Pavement failure and flooding of tunnel in limestone geology

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ABSTRACT: This paper describes a case study of cause investigation and countermeasure on pavement failure and flooding in a under service tunnel during a heavy rain constructed by NATM in limestone geology. Since caverns of various sizes were confirmed and a large amount of groundwater flowed into the tunnel during the excavation, the cause is assumed to be the high water pressure acting on the caverns connected to the lower part of the pavement, which could not be visually confirmed when the tunnel was excavated. After confirming the soundness of the tunnel structures and pavement concrete by non-destructive testing methods, the cause investigation mainly focused on reconfirming the original excavation surface under the tunnel pavement. A countermeasure was adopted to allow free drainage through the confirmed small caverns and new drilling holes to prevent the reoccurrence of high water pressure in the small caverns around the tunnel.

Keywords: Limestone, tunnel, cavern, water pressure, pavement failure, countermeasure.

1 INTRODUCTION

The reason why limestone areas are attracting attention at construction sites is that limestone is vulnerable to chemical weathering and the dissolution of groundwater causes erosion along the linear geological structures such as fault planes, fracture zones, and bedding to create small cracks, which gradually grow, then ultimately form irregular corrosion caverns. When these corrosion occur, the underground caverns expand as the flow of groundwater increases along the geological structural line and the direction of groundwater flow. For these reasons, problems such as bearing capacity of bridge foundation, stability of cut slope with large-scale caverns, and ground subsidence due to tunnel excavation have emerged during civil engineering work in limestone geology.

In this paper, as a new case related to these unique characteristics of limestone geology, rainwater flowing into the caverns around the tunnel during long heavy rainfall formed a high water head in the large cavern connected to the small ones under the tunnel pavement, as a result, the large water head difference acted on the pavement as a uplift pressure, causing damage to the pavement and flooding inside the tunnel. In addition, considerations for designing tunnels in limestone areas and countermeasures against troubles are discussed.

2 SITE SITUATION

2.1 Damage area survey

During 2 days of heavy rain with the total of rainfall of 233mm, the concrete pavement (thickness t=30cm) of the 970m-long tunnel in service was damaged. Groundwater flowed into the tunnel causing a flooding of about 500m-long section and disruption of traffic flow (Figure 1). The damaged section occurred at around 240m from the tunnel portal. Upon investigation of 2 days after the incident occurred, based on the level difference to upper surface of the shoulder, a rising phenomenon of pavement concrete due to lifting (up to 78mm) was confirmed. The occurrence of concrete cracks (maximum crack width of 22 mm) was also confirmed intensively in the 10m section where the rising phenomenon was the most prominent (Figure 2, Figure 3).

Figure 1. Flooding and groundwater inflow in tunnel.

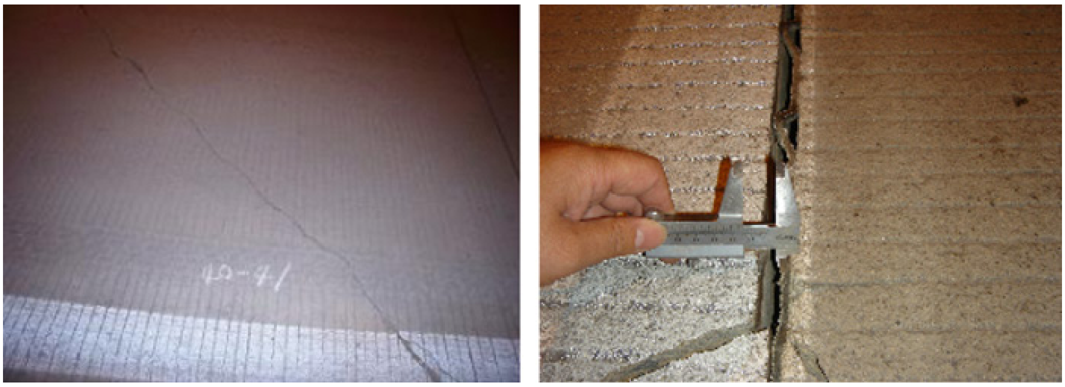

Figure 2. Damage of pavement concrete.

2.2 Construction records

The surrounding geology including the tunnel area is limestone. The uniaxial compressive strength of limestone using boring cores is from 100MPa to 170MPa.

Seismic survey and electrical resistivity survey were conducted during the Detailed Design stage. Based on the results of the seismic survey, the P-wave velocity in most of the tunnel sections is around 5.0 km/sec and low-velocity zones ranging from 2.5 to 3.3 km/sec are shown in 5 locations of the tunnel. In the electrical resistivity survey, low resistivity values are appeared in 2 locations, which indicates the possibility of weak zones.

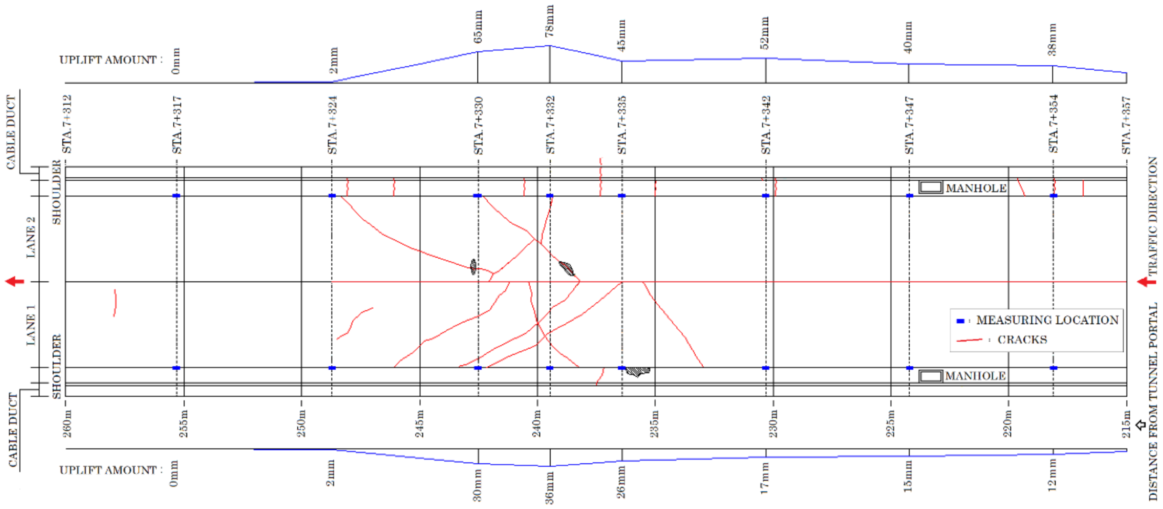

Figure 3. Details of damaged pavement concrete.

Figure 4 shows the longitudinal section of the tunnel, the result of the electrical resistivity survey and the location of the caverns that were confirmed during excavation. The tunnel has a maximum overburden height of about 160 m. The existence of a cavern was not confirmed in the section with high overburden height at the center of the tunnel, however, 15 caverns with a continuity of 2 m to 8 m were identified in the section below 100 m of overburden height. Location where the pavement was damaged or uplifted is also in section with overburden height of about 80m.

The shapes of the caverns are all different. Figure 5 shows the shape of the cavern with the longest extension in the longitudinal direction at 1m intervals. Larger caverns were not identified. The caverns were later filled with shotcrete.

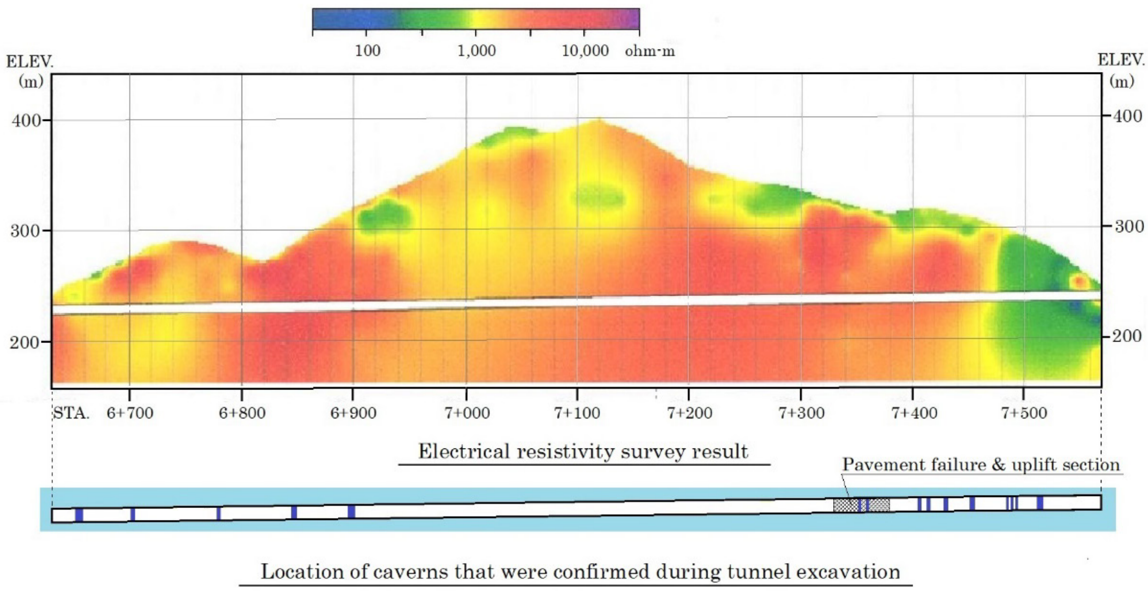

Figure 4. Result of electrical resistivity survey result and location of caverns that was confirmed during tunnel excavation.

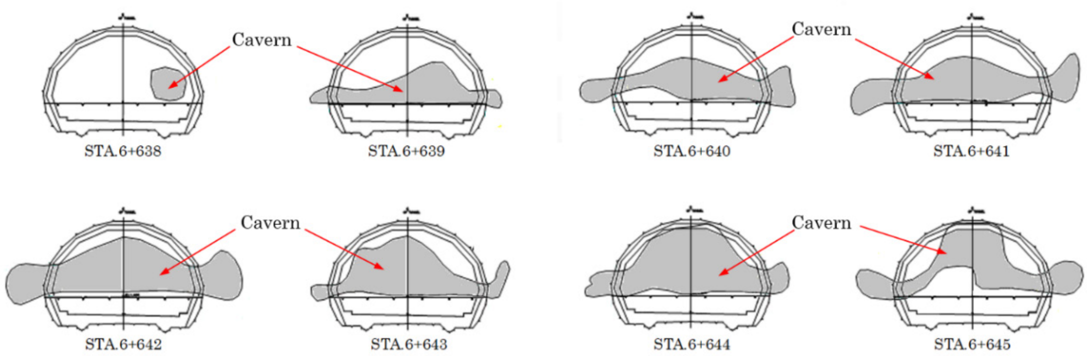

Figure 5. Example of distribution of cavern that was confirmed during tunnel excavation.

3 CAUSE INVESTIGATION

In order to check the soundness and damage of tunnel structures and pavement concrete, GPR (Ground Penetrating Radar) survey and thermal infrared imaging survey, which are non-destructive survey methods, were conducted.

The results of GPR survey shows that while in the section where cracks in the concrete pavement occurred there is a clear difference estimated to be ground disturbance or loosening in the reflected wave pattern, in the section where no cracks appeared in the pavement concrete and at the sidewall and crown of the tunnel lining, the abnormal reflected wave pattern was not confirmed.

Similarly, in the results by thermal infrared imaging survey, abnormal surface temperatures distributions were confirmed in the section where the uplift and cracks of the pavement concrete were visually confirmed. Abnormal temperatures were not measured in other linings.

Therefore, the cause investigation proceeded as follows targeting the lower part of the damaged pavement concrete since there was no damage in the tunnel structure except for the pavement concrete.

3.1 Hypothesis in cause investigation

Based on the following facts: (1) Geology is limestone, and many caverns were identified during tunnel construction; (2) During heavy rain in the previous year, there was a phenomenon in which inflow water spouted along the pavement concrete joint in the parallel tunnel with opposite traffic direction.

Therefore, the cause investigation is explained based on the following hypotheses. During the heavy rain, large amount of rainwater penetrated through the ground surface and quickly flowed into a big cavern near the tunnel, the large water head difference between the big cavern and the small caverns under tunnel pavement then was formed, which acted as an uplift pressure on the pavement concrete, finally uplift and failure of the tunnel pavement concrete occurred, leading to flooding in the tunnel.

3.2 Re-examination of original excavation surface under tunnel pavement

In order to confirm the hypothesis of pavement failure and flooding described in 3.1, in the 46m long section where the pavement concrete was damaged due to uplift and cracking, removal of the pavement structure to the original excavation surface was conducted.

The status of each pavement structure and drainage system as shown in Figure 6 was confirmed. Furthermore, to identify the presence of small caverns under the pavement structure, the geological conditions and caverns were surveyed while completely removing the upper part up to the excavated surface at the time of tunnel construction. 5 small caverns were identified in the 46 m long pavement damage section.

At one location clearly identified as a cavern, the excavation surface consisted of hard rock of limestone. However, a wedge-shaped loose soil was also observed in some part. As a result of removing the soil, groundwater flowed out, and a cavern with the entrance diameter of about 30 cm was identified at a depth of about 1.0 m from the bottom of the side drain pipe (Figure 7). This cavern located directly below the section where the damage of the pavement concrete was most noticeable, with a horizontal length of about 1 m and a horizontal width of about 40 cm. However, it was not possible to ascertain the connection to the adjacent cavern. At the other 4 locations, weak zone with a width of around 50 cm was identified between hard rocks, which could be connected to the cavern and was presumed to be in the process of erosion.

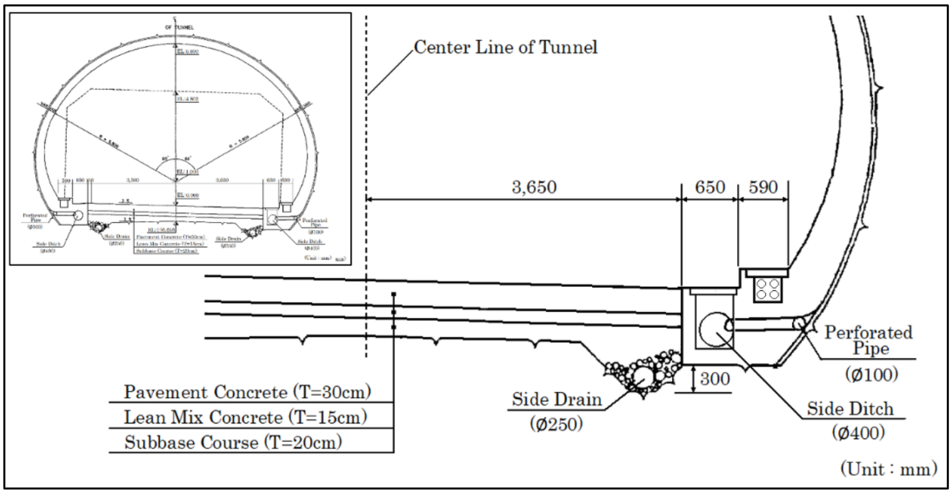

Figure 6. Pavement structure and drainage system.

Re-investigation of original excavation surface under pavement concrete

Small cavern found 1 m below side drain

Figure 7. Re-examination of original excavation surface and identified cavern.

4 COUNTERMEASURE

Since this incident occurred in a tunnel under operation in a limestone geology where caverns of various sizes are distributed and it is judged that the pavement concrete was damaged by high water pressure, based on the logic shown below, a countermeasure was adopted to actively remove the water that flowed into the caverns on the tunnel side.

① In the case of this tunnel, it has the topographical feature of cavern distribution in which a large amount of rainwater can quickly gather into big caverns around the tunnel, which are karstic characteristics in limestone areas, and it is difficult to improve this environment.
② A problem occurred because the damaged section was the most vulnerable condition of the tunnel extensions.
③ There is a limit to increase the resistance to water pressure by applying grouting, and even if it goes well, there is a possibility that it will be reproduced in other vulnerable sections. The same idea can be applied to placing the invert concrete.
④ It is caused by the rapid rise of the water level in the cavern around the tunnel, and it occurred in the most vulnerable section, so if the rise in the groundwater level can be suppressed in this section, the same problem will not occur in the entire section of the tunnel.

As a result, after changing the side ditch composed of a spiral pipe to a manhole cross section in the entire 46m section where the pavement concrete was lifted, 4m long perforated pipes were installed at intervals of 2.5m (Figure 8). In addition, PE pipes were connected to the side ditch from 5 small caverns identified under the pavement concrete to side ditch to drain groundwater.

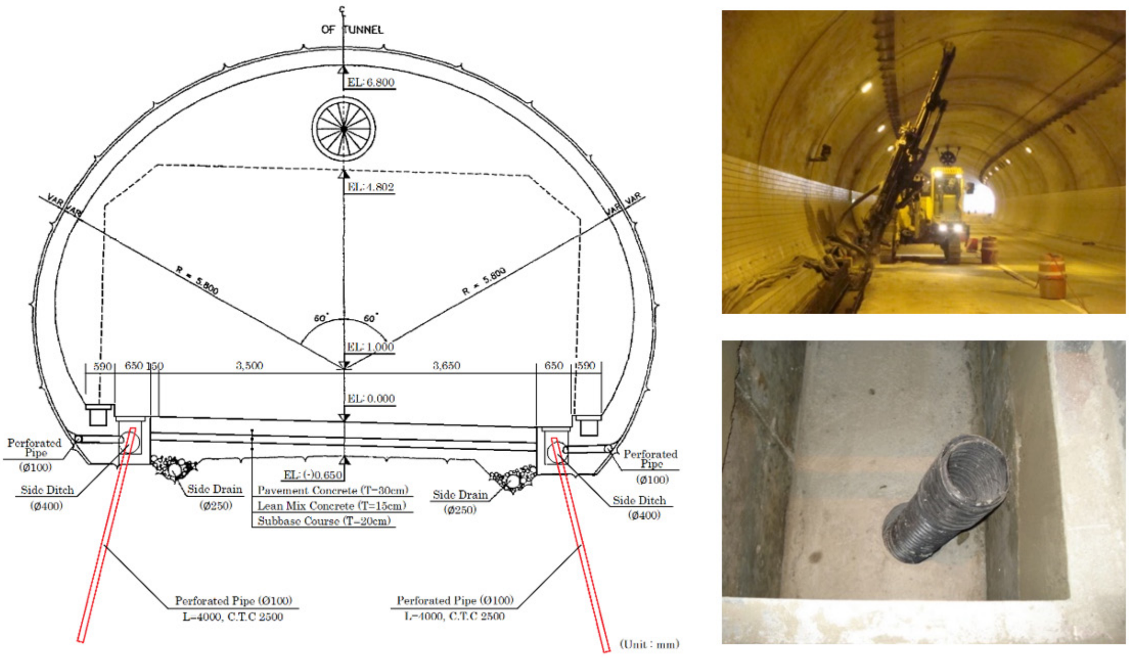

Figure 8. Countermeasure using drainage boring and related photographs.

5 CONCLUSION

This paper reported a case that a big incident occurred due to the presence of caverns distributed under the pavement that had not been paid proper attention during tunnel construction in limestone geology. Invert concrete can be used as a countermeasure during construction, but it is not a perfect countermeasure from this example. Site engineer should pay more attention to the presence of caverns.

In the case of this tunnel, more than ten years have passed since countermeasures were taken, but groundwater has never overflowed onto the road.