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A Heaving Phenomenon on Invert concrete lining in Mountain tunnels

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ABSTRACT

The invert concrete lining is an important component for the long-term stability of the tunnel. In mountain tunnels in Japan, A heaving Phenomenon may occur even if the invert lining is installed at the design stage. In fact, there have been reports of damage to invert linings in tunnels where invert linings were installed due to heaving. In this study, a numerical analysis was applied to investigate the effect of the ground pressure acting on the invert lining on the heaving of the invert. The results suggest that it may be possible to predict the degree of damage to the invert during tunnel operation by comparing the amount of heaving in a serviced tunnel with the numerical analysis in this study.

1. INTRODUCTION

In mountain tunnels, deformations may occur while in the tunnel. Among these, the heaving is the one that directly affects the driving performance of vehicles, so it is necessary to take immediate countermeasures when it occurs. The heaving is a phenomenon in which the tunnel deforms in the hollow direction due to ground pressure in the lower region of the base of a mountain tunnel. It has been reported that tunnels where the heaving occurred while in service are often found in the soft rock ground (especially in the green tuff areas) where overburden is more than 50 m, competence factor is low, and uniaxial compressive strength is less than 12 MPa (Shimamoto 2013). It is also considered that the engineering properties of soft rocks, squeezing (pushing out due to geological plasticity) and swelling (water absorbing expansion due to swelling clay minerals in the ground), are due to the heaving. The squeezing phenomenon is a process

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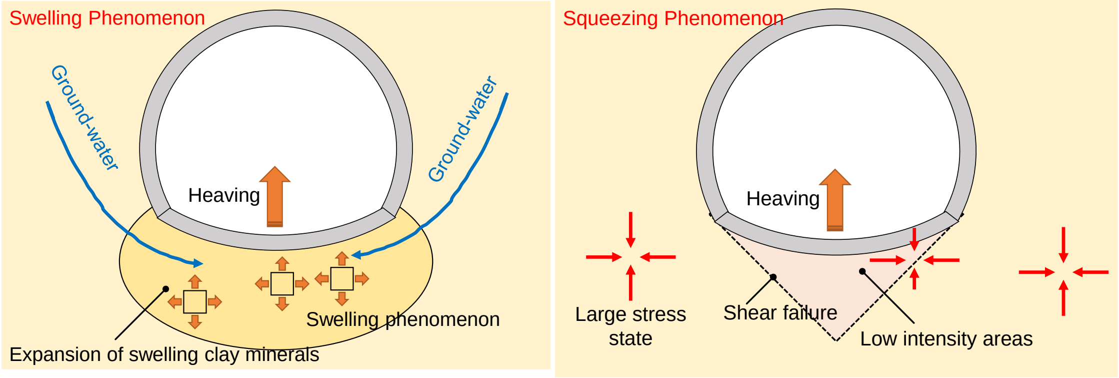


Fig. 1 Image of Heaving by Swelling and Squeezing (Shimamoto 2013)

Fig. 2 Example of damage to invert by Heaving (Okui 2009)

in which the secondary stress increases in relation to the strength of the ground, causing the geological formation to plasticize and the bottom of the tunnel to push out in the direction of the tunnel hollow. The swelling phenomenon (Fig. 1) occurs when groundwater flows into the bottom of a mountain tunnel and the swelling clay minerals in the bottom expand by absorbing the groundwater. In the case of heaving caused by the above, in the case of the ground containing tuff or serpentinite, the invert should be constructed in theory even in the ground class C which is relatively hard ground (Japan road association 2003). Therefore, the basic countermeasure for heaving is to install heaving during tunnel construction. However, it has been reported that invert was damaged by heaving in even tunnels with invert installed during construction (Fig. 2).

The cause of heaving seems to be mainly due to the expansion of the geological mountain by water absorption (swelling). However, the swelling phenomenon varies depending on the rock type, rock weathering, and the groundwater supply. Therefore, it is thought that the existence and scale of floor heave caused by heaving cannot be evaluated and understood at the time of design before tunnel construction. In addition, it is difficult to examine tunnel-invert during service as tunnel invert which has an effect of heaving phenomenon is located under the road surface. However, if the relationship between the magnitude of heaving and the invert damage state, and the correlation between the amount of road surface deformation and having can be determined, this information will be extremely useful for maintenance management.

In this study, a numerical analysis was applied to investigate the effect of the ground pressure acting on the invert lining on the heaving of the invert.

2. OVERVIEW OF NUMERICAL ANALYSIS

In this study, a three-dimensional finite difference method code FLAC3D (Itasca Consulting Group Inc.) was used to analyze a tunnel in which invert were constructed during tunnel excavation, in order to clarify the relationship between the degree of heaving and the state of invert. The outline of the numerical analysis is described below.

2.1 Analysis model and analysis conditions

In this study, the cross-sectional shape of the tunnel of numerical analysis is specified as support patterns with a ground grade C as shown in Fig. 3 with the expectation that a two lane road tunnel will be constructed on a ground type of tuff. The analysis area was set as a two-dimensional plane strain model with an overburden of 50 m and a depth of 1 m as shown in Fig. 4. In this study, the constitutive model of the ground is modeled as elastic perfectly plastic materials. In addition, the constitutive model of shotcrete, lining and invert was modelled as linear elastic materials. In addition, the physical properties were set as shown in Table. 1, for the physical properties of the ground grade C with referring to the documents (Japan Society of Civil Engineers 2006). Also, it can be concluded that the calculation values of axial force and shear force may be changed by modelling the joints between the invert and the lining or not. Therefore, in this study, while modeling invert and lining, the joints between lining and invert are struck, and elements with low stiffness are created at the joints. The boundary conditions of the analytical model were set to be roller supported except for the top surface of the analytical model, as shown in Fig. 4.

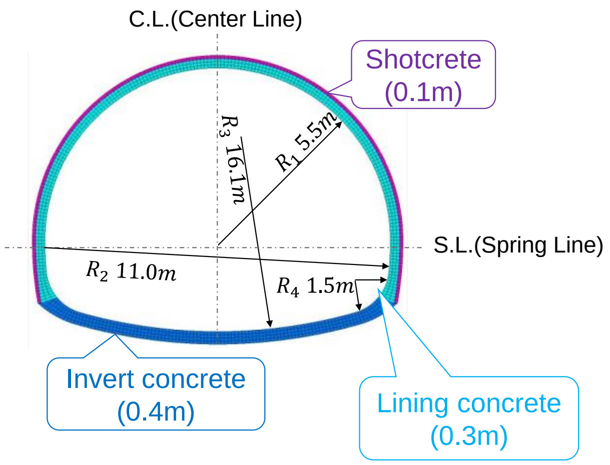


Fig. 3 Cross-section of the tunnel

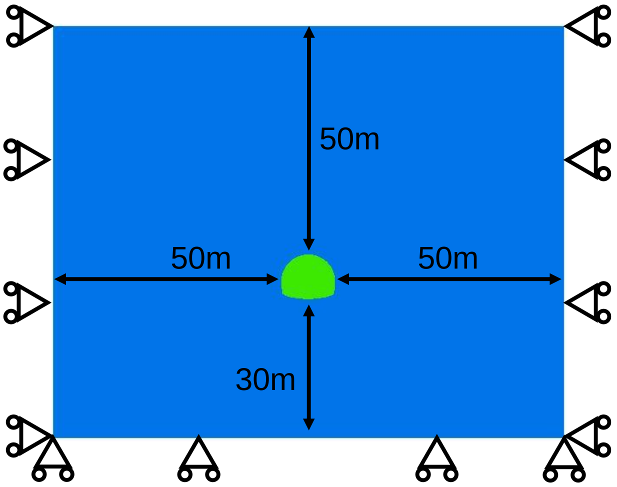


Fig. 4 Analysis model diagram

Table. 1 Analysis physical properties (Japan Society of Civil Engineers 2006)

	Symbols	**Ground**	**Shotcrete**	**Lining**	**Invert**
Constitutive model	-	Linear elastic material	Elastic	perfectly	plastic
Unit weight (kN/m^3)	γ	24.0	23.5	23.5	23.5
Young modulus (MPa)	E	1000	4000	20000	20000
Poisson's ratio (-)	v	0.25	0.20	0.20	0.20
Cohesion (MPa)	c	2.0	-	-	-
Internal friction angle (deg)	φ	35	-	-	-
Uniaxial tensile strength (MPa)	σ_t	0.20	-	-	-

2.2 Analytical steps

The initial stresses of the analytical model were calculated as shown in Fig. 4. Next, the excavation analysis of the tunnel was performed using the following procedure.

(1) Top heading excavation: Excavation of the top heading of the tunnel (stress release ratio of top heading is 40%). After that, the top heading of the shotcrete is installed (stress release ratio of top heading is 100%).

(2) Lower half excavation: Excavation of the lower half of the tunnel (stress release ratio of lower half is 40%). After that, the lower half of the shotcrete is installed (stress release ratio of lower half is 100%)

(3) Excavation of invert: Excavation of invert (stress release ratio of invert is 100%). Construction of lining and invert: The lining and invert were installed together, and no external force from the ground surface was acting on the lining and invert.

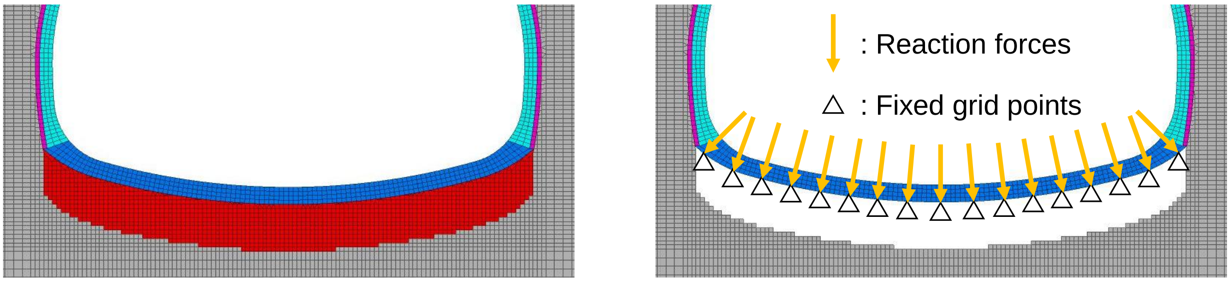
2.3 Heaving development analysis

In this study, to simply represent the swelling pressure acting on invert by heaving and to understand the effect of swelling pressure on invert, the analysis of the load shown in Fig. 5 (here after called equivalent heaving pressure) acting on invert was carried out in this study (Mochida 2021). At first, the ground element below invert (the red ground element in Step 1) is removed and the displacement of each node of the element below the shotcrete fixed. The horizontal and vertical reaction forces of the fixed shotcrete nodes are then calculated. The calculated nodal loads are applied to each nodal point of the shotcrete with the ground element removed (Step 1) to reproduce the stress state of the shotcrete element before the removal of the element. After that, an equal distribution load is applied vertically upward to the lower part of the shotcrete, and the load assuming the swelling pressure due to the blistering phenomenon is applied to invert. In addition, the area where the equivalent heaving pressure is applied is shown in Table. 2. As for the value of equivalent heaving pressure, the maximum water-absorbing swelling pressure of about 650 kPa has been confirmed by the study of rock tests on samples taken from the section where the deformation occurred during or after the construction of the tunnel was completed (Kawagoe 2016). In this study, it is assumed that the maximum swelling pressure due to heaving acts up to about 650 kPa. By gradually increasing the equivalent heaving pressure up to about 650 kPa, the swelling pressure exerted by heaving on the invert can be expressed in a simple manner, and the influence of the swelling pressure on the invert can be measured.

The next step in this study was to simulate the tensile failure of an invert by heaving. First, the tensile stresses in each element of the invert were calculated. When the tensile strength of the concrete was reached, the Young's modulus of the element was decreased drastically in the analysis. In this way, an attempt was made to represent the damage caused to the invert by heaving (see Fig. 6). The tensile strength of the concrete was calculated according to the following Eq. (1) (Japan Society of Civil Engineers 2017).

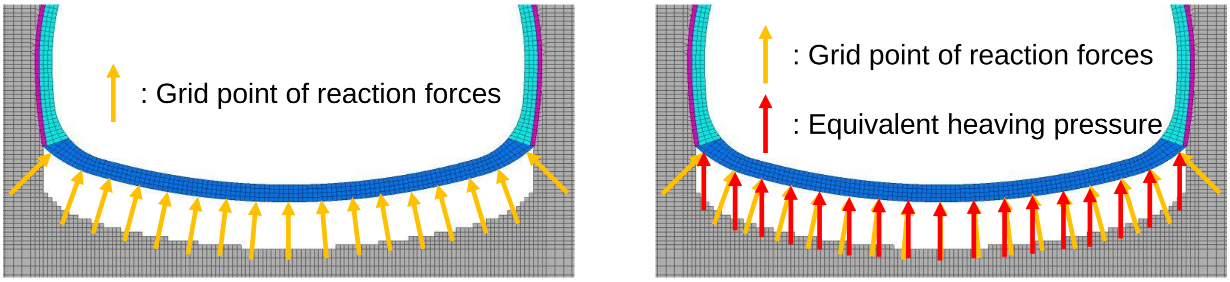
$$f_t = 0.23 \times f_c'^{\frac{2}{3}} \qquad (1)$$

where f_t is the tensile strength of concrete (MPa) and f_c' is the uniaxial compressive strength of concrete (MPa).



Step 1: Remove the ground elements in the red area

Step 2: Fixed element grid-point at the bottom of the invert to calculate reaction forces

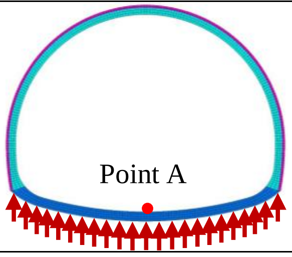
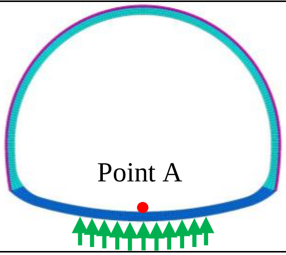
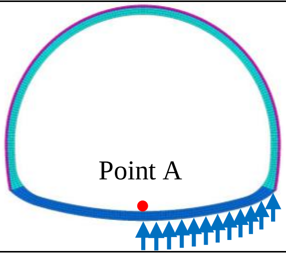


Step 3: Apply reaction forces to grid-point

Step 4: Apply vertical load (equivalent heaving pressure)

Fig. 5 The process of developmental analysis of heaving (Mochida 2021)

Table. 2 Analysis cases

	Analysis cases		
	Case 1	Case 2	Case 3
	All invert bottom	Center of invert bottom	Half side of invert bottom
Load condition			

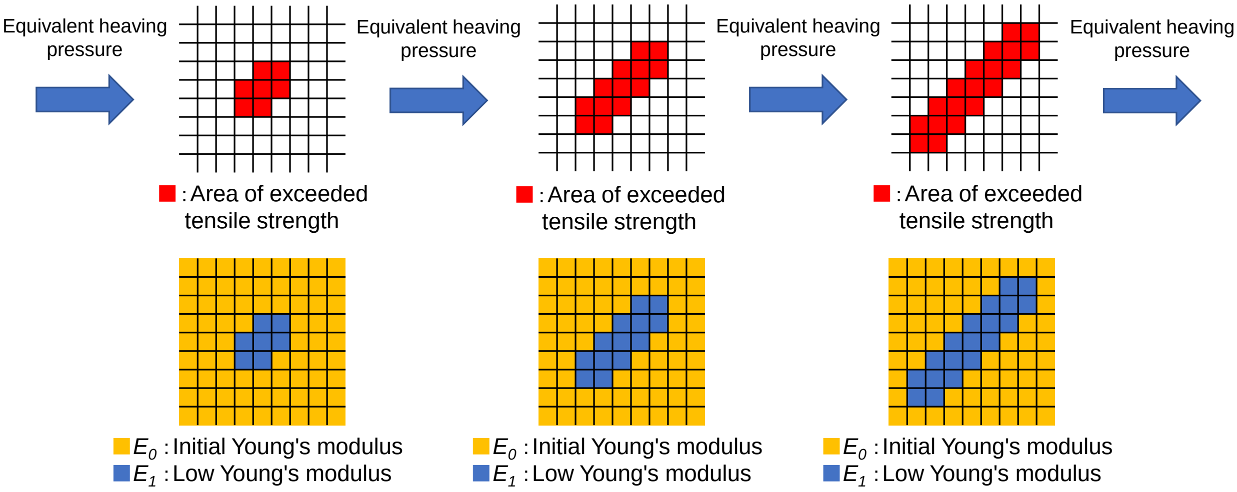


Fig. 6 Process diagram of the invert damage

3. NUMERICAL ANALYSIS RESULTS AND DISCUSSION

3.1 Vertical displacement of invert point A

Fig. 7 shows the change in vertical displacement at point A in the central part of the invert when the equivalent heaving pressure is 100kPa, 190kPa, 290kPa, 380kPa, 480kPa, 570kPa and 670kPa. Fig. 7 shows that the vertical displacement of point A at the central part of the invert gradually increases with the increase of equivalent heaving pressure. This result shows that the central part of the invert is gradually deformed by the action of equivalent heaving pressure.

Next, the effect of the equivalent heaving pressure on the region of the invert is analyzed. From Figure 7, the vertical displacement of point A at the central part of the invert is larger in the order of case1>case2>case3. Especially in case1, the increase of the vertical displacement of the central A point of the invert is remarkable when the equivalent heaving pressure exceeds 190kPa. The maximum deformation of case1 is about 240mm.

In Japanese road tunnels, many cases have been reported in which countermeasures were implemented when the total deformation due to heaving was about 200 mm (Japan Society of Civil Engineers 2013). Therefore, when the entire invert is subjected to equivalent heaving pressure, as in case 1, deformation of more than 200 mm occurs, and early countermeasures are considered necessary. Although the vertical displacement of point A in the central part of the invert increases linearly in case2 and case3, the maximum displacement is 80mm in case2 and 40mm in case3, which is relatively smaller than case1. In case2 and case3, the vertical displacement at point A did not increase as suddenly as in case1. Therefore, the heaving such as case2 and case3 are considered to have a smaller impact on vehicles and other objects travelling in the tunnel than case1. However, since the swelling of swelling clay minerals, which is one of the causes of the heaving phenomenon, may progress long-term and chronically, it is necessary to observe the deformation of the invert for a long time.

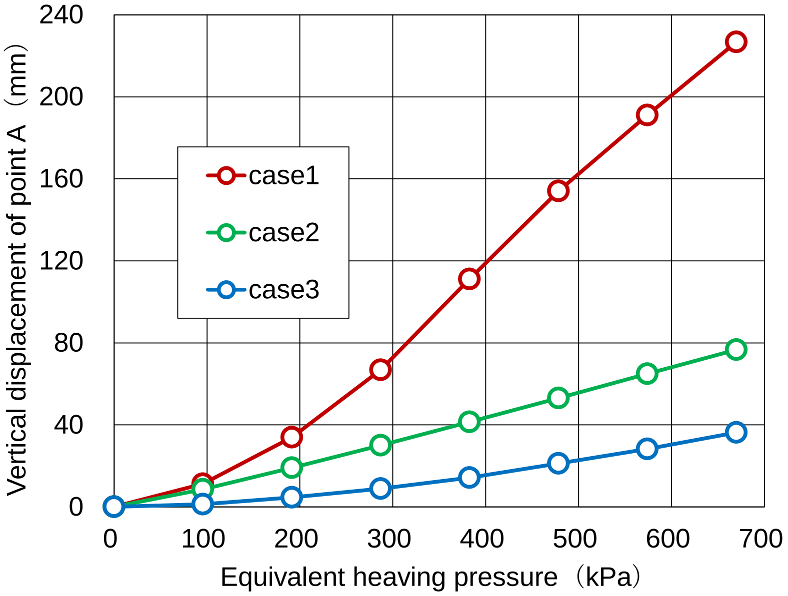


Fig. 7 Relationship between displacement at point A and equivalent heaving pressure

3.2 Tensile stress in the invert in case1

In this study, focus is placed on the change in the stress state of the invert due to the difference in the amount of lifting of point A. Particular attention is paid to case1, where the displacement of point A relative to equivalent heaving pressure is large in the analysis results. Fig. 8 shows the vertical displacement of point A in the central part of the invert and the contours of the tensile stress in the invert for the equivalent heaving pressure of case 1. In the contours in Fig. 8, the points where the tensile strength of the concrete is exceeded are shown in red. From Fig. 8, as the displacement at point A increases, the area of tensile stress exceeded gradually increases near the C.L. and at the point where the curvature of the invert is small. This indicates that the invert damage can be represented to some extent.

Since the invert is located under the road surface, it is difficult to investigate the condition of the invert while the tunnel service. Therefore, the measurement of the amount of heaving in the tunnel in service could be compared with the results of the numerical analysis in this study to determine the degree of damage of the invert in the tunnel in service.

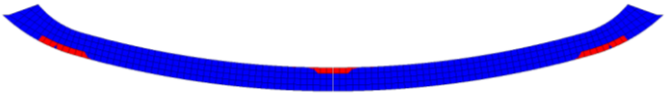
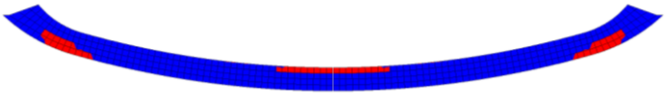
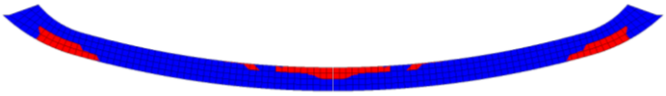
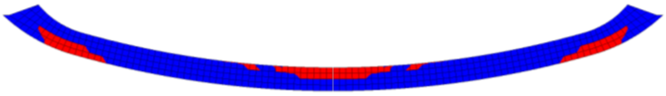
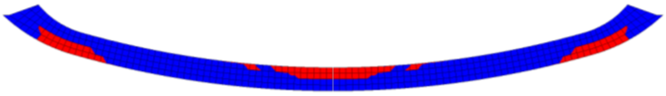
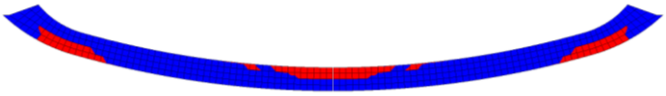
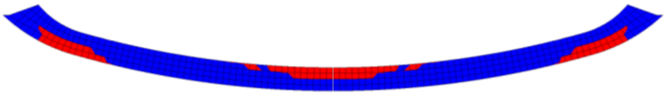
Equivalent heaving pressure (kPa)	Vertical displacement of point A (mm)	Contour	Legend
100	11		🟥$\geq f_t$
190	33		
290	66		
380	111		
480	154		
570	191		
670	227		

Fig. 8 Variation of tensile stress in the invert in case1

4. CONCLUTION

In this study, a numerical analysis was carried out to clarify the relationship between the degree of heaving and the condition of the invert in a tunnel where the invert was constructed during tunnel excavation. As a result, the following points were found.

(1) It was found that the vertical displacement of the central point A of the invert gradually increased with increasing equivalent heaving pressure. It was also found that the central part of the invert was gradually increased by the action of equivalent heaving pressure, which deformed the invert.

(2) It was found that as the displacement at point A increased, the area of tensile stress exceeded gradually increased near the C.L. and at the point where the curvature of the invert was small, indicating that the invert damage could be expressed to some extent.

(3) Since the invert is located under the road surface in the maintenance of tunnels, it is difficult to investigate the condition of the invert while the tunnel is in service. The measurement of the amount of heaving in the tunnel while the tunnel is in service can be compared with the results of the numerical analysis in this study to determine the degree of damage of the invert while the tunnel is in service.

In the meantime, the analysis of other support patterns will be performed and the consistency with real phenomenon will be studied.

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