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Special Contribution

Subsurface cavities and road cave-ins

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1. Introduction

Sinkholes and ground cave-ins are usually initiated by the formation of cavities in the ground. When a cavity forms for some reason, and grows/expands by the instability of the cavity ceiling, it may result in the surface collapse. In many ground cave-in cases, it looks as if the collapse occurs all of sudden. It is difficult to catch a sign of the collapse in advance. But, of course, it takes some time for the process from the original cavity to the final surface collapse, as shown in Fig. 1.

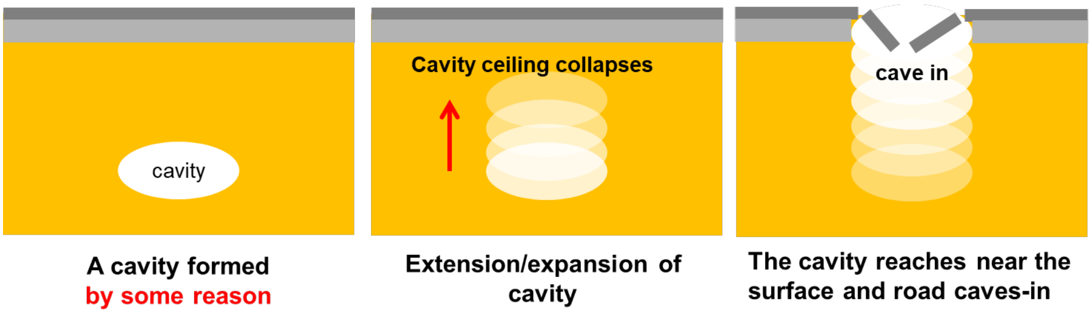

Fig. 1. process of cavity expansion and ground cave-in

In the ground, countless cavities of various causes, sizes and depths exist. Some of them may be on the edge of collapse. But without visible sign such as ground settlement, a cave-in would occur in a very short moment. This makes the countermeasure for the ground cave-in more difficult.

2. Road cave-ins in urban area

The cause of underground cavities can be roughly categorised into two. One is naturally formed cavities such as a cave eroded in calcareous ground. The other major factor is old deteriorated buried infrastructure in urban cities. Especially there is a clear correlation between the aging of sewer pipes and the occurrence of road cave-in. The number of road cave-in due to the failure of sewer pipes starts to increase when the age of sewer pipes exceeds 30 years, as indicated in Fig. 2. However, it is not always easy to identify the cause of road cave-in. In fact, about one third of urban road cave-in cases are due to unknown reasons, as shown in Fig. 3.

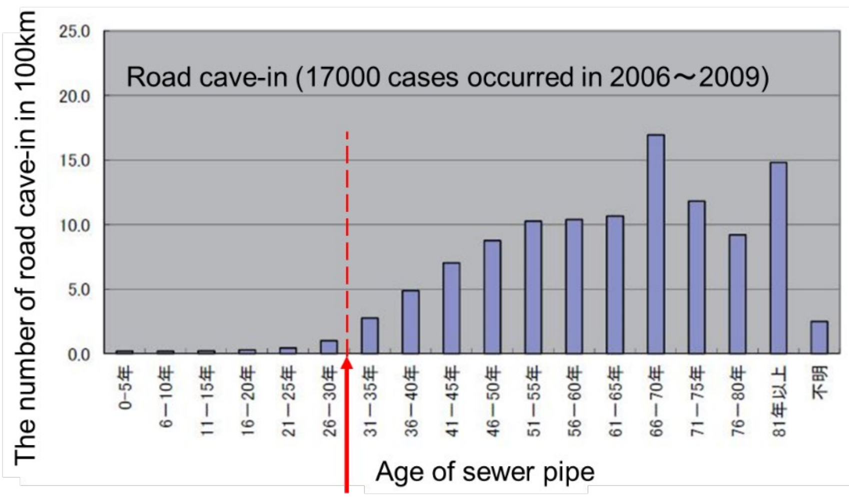

Fig. 2. Relationship between age of sewer pipe and frequency of road cave-in (after Yokota et al, 2012)

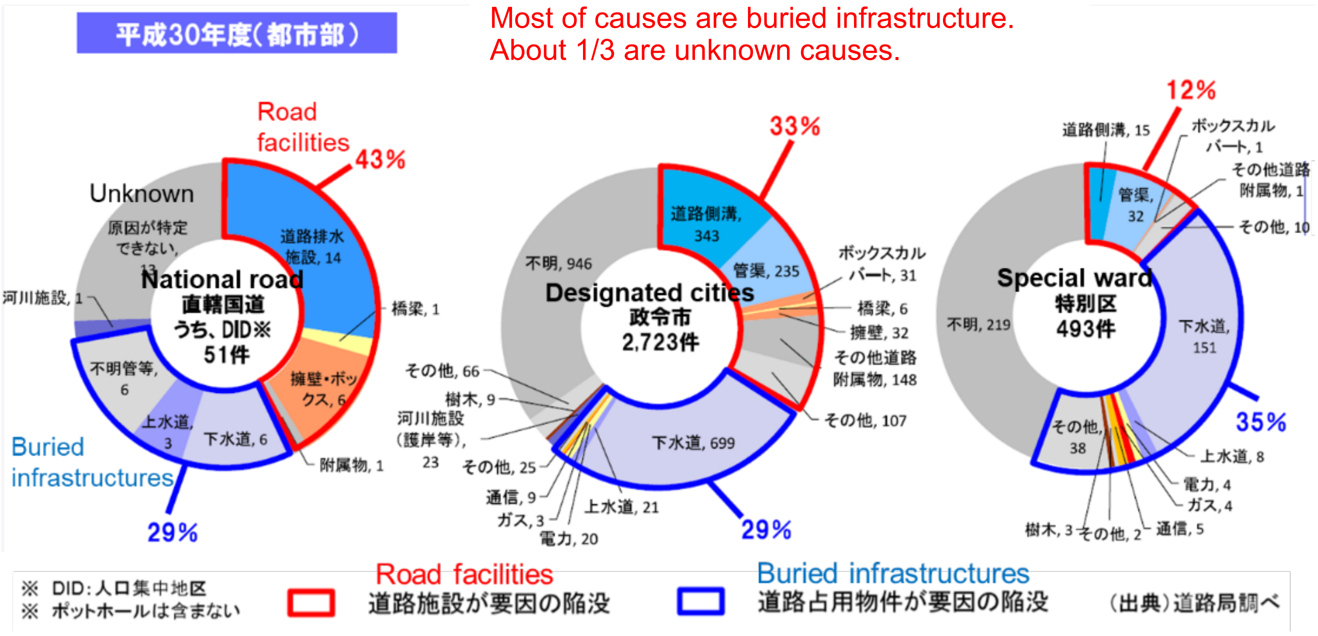

Fig. 3. The number of road cave-ins in urban area and their causes in 2018 (from MILT website)

When the sewer pipe is damaged, the soil with groundwater above the broken point flows into the pipe and a cavity forms in the ground. Fig. 4 schematically shows the process of cavity formation and expansion in the case of leakage of unbound soil through a hole. Using the soil chamber having an opening in the base, this phenomenon was simulated in a series of model tests. Even though a hole is small, if the leakage of soil continues, a cavity can grow and expand. It is only the last moment that the deformation on the ground surface is recognized. Change of water level, or high water level are one of main factors for cavity expansion.

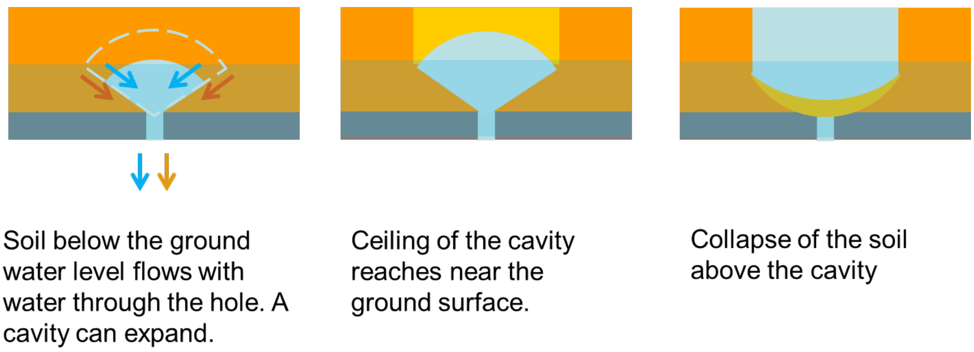

Fig. 4. Process of cavity formation/expansion

According to the survey conducted by Kuwano et al. (2010) in seven cities enquiring the relationship between the state of sewer pipe and road cave-in situation, following facts were revealed.

- Although the life time for sewer pipes is considered to be 50 years, the damage and failure of underground pipes causing cave-in's in the road distinctively increase after 30 years from the construction.
- Even small gaps or cracks of pipes could lead to road cave-ins.
- Rainfall appears to be one of the most important factors.

The size of subsurface cavities caused by damaged buried pipes is generally small and the location is shallow. The shallow subsurface cavities of less than 1.5m deep from the surface can be detected using the ground penetrating radar (GPR) technique. The road managers regularly carry out the GPR surveys as the road maintenance operation. The frequency of the subsurface cavities (the number of cavities found in the road of 1km) is shown in Table 1. The depth of cavity ceiling is typically just under the pavement, 0.3 to 0.6m deep. The thickness of cavity is less than 0.6m for the most cases.

Table 1. Frequency of cavity generation in roads

Administrative area	The number of subsurface cavities in unit length of road (/km)
National, prefectural	0.59
Tokyo, designated city	2.06
Tokyo 23 ward	2.09
Other municipality	1.37

From the data Geo Search Co. investigated in 2014 and 2015
(road length: 10,091km, the number of cavities: 9984)

Factors of the cavity formation and expansion are shown in Fig. 5. The contribution of each parameter for pre-existing factors was estimated from the actual data for the distribution of subsurface cavities in Fukuoka and Fujisawa city respectively. Then, cavity potential, the likeliness of cavity formation, was evaluated and presented as a cavity potential map, as shown in Fig. 6. For both Fukuoka and Fujisawa cities, one of the most important factors in the cavity potential was found to be the age of sewer pipes.

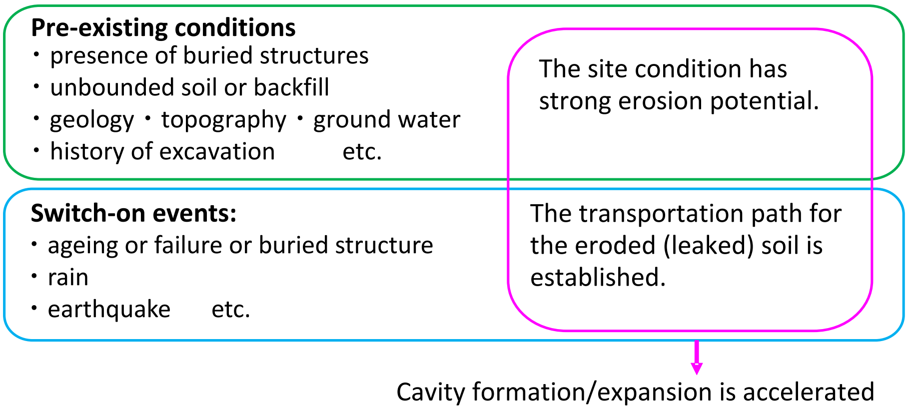

Fig. 5. Factors of cavity formation/expansion

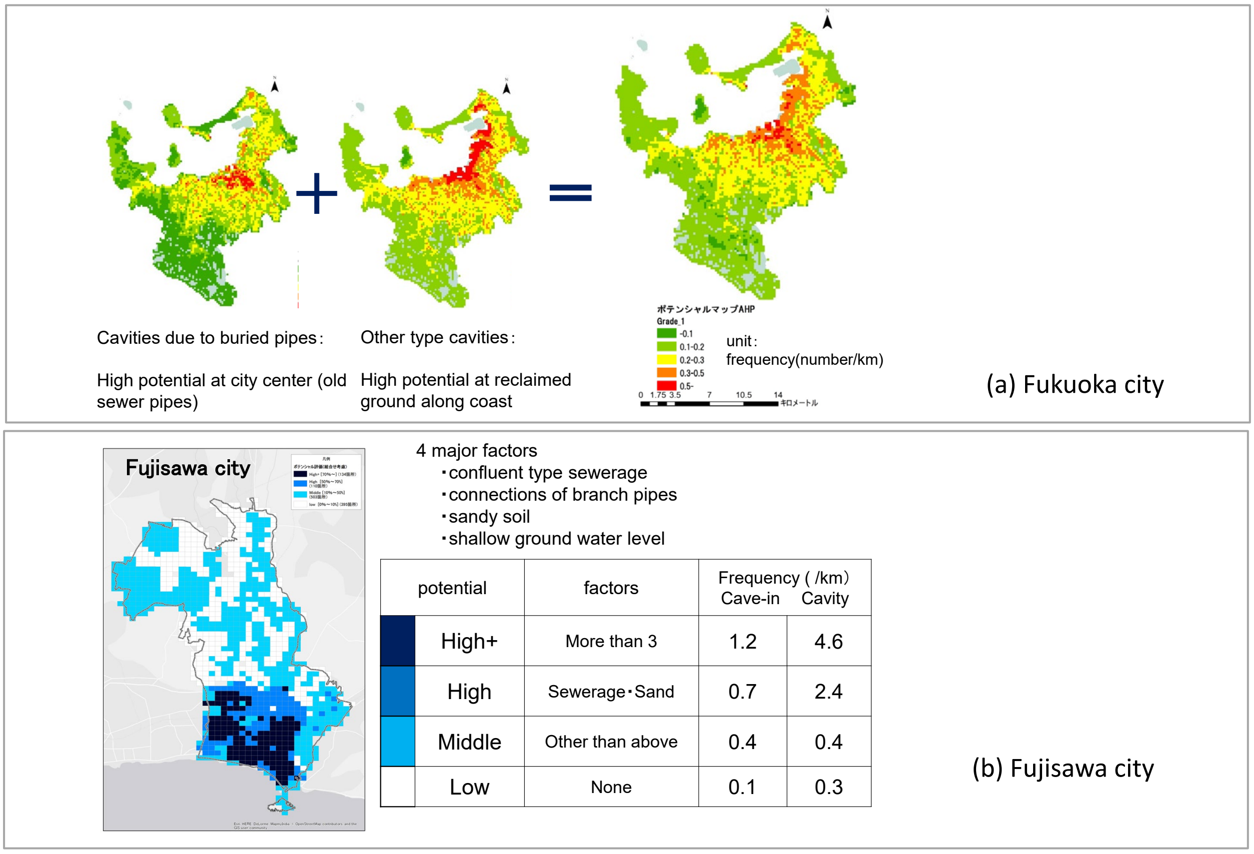

Fig. 6. Cavity potential map

The most important factor of the trigger for the cavity expansion is rainfall. In fact, the number of road cave-in reported in the newspaper increased in June, July and August, when there are a lot of rain in Japan, as shown in Fig. 7. Earthquake is another major factor for the cavity expansion. According to the survey analysis before and after Niigata-ken Chuetsu earthquake (2007), Great east Japan earthquake (2011), and Kumamoto earthquake (2016), it is revealed that the number of cavities increased at the locations where the seismic intensity exceeded 5 (Fig. 8).

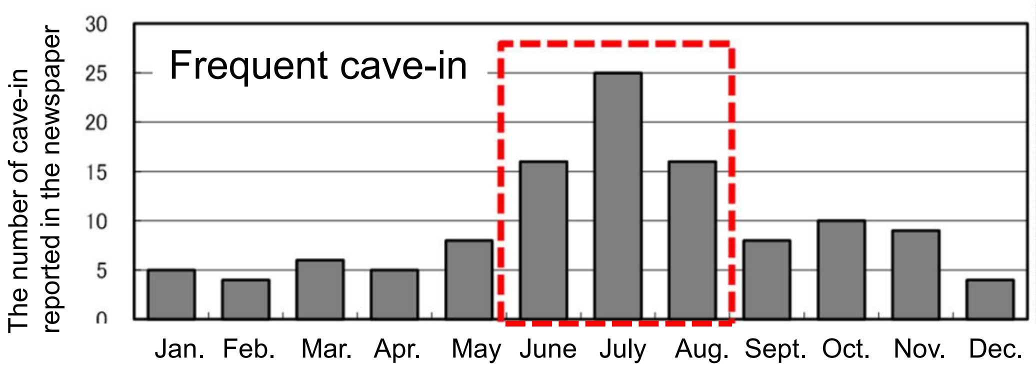

Fig. 7. The number of road cave-in in Japan reported in the newspaper (1988-2006)

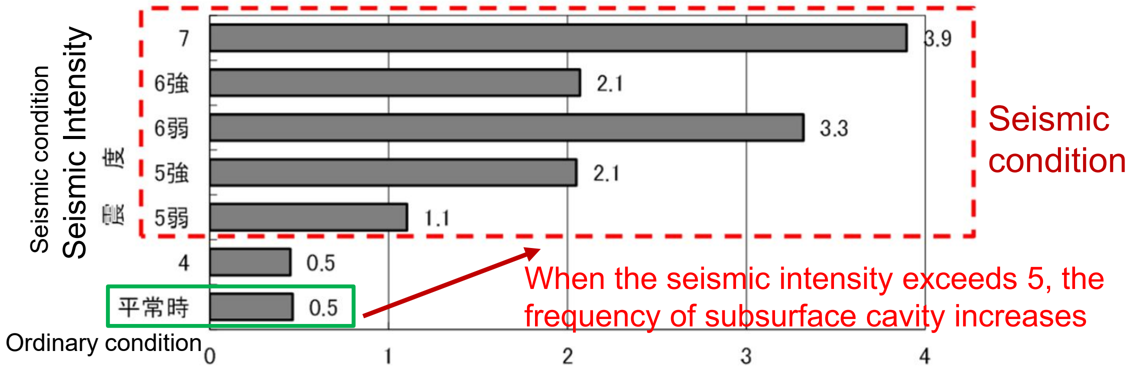

Fig. 8. Frequency of underground cavities according to seismic intensity due to Niigata-ken Chuetsu earthquake

3. Evaluation of collapsing risk

From the practical point of view, the risk evaluation of road cave-in is quite important. Fig. 9 shows the process of cavity formation, expansion and surface collapse observed in the model test. Soil with water drained from the opening in the center of base plate in a soil chamber and the vertically elongated chimney-like cavity was initially formed. When the water was supplied again, the soil below the water level flown out and the width of the cavity became larger. The soil above the cavity was kept stable by the apparent cohesion in unsaturated sand and arching action while the depth/width of cavity was large enough. When it becomes less than the threshold value (0.2-0.3), the soil above the cavity lost the stability and collapsed into the cavity. In Fig. 9, the plot of cavity depth versus cavity width moved rightward as the cavity expand, and finally reached on the line that the inclination was -0.2 to -0.3 just before the collapse. It means that wet uniform sand above a cavity collapses due to its self-weight, when the ratio of depth and cavity width becomes below 0.2 to 0.3.

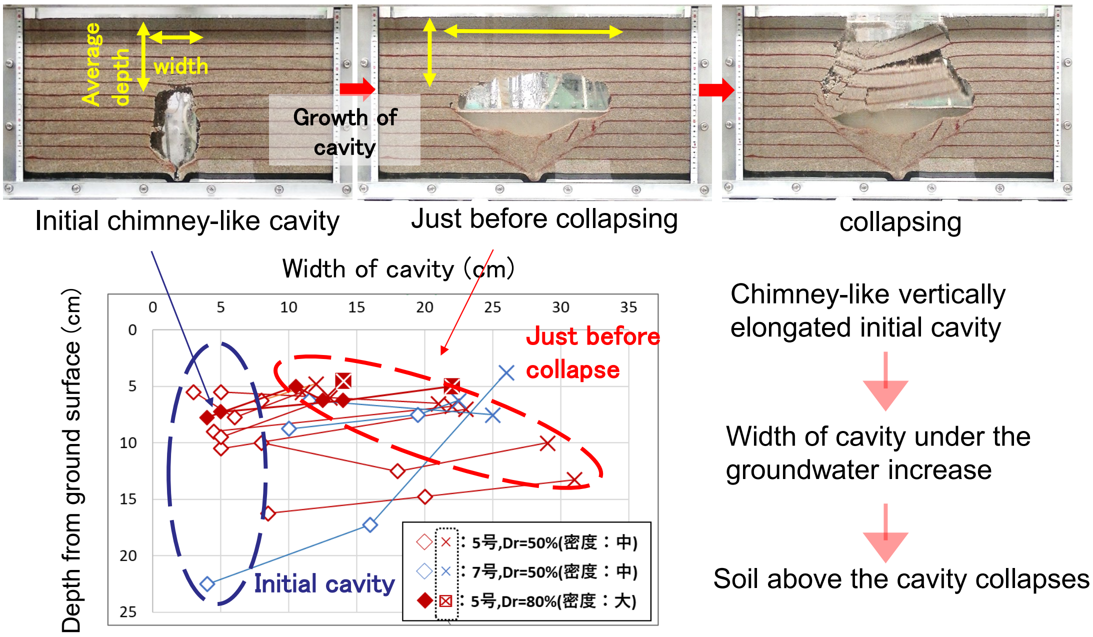

Fig. 9. Process of cavity formation, expansion and surface collapse

Using the data of subsurface cavities and road cave-ins in national road, the depths of cavities are plotted against the widths of cavities in Fig. 10. Most collapsed cases are found to be the area that the depth/width is less than 0.2 to 0.3. It can be stated that the phenomenon observed in a series of model tests can be extended to the practice. The threshold value of collapse can be dependent on properties of pavement, ground condition, water level and so on. Further investigation is needed on this issue.

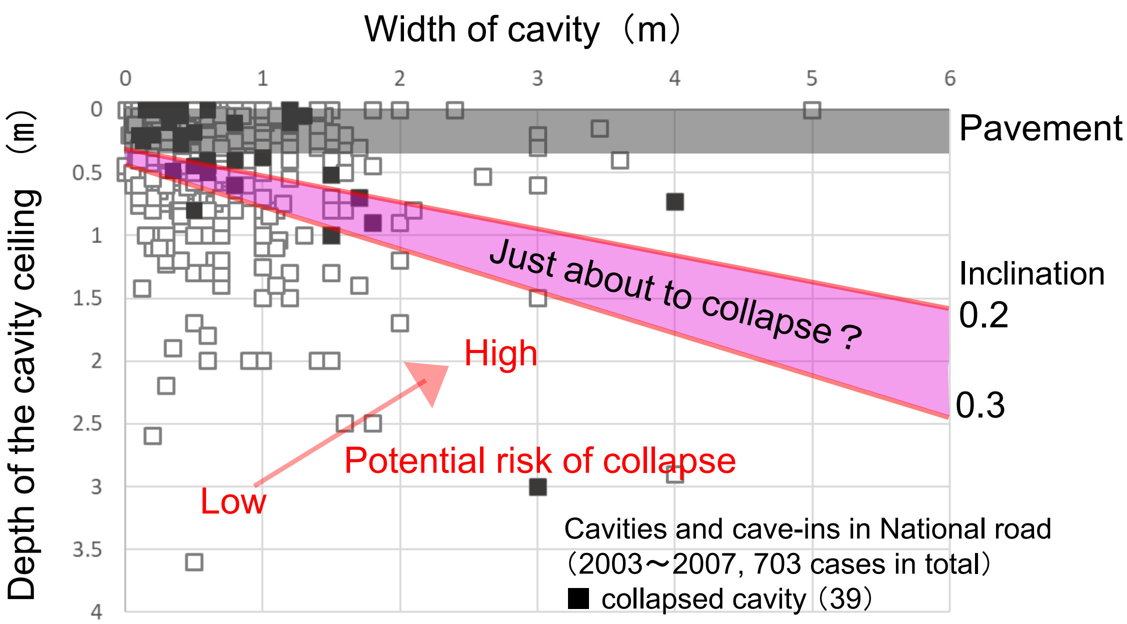

Fig. 10. Cases of real cavities and collapses in national road

In practice, the growth rate of cavity, how fast the point moves from lower left to upper right in Fig. 10, is also important. In the model tests, in the particular condition, the rate of cavity growth is observed to be very fast. In the monitoring survey of subsurface cavities in Fujisawa city, there is the case that a deep small cavity due to the failure of the sewer pipe moved up to shallow ground within a couple of months. On the other hand, most of the cavities in national roads are reported to be stable in several years. The growth rate observed for the cavities in national roads are shown in Fig.11. We should further collect this type of data from the monitoring practice to analyse the growth rate of cavities.

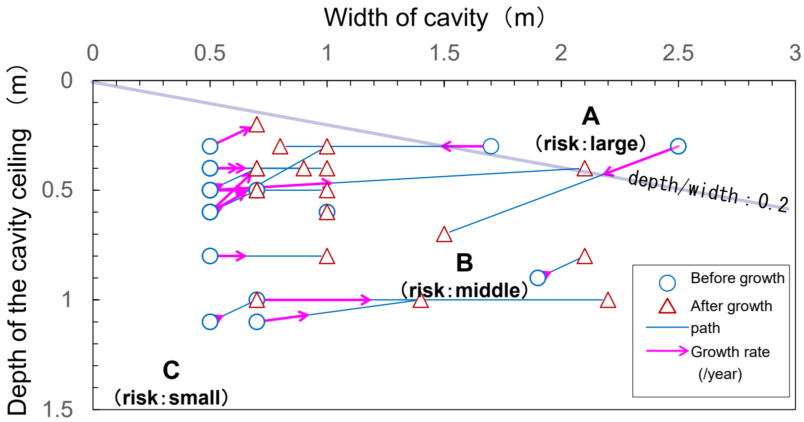

Fig. 11. Growth rate of 19 subsurface cavities monitored in national roads detected in 2012-2016

4. Repairment of subsurface cavity

The detected cavities by the ground penetrating radar technique should be appropriately repaired according to their potential risk of collapse. Generally, a cavity is filled by the open-cut method. Recently the injection of air mortar into a cavity is also applied. If the potential risk of collapse is low, it is possible to keep monitoring the cavity. It is preferable to accumulate and utilize the cavity data to update the knowledge and share the experience among infrastructure managers and engineers.

5. For road policy quality improvement

Current standard practice against a subsurface cavity is “finding a cavity and backfilling it by open excavation before its collapse”. It works well and contributes to the mitigation of cave-in accidents. For more rational and effective measures, following are considered important; appropriate survey planning considering regional trend and cavity formation potential, the evaluation of collapsing risk for a cavity, and choice of repairing methods according to cavity properties.

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◆ A brief CV of Prof. Reiko Kuwano

Reiko Kuwano is a professor of Institute of Industrial Science, the University of Tokyo, Japan. She graduated from the University of Tokyo, Japan, in 1988, with a Master degree in Civil Engineering. After practical work experience as an engineer in Taisei Corporation for five years, she obtained a PhD degree at Imperial College, London in 1999. Then she worked at Public Work Research Institute as a senior researcher before she moved to the University of Tokyo in 2006. Her major interest includes laboratory soil testing, mechanical behaviour of soil, internal erosion, subsurface cavity and ground cave-in, long-term behaviour of buried/earth structure, and so on.