Mechanism of sand eruption from liquefied ground through gap of pavement and subsurface cavities

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ABSTRACT

Significant number of subsurface cavities was found in the liquefied ground after the 2011 Great East Japan earthquake. Using the results of the radar exploration conducted in Urayasu-city, Shinkiba-area and Narashino-city, all of those suffered from damage by the ground liquefaction, characteristics of subsurface cavities are investigated. It was found that cavities tended to form near man-holes and joints in pavement. Size and shape of the cavities are larger and thinner compared to those of cavities observed in the non-liquefied ground. A series of model tests was conducted in order to understand the mechanism of sand eruption and underground cavity formation when liquefaction occurs. Liquefaction and sand boiling was simulated in the model test by the upward seepage flow. With the increase in the hydraulic gradient, sand grains initially moved horizontally and then vertically, causing disturbance and loosening in the ground. The flow rate at the gap to cause sand eruption increased with the increase in the grain size. The hydraulic gradient causing sand eruption was much higher than the critical hydraulic gradient in all the test cases.

Keywords: liquefaction, sand eruption, grain size, pavement, subsurface cavity

1. INTRODUCTION

Damage of roads was widely found in Tokyo Bay area, which suffered from damage by liquefaction, after the 2011 Great East Japan Earthquake with M=9.0. Ground penetration radar exploration from a specially equipped car running at the maximum speed of 60 km/h was carried out in Urayasu City, Shinkiba area and Narashino City for the total distance of 355 km. 709 hidden subsurface cavities were found by the radar and their characteristics were investigated (Sera et al., 2013 & 2014). Locations of liquefaction subsurface cavities found by the investigation are shown in Fig.1.

Cavities under roads are not always caused by ground liquefaction as described in this study. Ordinary cavities are caused by other factors such as breakage of sewer pipes in ordinary conditions. Subsurface cavities are formed when soil particles or subbase materials are washed away into the pipe. Cavities thus formed

![Fig. 1. Locations of subsurface cavities caused by ground liquefaction](http://doi.org/10.3208/jgssp.JPN-111)
Table 1. Summary of subsurface cavity investigation.

|                        | Ordinary cavities | Liquefaction cavities |
|------------------------|-------------------|-----------------------|
| Occurrence ratio       | 0.22 cav./km      | 1.56 cav./km          |
| Average                |                   |                       |
| Area                   | 1.68 m²           | 2.38 m²               |
| Thickness              | 0.20 m            | 0.13 m                |
| Depth of cavity ceiling| 0.38 m            | 0.37 m                |

expands with time, and when the strength of the pavement is not enough, a sudden cave-in finally occurs. Table 1 compares features of ordinary cavities and liquefaction cavities found in Tokyo Bay area. It is seen that the cavity occurrence ratio in liquefied areas was 7 times larger than that in the ordinary condition. The cavity occurrence ratios in the liquefied area are 1.06 cavities/km for arterial roads, 1.30 cavities/km for sub-arterial roads and 2.07 cavities/km for community roads. Such difference in the cavity occurrence ratios is probably due to the difference in density of buried pipes and in the pavement structures among the roads. Many of these cavities were thin, large in area occasionally more than 10 m², and made by erosion at the road subbase leaving undulation at the cavity bottom according to the borehole camera pictures as shown in Fig. 2 for example. Locations where many cavities were found coincided with large scale sand boiling, subsidence or cave-in of the road surface. The cavities were formed especially along pavement joints and around manholes, where there were gaps of pavement, and around buried sewer line structures.

In this study, a series of model tests was carried out in order to understand the mechanism of sand eruption from the liquefied ground through the gap of pavement and the formation of the cavity beneath the pavement caused by liquefaction. Penetration resistance was also measured to evaluate the ground loosening created around the cavities.

2 TEST OUTLINE

A model ground was prepared in a soil chamber of 30cm long, 8cm wide and 20cm high, as shown in Fig. 3. Water was supplied from the bottom of the model ground simulating upward seepage flow caused by liquefaction. Hydraulic gradient of the water supply could be adjusted by the elevatable water tank connected to the bottom of the soil chamber. Surface of the model ground was covered by an acrylic lid having a 2mm wide opening, from which boiling sand could be erupted. Water table was adjusted by the drainage at the side wall of the chamber.

Water was slowly penetrated and the model ground was saturated in advance. Then the water tank was elevated at 5 cm intervals to apply additional hydraulic gradient to generate liquefaction in the ground. Sand grains lost effective stresses and upward seepage flow caused sand boiling from the opening in the lid. After the test, water in the model ground was drained for...
Table 2. Test conditions and sand eruption conditions.

| Case No. | Silica sand | $D_{50}$ (mm) | Opening at x(cm) | Pipe center (x, z) | Sand eruption $\Delta h$ (cm) | Flow rate (cm/s) |
|----------|-------------|---------------|------------------|--------------------|-----------------------------|-----------------|
| 1-1      | No. 7       | 0.131         | 0                | None               | 25                          | 0.660           |
| 1-2      | No. 7       | 0.131         | 0                | (0, -9)            | 25                          | 0.660           |
| 1-3      | No. 8       | 0.080         | 0                | None               | 15                          | 0.539           |
| 1-4      | No. 5       | 0.360         | 0                | None               | 55                          | 2.630           |
| 1-5      | No. 7       | 0.131         | No lid           | None               | 60                          | ---             |

The opening is at $(x, z) = (0, 0)$. Pipe diameter is 6 cm.

more than 24 hours and penetration resistance was measured at five locations using a 3mm diameter needle.

In total, five tests were conducted as shown in Table 2. Silica sand No.7 was used for the material of the model ground. It has mean diameter of 0.131 mm. Maximum and minimum void ratios are 1.24 and 0.74 respectively. Loose sand ground, relative density of approximately 75%, was prepared by the air-pluviation. The permeability of the ground was around 3.83 $\times$ 10$^{-3}$ cm/s. Silica sand No.5 ($D_{50}=0.360$ mm, $k=7.17$ $\times$ 10$^{-3}$ cm/s) and silica sand No.8 ($D_{50}=0.0799$ mm, $k=3.79$ $\times$ 10$^{-3}$ cm/s) were also used to see the effect of grain size on the sand eruption. Colored sand was put on the surface and in front of the ground, as shown in Fig. 3, for the observation of sand grains’ movement. Regarding silica sand No.7, two extra cases were conducted, i.e. Case 1-5 in which the acrylic lid was not used to observe the effect of pavement on sand eruption, and Case 1-2 in which a model pipe was buried.

3 RESULTS AND DISCUSSION

In the Cases 1-1 to 1-4, in which the pavement model of acrylic lid with a 2mm wide opening at the center was set on the ground surface, with the increase in the hydraulic gradient, sand grains initially moved horizontally over the ground surface causing erosion at the ground surface and undulation at the cavity bottom as shown in Fig. 4, which is similar to the subsurface cavities observed in the liquefied area. With the further increase in the hydraulic gradient, sand grains then moved vertically through the gap of pavement model and sand eruption occurred. The flow rate at the gap to cause sand eruption was measured by measuring the amount of drained water per unit time. They are shown in Table 2.
Test conditions were the same in the Cases 1-1, 3 and 4 except the grain sizes. As seen in Table 2, flow rate at the gap to cause sand eruption increased with the increase in the grain size. Pidwirny (2006) and Yee (2012) showed the relationship between stream flow velocity and particle erosion, transport, and deposition as shown in Fig. 5. Measured flow rates to cause eruption of three sands with different grain sizes are plotted in Fig. 5. It is seen that the data are located at the boundary between “Transport” and “Deposition”. Flow rate at the opening should be high enough to bring out sand grains through the gap of pavement.

When a buried pipe was located near the opening in the Case 1-2, water flow path seemed to concentrate around the buried structure, and finally boiling or upward turbulence flow was observed as shown in Fig. 6. It caused serious ground disturbance and loosening as compared to the Case 1-1. However, the head difference to cause sand eruption was same and 25 cm in both cases as seen in Table 2. The head difference of 25 cm is 1.34 times as large as 18.6 cm to cause critical hydraulic gradient.

When the ground surface was not covered with the pavement model in the Case 1-5, the model ground started to inflate almost uniformly at the head difference of 30 cm which is 1.61 times as large as the critical value. However, further increase in the head difference of 60 cm (3.22 times as large as the critical value) resulted in the boiling or upward turbulence flow as shown in Fig. 7. It is to be noted that in all the cases the sand ground did not show boiling at the critical hydraulic gradient, though the ground liquefied with zero effective stress.

4 CONCLUSIONS

A series of model tests was conducted to simulate sand eruption and subsurface cavity in the liquefied ground. Following conclusions were drawn from the study.

The cavity occurrence ratio in liquefied areas was 7 times larger than that in the ordinary condition. Many of these cavities were thin, large in area, and made by erosion at the road subbase leaving undulation at the cavity bottom.

Horizontal movement of sand grains was observed in the early stage of sand boiling. When larger hydraulic gradient was applied, vertical movement of sand occurred.

Flow rate at the opening should be high enough to bring out sand grains through the gap of pavement. The sand ground did not show boiling at the critical hydraulic gradient, though the ground liquefied with zero effective stress.

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