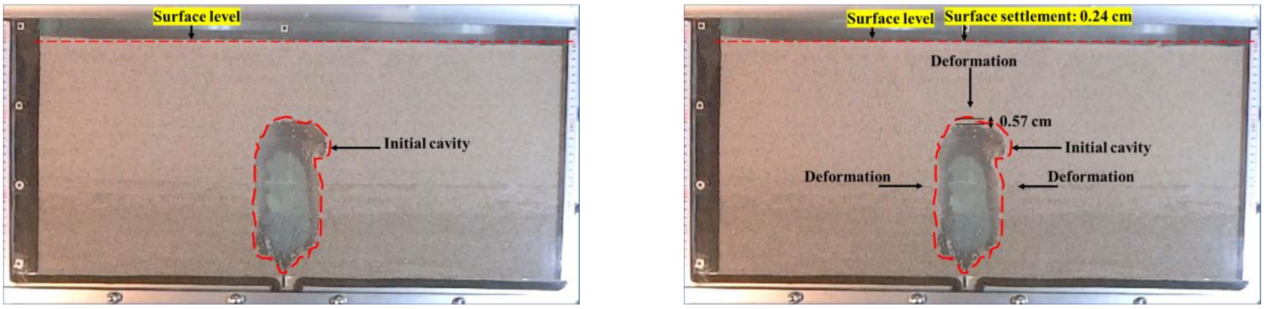


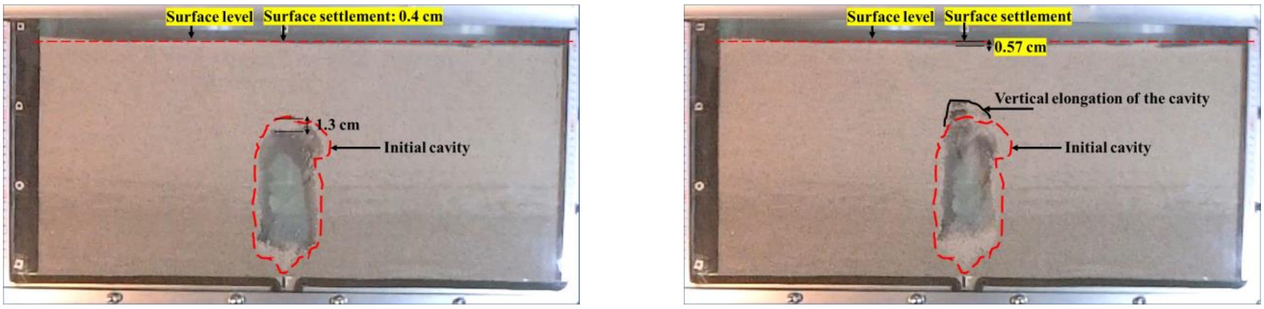
Fig. 5 – A cavity with dimension (Fully drained condition).

A stepwise increase in sinusoidal wave seismic motion was applied to the model ground having subsurface cavity. The initial input acceleration was set to 100 gal and step wise increased with the increments of 100 gal after each step until the failure of cavity. Fig.6 shows the behavior of cavity at different level of input acceleration. No surface settlement and no deformation of soil was observed until the input acceleration of 1000-gal shown in Fig.6 (a). So, the subsurface cavity and its arch shows stable behavior up to the acceleration 1000-gal. The deformation of soil from the side wall and top of the cavity was observed at the acceleration of 1100-gal as shown in Fig.6 (b). The size of the cavity slightly decreased from initial size due to the deformation of soil towards cavity. The deformation of soil just above the cavity was higher than the surface settlement shown in Fig.6 (c).

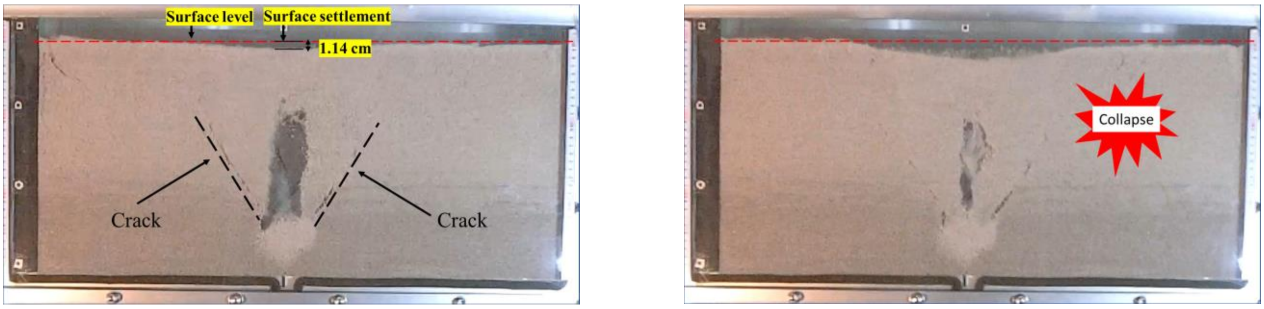
The vertical deformation of soil was increased with the corresponding increase in seismic motion and cause the instability of arch of the cavity. So, vertical expansion of the cavity was observed in 4th sec of the input acceleration of 1200-gal shown in Fig.6 (d). The surface settlement of the model ground was rapidly increased after the vertical expansion of cavity. In addition, increase in surface settlement caused increase in instability of underground cavity and vertical crack formation was occurred on the side wall of the cavity shown in Fig.6 (e). Finally, the arch of the cavity was unable to support the structure and the cavity was as collapsed in the 5th sec of the input acceleration of 1200-gal shown in Fig.6 (f).



(a) 1000-gal (b) 1100-gal



(c) 1200-gal (3 sec) (d) 1200-gal (4 sec)



(e) 1200-gal (5 sec) (f) 1200-gal (5 sec)

Fig. 6 – Behavior of cavity under seismic motion (Fully drained condition).

3.2 Experiment case 2 (Partially drained condition)

A cavity with similar shape and size to the experimental case 1 was formed after opening the slit shown in Fig.7. An arch to support the cavity was formed at the top of the cavity. The cavity height and width were about 19 cm and 7 cm respectively. The amount of soil and water flowed out from the model ground to form the cavity was around 2382 gm and 3231 gm respectively. Most of the sand from the deformed part flowed out quickly with water through the opening. So, the amount of soil flowed out to form the cavity was almost equal in amount in both experimental cases which means the volume of the cavity is almost same. Difference between the amount of drained water in fully drained case and partly drained case is considered to be the water remained in the ground. Therefore, the lower part of the ground could be saturated. In this case, shaking was applied after the 10 minutes of drain of water from the model ground.

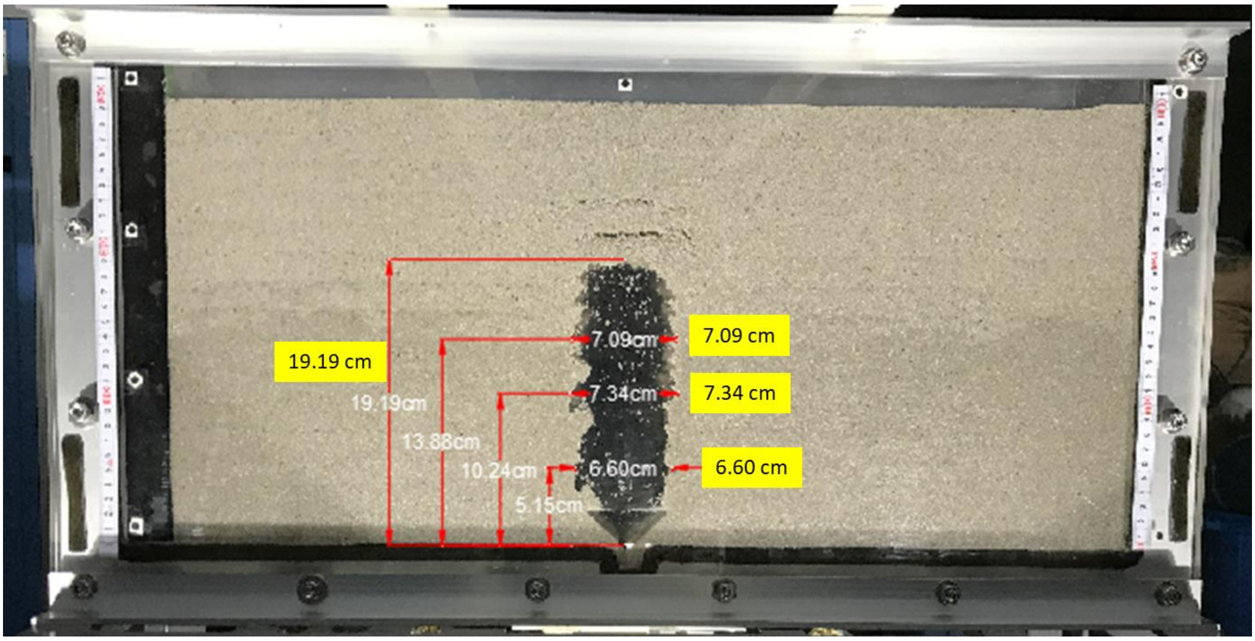
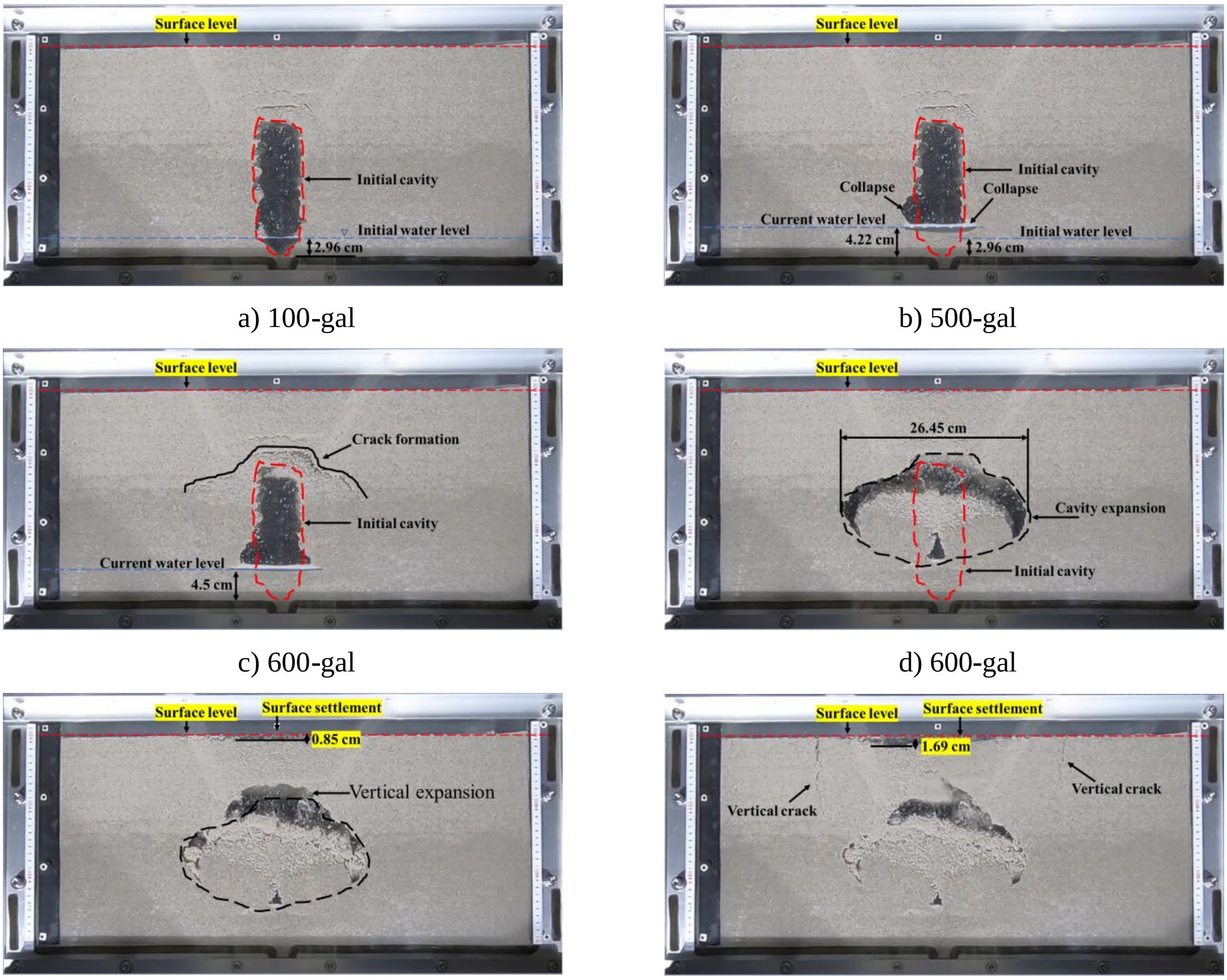


Fig. 7 – A cavity with dimension (Partially drained condition).

Like the experimental case 1, a stepwise increase in sinusoidal wave seismic motion was applied to the model ground having subsurface cavity. The initial input acceleration was set to be 100 gal and step wise increased with the increments of 100 gal after each step until the failure of cavity. Fig.8 shows the behavior of underground cavity subjected to the different input acceleration. This is the case of partially drained condition; some amount of water was remained at the bottom of the cavity before shaking shown in Fig. 8 (a). Initially, the remained water level on the model ground was 2.96 cm from the bottom of the model ground. It means, the soil grains below the water level of the model ground was in fully saturated condition. When the horizontal shaking was applied to the model ground, the water fluctuated like wave and hits the side wall at the bottom of the cavity. In addition, the fluctuation of water cause to increase the saturation level of sand just above the water level. So, the sand just above the water level lost their strength and collapsed at the input acceleration of 500-gal shown in Fig.8 (b). Some parts of the bottom side of the cavity was collapsed and sand deposited at the bottom of the cavity. Probably, the collapse of sand at the bottom side of the cavity is due to the liquefaction of sand. Due to the deposition of sand at the bottom of the cavity the water level on the model ground was increased to 4.22 cm.

The deposited amount of sand at the bottom of the cavity was increased with the increase in seismic motion. The sand grains at the bottom side wall of the cavity lost their strength and unable to support the arch of the initial cavity. So, the crack formation at the side wall of the cavity was observed at the seismic motion of 600-gal shown in Fig.8 (c). The initial cavity was unstable and propagated to the horizontal direction at the input acceleration of 600-gal shown in Fig.8 (d). The shape of the cavity looks like horizontal ellipse after the horizontal expansion. The diameter of the arch of the cavity was increased after the expansion of cavity which causes the instability of the subsurface cavity. The surface settlement of the model ground was rapidly increased after the expansion of cavity. The sand at the top roof of the cavity was collapsed at the input acceleration of 800-gal shown in Fig.8 (e). Probably, the top roof collapse occurred due to the rapid increase in surface settlement. With the increase of surface settlement, the shear cracks generated vertically shown in Fig.8 (f) and the cavity was collapsed at the input acceleration of 900-gal.



a) 100-gal

b) 500-gal

c) 600-gal

d) 600-gal

e) 800-gal

f) 900-gal

Fig. 8 – Behavior of cavity under seismic motion (Partially drained condition).

4. Conclusions

The effect of seismic motion on the subsurface cavity was studied. Two experiments were conducted with considering the condition of different duration of drain. Following conclusions were drawn from the study.

The stability of the subsurface cavity subjected to seismic motion is greatly affected by the presence of amount of water around the cavity. The stability of the underground cavity decreased with the increase of water level at the bottom of the cavity.

The failure mechanism of subsurface cavity depends on the presence of water level in the model ground. In the case of fully drain condition, shear cracks generated vertically before the collapse of the cavity. But in the case of partially drain condition, cavity propagate in the horizontal direction, widen the arch of the cavity and finally failure occurred. Probably, the expansion of the cavity is due to the liquefaction in the sand around the bottom side of the cavity.

5. References

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