Collapse risk evaluation of subsurface cavities in pavements of full scale test roads

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ABSTRACT

In order to solve the problem of subsurface cavities in urban areas, industry, government and academia carried out collaborative research over 2018-2020. In this joint research, analysis of existing cavity data, laboratory model experiments, numerical analysis, and full-scale field test, monitoring of the cavity in the road, etc. were conducted. In this study, a full-scale test road was constructed with artificial cavities installed to evaluate the risk of collapse in consideration of the road structure. A series of plate loading tests and falling weight deflectometer tests was conducted on the road surface above a cavity to understand the cavity behaviour. A surface wave survey was also conducted to evaluate the wave propagation on and around cavities. It was found to be reasonable to evaluate the collapse risk of subsurface cavities by the ratio of depth and width of cavities, in which the thickness of the pavement should be excluded from the depth.

Keywords: subsurface cavity, road cave-in, internal erosion, full-scale test road.

1. Introduction

As urban cities mature, cavities under roads may generate due to a variety of factors, causing up to 10,000 road cave-in per year recently in Japan. As a measure to prevent road cave-ins, ground-penetrating radar surveys are effective in detecting cavities under the road surface and repairing them before they collapse. The cost is expected to increase further in the future due to ageing infrastructures, which is the main cause of cavities, and the increasingly severe weather in recent years. The establishment of an efficient and rational road maintenance and management system is, therefore, an urgent issue.

Technical issues in the problem of subsurface cavities and cave-ins include, a) difficulty in understanding the underground condition, b) unknown growth rate of cavities and the risk of cave-ins, and c) inability to select the appropriate repair method rationally and efficiently according to the cavity characteristics. Although empirical and qualitative evaluation of the generation and propagation mechanisms of cavities is possible in laboratory tests, the stage has not yet been reached where the growth rate and collapse risk of cavities can be quantitatively evaluated in practice. On the other hand, although cavity exploration and repair are carried out in road management practice, the systematic accumulation, analysis, and effective utilisation of data is far from satisfactory. Therefore, in this study, issues were identified through analysis of existing cavity data, mechanism understanding through laboratory tests and numerical analysis, full-scale field tests, monitoring on the current road, which were integrated and examined in a three-year joint industry-government-academia research project starting in 2018 (Kuwano et al., 2023). The current technical issues related to road cave-ins were organised into three stages, namely cavity investigation, diagnosis, and repair, with the aim of finding solutions for each and proposing an integrated response in conjunction with preventive measures.

Many cases of road cave-in in urban areas are caused by old sewage pipes. With regard to the formation and expansion mechanism of cavities under road surfaces, model experiments have been conducted to reproduce the process whereby soil flows into the damaged part of a buried pipe and creates a cavity in the ground (Kuwano et al., 2010, Mukunoki et al., 2009, Sato and Kuwano, 2015, Kumano et al., 2015, Indiketiya et al., 2019, Kuwano et al., 2019, Karasaki and Kuwano, 2022, etc.). In a series of studies, the relationship between the pattern, formation and growth rate of cavities, loosening, the type of soil, fine-grain content, maximum grain size, relative density, overburden load, extent (aperture width) and direction of damage of buried pipes, groundwater table and groundwater infiltration direction have been discussed. Furthermore, Konishi et al., 2018, Hirako et al., 2019 and Kuwano and Ohara, 2021 examined the bearing capacity of ground with cavities based on the results of cavity formation model experiments. Kawamura and Tsubokawa, 2017 reported the effect of cavities under the pavement on the deflection of Falling Weight Deflectometer (FWD).

In road management practice, road managers in municipalities across the country have evaluated collapse risk of subsurface cavity using cavity ceiling depth and cavity width as parameters, which were established empirically based on the relationship between road surface deformation and cavity size on national roads.

In this study, quantitative assessment of the risk of cave-ins was made, considering the size and location of the cavities and the road structure conditions, by full scale field tests. A surface wave survey was also conducted to evaluate the wave propagation on and around cavities.

2. Cavity behaviour in full-scale test road

A full-scale test road with artificial cavities was constructed to validate the cave-in risk assessment through laboratory experiments and analysis of existing data, as well as to understand the behavioural characteristics of pavements over cavities in multiple patterns of pavement construction.

2.1. Construction of the full-scale test road

2.1.1. Structure of the pavement

A full-scale test road of 30 m long and 6 m wide was constructed in the Saitama University campus as shown in Fig. 1. A cross section of the test road with artificial cavities is also shown.

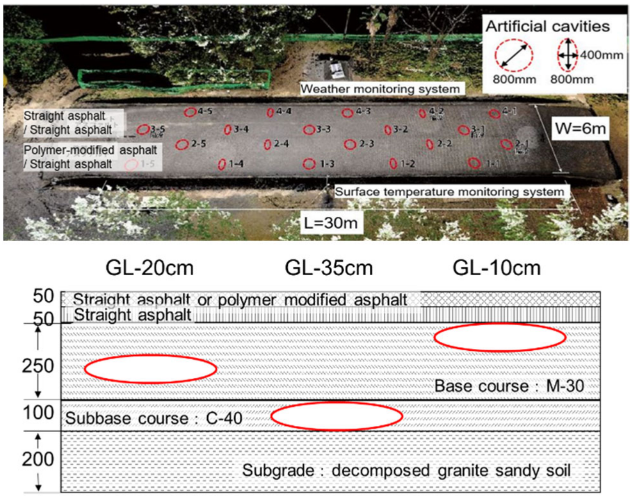

Figure 1. Aerial view of prototype scale test road and cross section of test road with hidden cavities (unit: mm)

The test road consisted of 50mm surface course and 50mm binder course. The surface course was a straight asphalt mixture or polymer modified asphalt mixture, and the binder course was a straight asphalt mixture. Layers below the surface course were 250 mm base course with M-30 graded crushed stones, 100 mm subbase course with C-40 graded crushed stones, and 200 mm subgrade with decomposed granite sandy soil.

As for the occurrence of the cavities observed on the actual road so far (about 5,000 locations), the most frequent occurrence depth was 0.3-0.59 m, followed by 0-0.29 m, with 87% of the cavities being less than 0.6 m, and the area of the cavities was less than 1 m^2 (Koike and Sera, 2012). Considering the size of the test road and the various test conditions for the cavities, the cavities created were based on two types: the largest cavity was 80 cm in diameter and a cavity of about half that size (80 cm x 40 cm: cavity with long and short axis). With regard to depth, three types were used: in the subbase course, in the lower part of upper base course and on the top of the upper base course.

2.1.2. Installation of artificial cavities

Subsurface cavities were made artificially by burying bags filled with crushed stone #7 (D=2.5-5 mm) in well-compacted base course layers. Fine gravel in bags was removed by a vacuum cleaner through the φ=50 mm hole after the completion of the surface course as shown in Fig. 2. About 60% crushed stone #7 could be removed from the buried bags. Although the bags could not be emptied, the top part of the cavity, which are key in the stability problem, were thought to be made properly. Size and depth of the cavities were measured by radar. Point cloud observation was also made (Kuno & Kuwano, 2021). Fig. 3 is an example of a photograph taken by a borehole camera.

Figure 2. Crushed stone #7 in a bag and its removal by a vacuum cleaner from the pavement surface

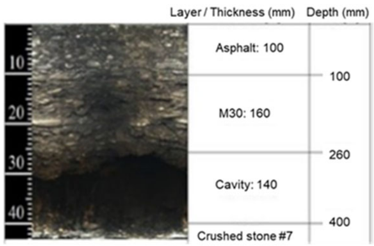

Figure 3. Example of a photograph taken by a borehole camera

2.1.3. Monitoring of the test road

In the test road, meteorological sensors, cameras for observing the temperature of the road surface and for monitoring the road surface condition were installed as ancillary facilities. An example of road surface measurements is shown in Fig. 4.

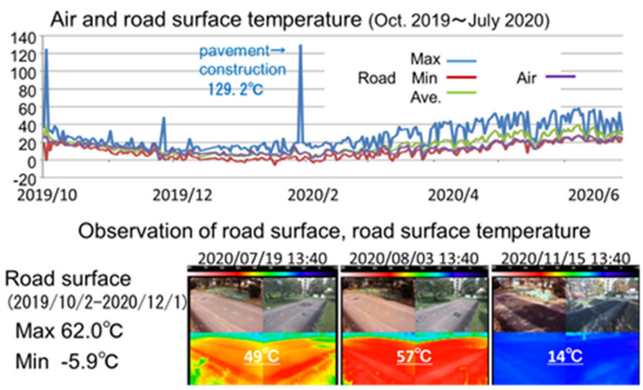

Figure 4. Road surface observation

2.2. Surface wave survey around cavities

A surface wave survey was conducted to see the effect of cavities on the wave propagation (Karasaki 2022). Among the multiple cavities in the full-scale test road, three cavities located at depths of 350~450 mm below ground level were targeted, and the survey line was taken to reconstruct the 2D S-wave velocity model of the cross sections with these cavities. A line of survey and cavity locations are shown in Fig.5, and detailed condition of the measurement is presented in Table 1.

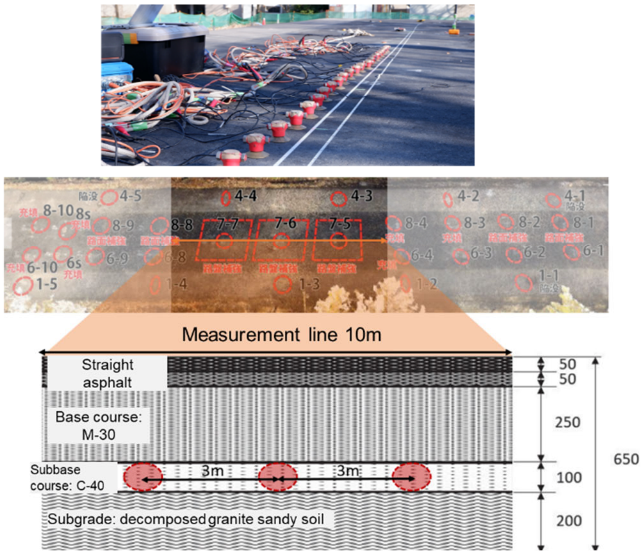

Figure 5. Surface wave survey

Table.1 condition of surface wave survey

Number of receivers	24ch
Survey line length	10m
Vibration point interval	0.2m
Receiving point interval	0.2m

S wave velocity model is reconstructed as shown in Fig.6. The maximum frequency of the dispersion curves used in the analysis was set to be 230 Hz, which is higher than the analysis software's default value of 40 Hz. Overall, the S-wave velocity was distributed in a horizontally stratified manner, with the S-wave velocity decreasing at a depth of 0.8 m.

A region of locally high S-wave velocity appeared at a distance of one cavity from the actual cavity location to the originating point. In the actual two-dimensional S-wave velocity structure, the velocity is zero because S-waves do not propagate in the cavity, but in this case, on the contrary, a region with high S-wave velocity seems to exist next to the cavity. It is thought that elastic waves propagating in the ground reached the cavity and propagated to the receiver, which was affected by the existence of the cavity.

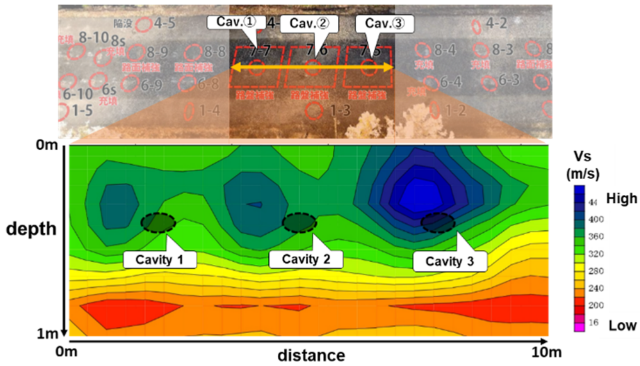

Figure 6. S wave velocities analised by surface wave survey

2.3. Loading tests in the test road with cavities

2.3.1. FWD tests

Loading tests were carried out to measure the bearing capacity of the pavement over the cavity of a full-scale test road using FWD (Falling Weight Deflectometer, ASTM D 4694). The measured FWD deflections were load-corrected to a standard load of 49 kN and temperature-corrected to 20 °C.

An example of the deflection shapes before and after cavity creation is shown in Fig.7. In general, the deflection shape after cavity formation changed closer to the deflection shape before cavity formation as the depth of the cavity increased, confirming the contribution of the base course above the cavity to the bearing capacity (arching effect). The deflection shapes of the points between the cavities were almost the same as the deflection shapes before cavity creation at the cavity locations. It seemed possible to compare the bearing capacity before and after the cavities were fabricated.

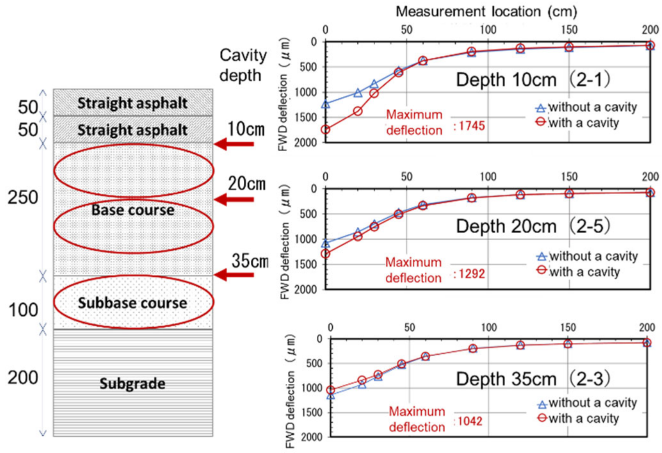

Figure 7. FWD loading test on the cavities of different depths

The relationship between the depths of the cavity ceiling and the maximum FWD deflection (deflection just below the loading plate) is shown in Fig.8. The average value of the maximum deflection at the sound point (midway between the cavities) for each asphalt layer thickness (3 conditions: 5 cm, 10 cm and 20 cm including the asphalt-stabilised base) is shown as a dashed line, for example. Again, the deeper the cavity, the smaller the maximum deflection.

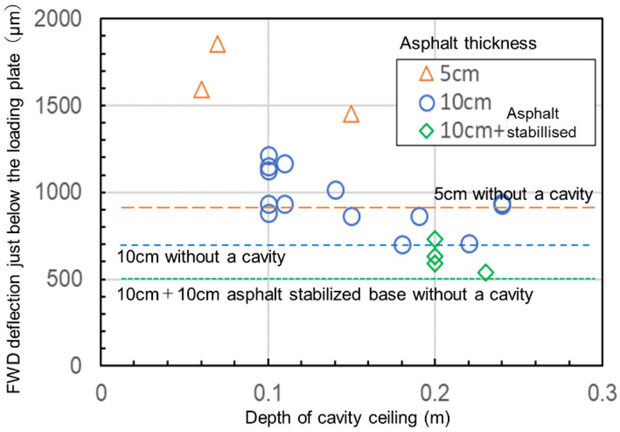

Figure 8. FWD loading tests on the cavities of different depths

Laboratory model tests have confirmed that the risk of ground cave-in potential increases when the depth/width of the cavity is below 0.2~0.3 (Kuwano and Ohara, 2021), so the FWD maximum deflection plotted against the depth/width (short or long axis) is shown in Fig.9. For pavement structures with 10 cm asphalt thickness and 10 cm asphalt thickness plus stabilisation, it was found that the maximum deflection between the cavity and the sound section was almost equal when the ratio of the cavity depth to the cavity width was greater than 0.4, but the deflection was greater when the ratio was less than 0.4. There was little difference in the trend when short and long axis were taken as the cavity width, probably because the difference between the short and long axis was not so great in the cavities fabricated in this study. The deflection was smaller in the case of the asphalt stabilisation treatment, which may contribute to the retention of pavement bearing capacity over the cavities.

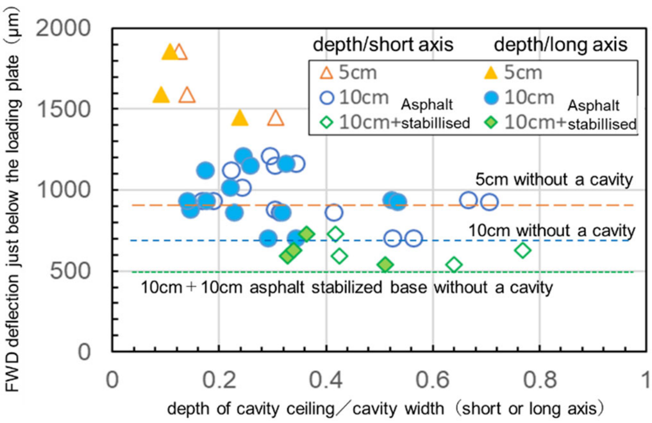

Figure 9. FWD deflection and cavity characteristics

2.3.2. Plate loading tests

A series of plate loading tests (ASTM D1194) was carried out using a flat plate (ø 30 cm or ø 15 cm) loading test device above a cavity. The load on the flat plate was applied approximately in steps of 2 kN, the amount of settlement (displacement) of the flat plate was measured and the test was carried out until signs of road surface distinct sinking occurred (i.e. the loading load was released). An example of test results, corresponding to test cases in Fig.7 (asphalt layer thickness of 10 cm, road surface temperature of about 25°C) is shown in Fig.10.

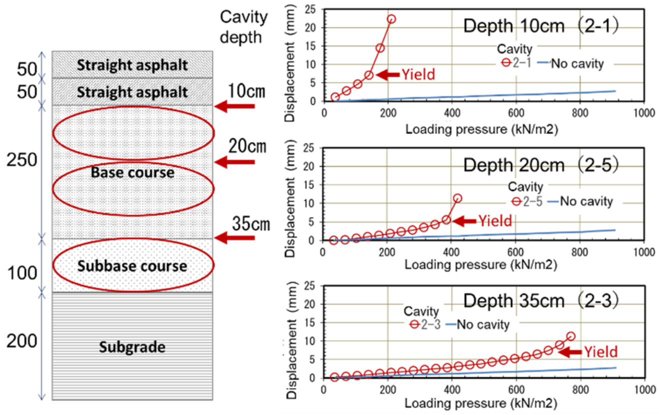

Figure 10. Plate loading tests on different cavity depths

The deeper the cavity, the greater the load resulting in forced subsidence, confirming the contribution of the base course above the cavity to the bearing capacity (arching effect). It was also assumed that deformation occurred within the pavement during the loading tests in all cavities, and observations inside the cavities during post-test scoping revealed delamination between the surface and base layers, gaps between the asphalt layers and base course, and partial collapse of the upper base course material.

The loading pressure at which displacement rapidly increases in a plate loading test is taken as the yield stress, and the yield stress versus cavity depth/width is plotted in Fig.11. The asphalt concrete thickness is 10 cm unless otherwise stated and the yield stress is uniformly expressed as 1000 kN/m^2 if the yield stress cannot be verified before the loading limit. A positive correlation between yield stress and cavity depth/width was observed.

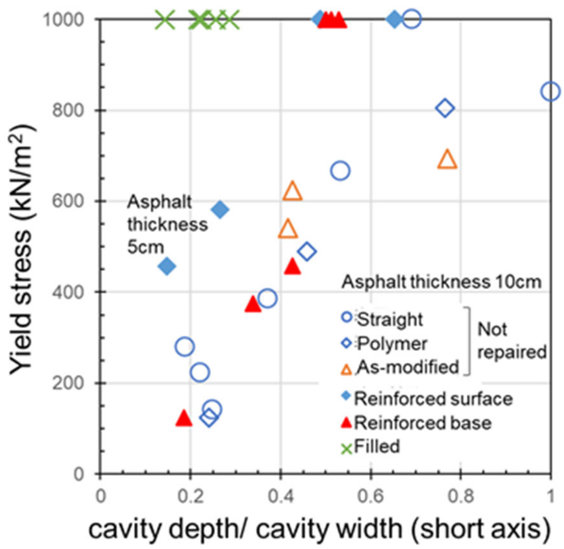

Figure 11. Yield stress in plate loading tests and cavity characteristics

3. Cave-in risk evaluation

Loading tests were also conducted in 2D laboratory model experiments (Kuwano and Ohara, 2021). A loading plate was placed on the model sand ground above a cavity and the bearing capacity was measured. The peak (yield) stresses are plotted against depth/width of cavities in Fig.12. It also indicated that depth/width of cavity is a key factor to evaluate the cave-in risk of cavities. The pavement may delay the surface collapse. But in summer, when the road surface temperature becomes high, up to 10cm thick asphalt pavement cannot bear the load if the cavity location is shallow. In practice, it is suggested to evaluate the risk of cave-in without taking into account the thickness of asphalt surface. The concept of cave-in risk assessment is shown in Fig.13. When the depth/width of cavity is less than 0.2, the soil above the cavity cannot sustain and it is likely to collapse.

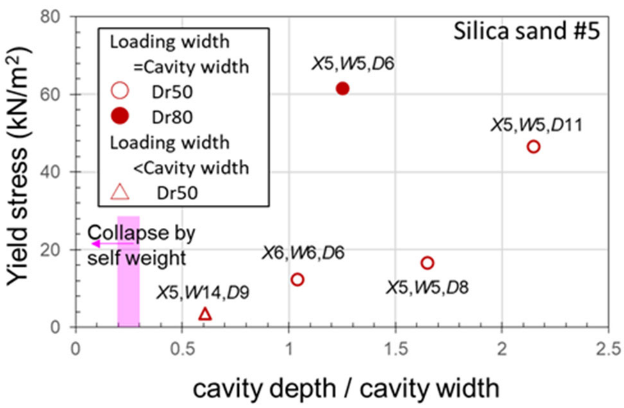

Figure 12. Plate loading tests in laboratory sand model ground

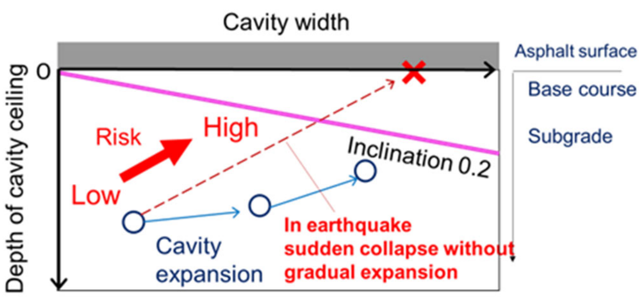

Figure 13. Road cave-in risk evaluation

4. Conclusions

The technical issues behind the problem of road cave-in have been identified, and attempts have been made to understand the behaviour of subsurface cavities and to establish the risk evaluation method of road cave-in. A full-scale field tests were conducted to investigate the behaviour of cavities.

Full-scale test roads with cavities in or under the base course were constructed. Surface wave survey was conducted and it was found that the wave propagation was affected by the presence of subsurface cavities. Loading tests were carried out, showing a correlation between cavity depth and pavement bearing capacity. Although there were differences in the flat plate loading test and FWD values depending on the pavement specification, the base course was on the verge of collapse as it eroded and became thinner, and the cavity approached the asphalt layer. In this case, the cave-in occurs on a daily basis in summer and on a monthly basis in winter. Therefore, it is reasonable to exclude the thickness of the asphalt layer when assessing the risk of cave-in as the ratio of the cavity depth to the cavity width. It should be noted that FWD performed on pavements is highly dependent on road surface temperature, suggesting that FWD is not always effective in detecting sub-surface cavities, even when temperature compensation is applied.

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