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NUMERICAL ANALYSIS TO EXAMINE THE EFFECT OF LANDSLIDES ON TUNNELS

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ABSTRACT

In the vicinity of known landslide zones, tunnel routes should be designed such that the distance between the landslide and the tunnel is sufficient to avoid adverse impact of the landslide on the tunnel. This requires a good understanding of the effects of the landslide on the tunnel. We modeled the ground surrounding the tunnel and the landslide using numerical analysis to evaluate the quantitative effect of the tunnel offset from the landslide on ground stresses and displacement of the ground surface and tunnel crown. We considered the effects under different ground conditions and examined two different cases, when the landslide occurs before tunnel construction and where the landslide movement occurs after tunnel construction. We found that the required offset distance between the landslide and the tunnel depended on whether the landslide occurred before or after tunnel excavation and the characteristics of the site conditions, and the method of setting the offset distance needs to consider the conditions at each site. As a result, we conclude that under some conditions, the offset required by current technical standards may be inadequate and further investigation would be required.

INTRODUCTION

The route of mountain tunnels should be designed to avoid any influence from landslides to prevent problems before, during, or after construction. If a planned tunnel is within proximity of a landslide, additional investigations are needed to determine whether construction can proceed or whether a change of route is required (Japan Society of Civil Engineering, 2006a).

In Japan, the distance between a tunnel and landslide zone is established by technical standards that are based on case study sites that indicate the separations required to avoid the effects of existing landslides on nearby tunnels. These examples show that if a tunnel is within 20 m of a landslide, it is necessary to measure landslide movement (Okuzono, 1997; Nippon Road Public Corporation, 1998).

When using the technical standard, it is important to check whether the conditions of the site are suitable for the application of the technical standard or not, because generally the influence of tunnel excavation will be closely related to the ground conditions around the tunnel. Hence it is essential to investigate the characteristics of the site conditions between the planned tunnel and the landslide to enable these conditions to be taken into account when planning a tunnel route. However, the means by which to take the ground conditions into account have not been clearly established.

This paper reports on desktop investigations to evaluate the effect of a landslide on a tunnel by means of numerical analysis. We modeled the ground surrounding the tunnel and the landslide to evaluate the effect of the landslide on the tunnel over a range of offset distances, and identified the minimum offset distance under differing ground conditions. The paper has been prepared from reports already published in Japanese by the Public Works Research Institute (PWRI) based on joint research conducted by five companies (Public Works Research Institute, 2010). In addition, we changed the preconditions for the landslide assumed in the manual, and indicated the necessity to use numerical analysis modeling properly by comparing our results with the requirements of the manual.

METHOD OF NUMERICAL ANALYSIS OF LANDSLIDE AND TUNNEL

This section presents an outline of the method used for numerical analysis, selection of parameter values, and the response variables used.

Method Used for numerical analysis

Numerical analysis, such as the finite element method and distinct element method, is used to model the deformation of ground. For this research, we selected the distinct element method (DEM) to investigate the influence of tunnel excavation on nearby landslides and the influence of the landslide on the tunnel. Using DEM, we performed a sensitivity analysis on the influence of several different ground parameters and tunnel positions on the subsidence by tunnel crown settlement and on strain around the tunnel.

The DEM software used for modeling the landslide and tunnel and to analyze the excavation of the tunnel was UDEC (Itasca Consulting Group Inc., Minneapolis, USA). UDEC is used for simulation of rock fall, toppling and movement along a sliding surface. It can also evaluate large displacement of the model and minute displacement after the excavation of a tunnel, and can be used to apply the finite element method.

UDEC uses block elements for modeling rock and regolith, and joint elements for modeling discontinuous surfaces such as cracks. The block elements are further divided into differential elements, a method which provides the same precision for deformation and stress of rock and soft ground as the finite element method.

In this case, the landslide moving mass and the ground around the tunnel were modeled by block elements, and the sliding surface between them was modeled as a joint element.

The conditions examined in the numerical analysis

A landslide moving mass has a three dimensional geometry, so is normally best modeled by three dimensional analysis. However, the main purpose of this analysis was to identify the interaction between ground condition around the tunnel and the landslide, therefore, a two dimensional analysis was selected.

Figure 1 shows the configuration of the model used for analysis. The model was given a 30-degree decline slope and three components, the landslide moving mass, the bedrock I around tunnel, and bedrock II beneath the tunnel. For the analysis, the position of the tunnel was set in different positions: at the toe, middle, and top of the landslide moving body, and for each tunnel five distances from the landslide were examined: 0.5(D), 1.0(D), 1.5(D), 2.0(D), and 3.0(D), where D is the width of the tunnel.

Table 1 shows the properties of the ground material adopted for the analysis. The material of the landslide moving body was set to detritus, and the material of the bedrock I around the tunnel was set to grade DII or E, as defined by Nippon Expressway Company standard (Test and Research Center of Nippon Road Public Corporation, 1998).

The constitutive law applied was the elastic fully plastic law, and the yield law was defined by Mohr–Coulomb failure criteria. The ground water condition was not considered in the model in this case.

The analysis comprised 30 combinations of tunnel position (3) offset distance (5) and ground material (2).

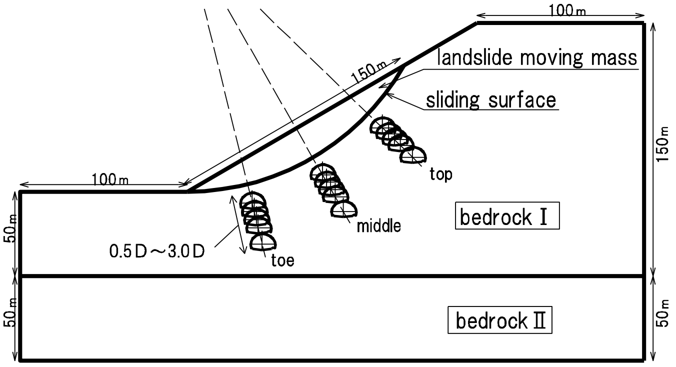


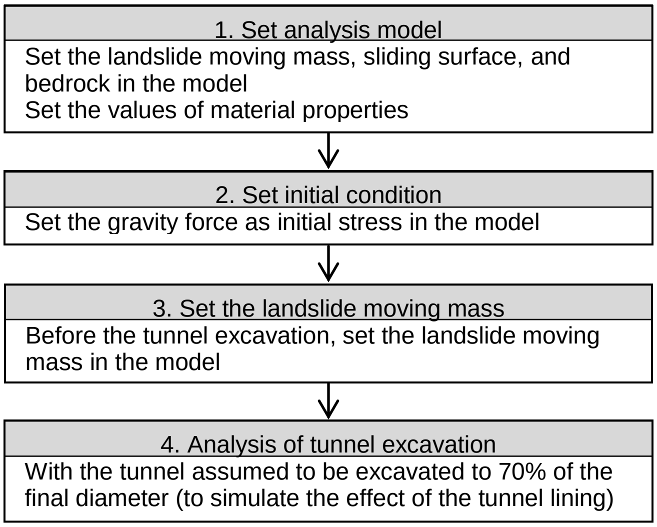
Fig. 1. Configuration of the model used for analysis.

Table 1. Properties of the ground material adopted for analysis

		unit weight γt(kN/m^3)	cohesion c[kN/m^2]	internal friction angle ϕ(°)	poisson's ratio ν	modulus of deformation E[MN/m^2]
landslide moving mass		18.0	20.0	25.0	0.35	50.0
bedrock Ⅰ	grade:E	22.0	100.0	30.0	0.30	100.0
	grade:DⅡ		200.0			150.0
bedrock Ⅱ		22.0	500.0	40.0	0.30	250.0

For the two dimensional analysis of a tunnel, the tunnel excavation process in the model is defined by the excavation rate (Japan Society of Civil Engineering, 2006b). This rate is usually divided into two steps. At first, 30–50% of the total excavation load is set before the installation of the tunnel lining, and then the remaining load is set after that. However in our analysis, the excavation rate of the tunnel provided 70% of the load instead of the lining model, and 30% of the load was regarded as the effect of the lining. This setting was used instead of setting the tunnel lining structure. Figure 2 shows the analysis flow in this case.

The first step was to set the initial stress of the model by gravity load. In this first step, the strength of the sliding surface was given a high value that would not produce a failure. After this step, changes were made as shown in Table 2. The strength property was almost equal to 1.1 of the safety value which is defined by the ratio of normal stress to shear stress.



1. Set analysis model
Set the landslide moving mass, sliding surface, and bedrock in the model
Set the values of material properties

2. Set initial condition
Set the gravity force as initial stress in the model

3. Set the landslide moving mass
Before the tunnel excavation, set the landslide moving mass in the model

4. Analysis of tunnel excavation
With the tunnel assumed to be excavated to 70% of the final diameter (to simulate the effect of the tunnel lining)

Fig. 2. Analysis flow.

Table 2. The strength of sliding surface

	cohesion c[kN/m^2]	internal friction angle ϕ(°)
Sliding surface	20.0	25.0

The response variables

After tunnel excavation, the ground around the tunnel was loosened to represent the landslide acting on a close-set tunnel, and the difference in the offset distance was reflected in the results.

Subsidence of the tunnel crown and the maximum displacement of the landslide moving mass surface for each case are determined for each offset distance.

The results of the analysis included the influence of the offset distance and tunnel depth relative to the landslide. The subsidence of the tunnel crown, for example, is related to the offset distance. The smaller the offset distance the greater the influence. Similarly, subsidence of the tunnel crown is subject to the tunnel depth, the shallower the tunnel, the less the influence. If the tunnel is deep, the initial stress around the tunnel is large, as is the excavation load. As a result, the subsidence of the tunnel crown will be large. The other way of examining the results of the analysis is with respect to the combined influence of the offset distance and the tunnel depth (Fig. 3).

Because the purpose of this analysis was to indicate the influence of the offset distance between the landslide and the tunnel, it was necessary to identify the influence of the offset distance only. To isolate the influence of offset distance, subsidence of the tunnel crown and the maximum displacement of the landslide moving body were measured relative to (divided by) the tunnel depth to give a dimensionless quantity and report it against offset distance. The influence of offset distance was also indicated by the strain around the tunnel.

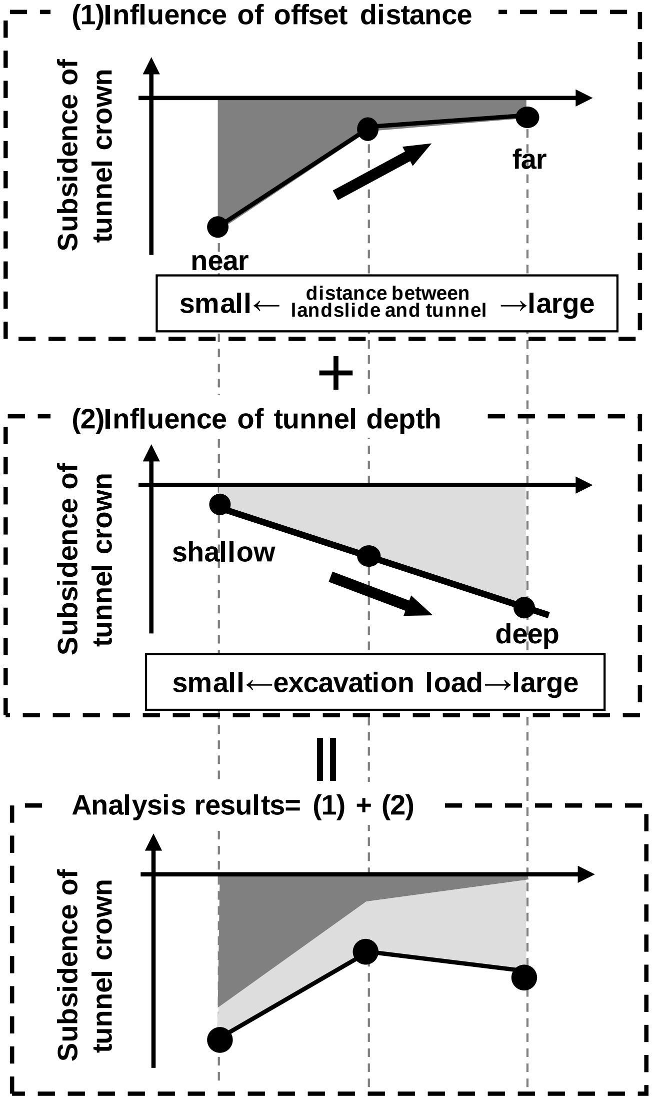


Fig. 3. General anticipated influence of offset distance and tunnel depth on displacement of the tunnel crown.

RESULTS OF ANALYSIS

Tunnel at middle of landslide moving mass

Figure 4 shows the relationship between offset distance and relative subsidence of the tunnel crown and vertical and horizontal displacement of the landslide moving mass surface when the ground property type is set to DII.

Figure 4 indicates the rate of change of subsidence and displacement. The results show that the rate is large from 0.5(D) to 1.0(D) and gradual from 1.0(D) to 2.0(D) and beyond. Figure 5 is the same as for Fig. 4 except that the ground property type is set to E. In this case, the rate of change of displacement is more constant up to 3.0(D) offset distance.

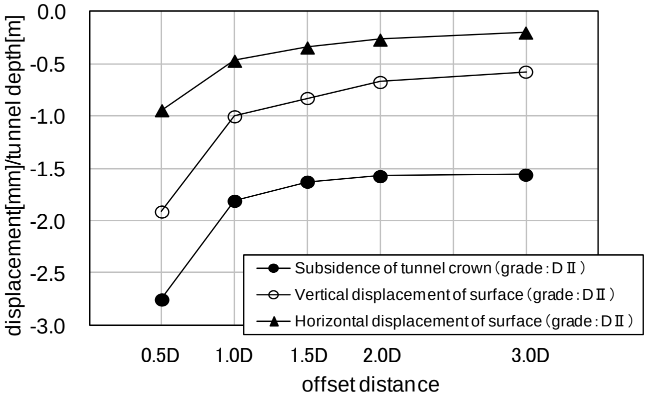


Fig. 4. Relationship between offset distance and three types of displacement for the tunnel position at the middle of the landslide and ground material property type set to DII.

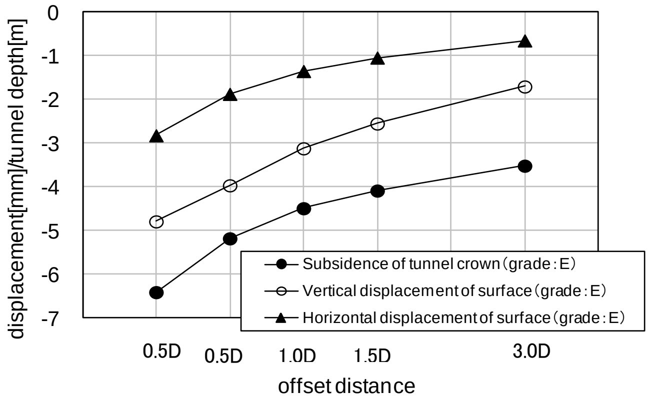


Fig. 5. Relationship between offset distance and three types of displacement for the tunnel position at the middle of the landslide and ground material property type set to E.

Figures 6 and 7 show the distribution of maximum shear strain of the ground after tunnel excavation. The area with strain >1.5% is shaded dark gray to indicate the relative differences between the various cases. These figures show that offset distance influences the distribution range of strain. When the offset distance is 0.5(D), the strain is distributed around the tunnel and inside of the landslide moving mass, but when the offset distance is 1.5(D) or more, very little of the strain is distributed inside the landslide moving mass.

With ground property type E, the strain is distributed inside of the landslide moving mass at each offset distance, and the longer the offset distance, the larger the strain values. This is a result of the tunnel excavation load related to the tunnel depth.

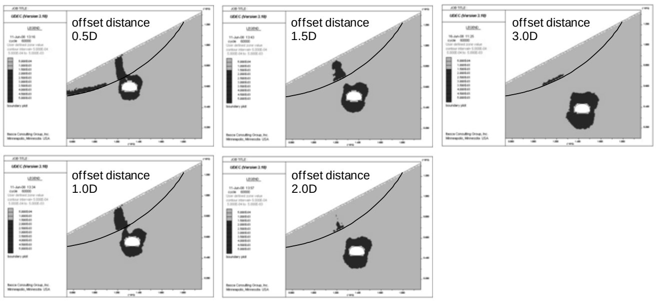


Fig. 6. The distribution of maximum shear strain after tunnel excavation (strain >1.5% is shaded dark gray; ground material property type: DII).

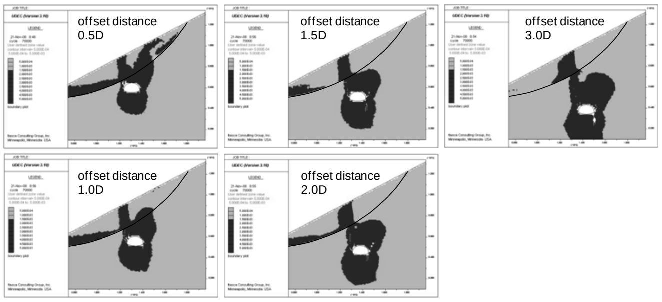


Fig. 7. The distribution of maximum shear strain after tunnel excavation (strain >1.5% is shaded dark gray; ground material property type: E).

Tunnel at toe and top of the landslide moving mass

Figures 8 and 9 show the relationship between offset distance and relative subsidence of the tunnel crown and vertical and horizontal displacement of the landslide moving mass surface when the tunnel position is set to the toe and top of the landslide. Figures 10 and 11 indicate where strain >1.5% with offset distances of 0.5(D) and 3.0(D).

The rate of change of each displacement when the tunnel position was set to toe tended to converge on a steady value over 2.0(D) regardless of the ground condition.

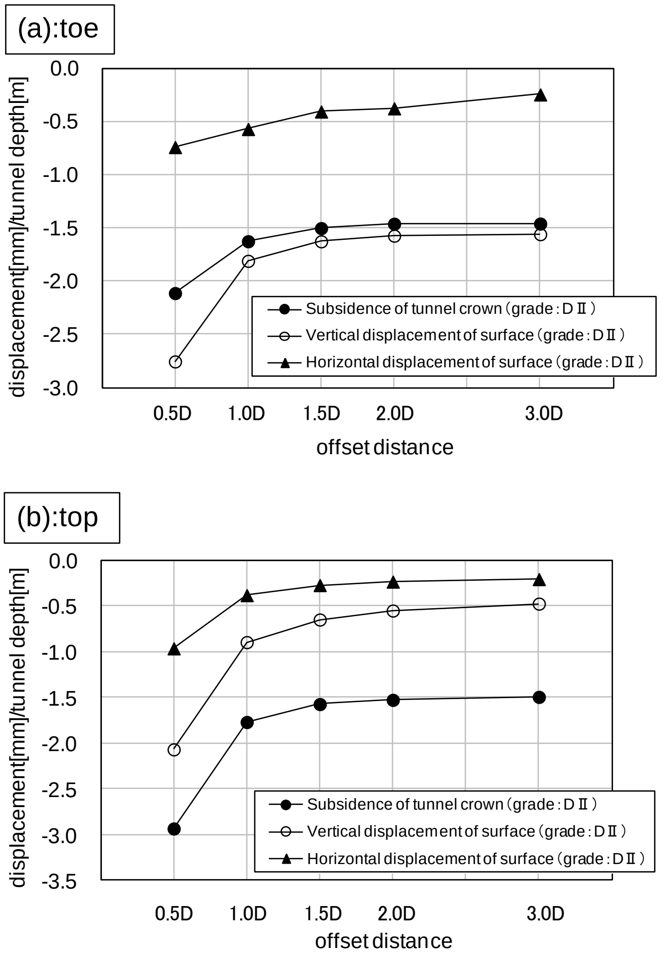


Fig. 8. Relationship between offset distance and relative displacement for ground material type DII when the tunnel position is at (a) the toe and (b) the top of the landslide.

When the tunnel position was set to top and the ground condition was set to E, no convergence on a steady value was recorded even at an offset distance of 3.0(D).

In this case, the strain was distributed around the tunnel and inside the landslide moving mass (see Figs. 10 and 11), so this indicated that the tunnel excavation affected the landslide moving mass.

A summary of the results of the analysis for each tunnel position and ground property type is as follows:

1. When the ground conditions around the tunnel were set to DII, the rate of change in displacement became mostly independent of offset distance at offset distances greater than 2.0(D). The present technical standard indicates that the offset distance should be greater than 2.0(D), so the results of the analysis suggest that the standard value can be reduced to 2.0(D) (Japan Road Association, 2010; Express Highway Research Foundation of Japan, 1981).
2. When the ground condition around the tunnel was set to E, the rate of change in displacement was dependent on tunnel position. If the tunnel position was set to the toe of the landslide, the rate of change of displacement tended to converge on a steady value at offset distances over 2.0(D), but if the tunnel position was set to middle or top of the landslide, the displacement steadily varied with offset distance up to 3.0(D).

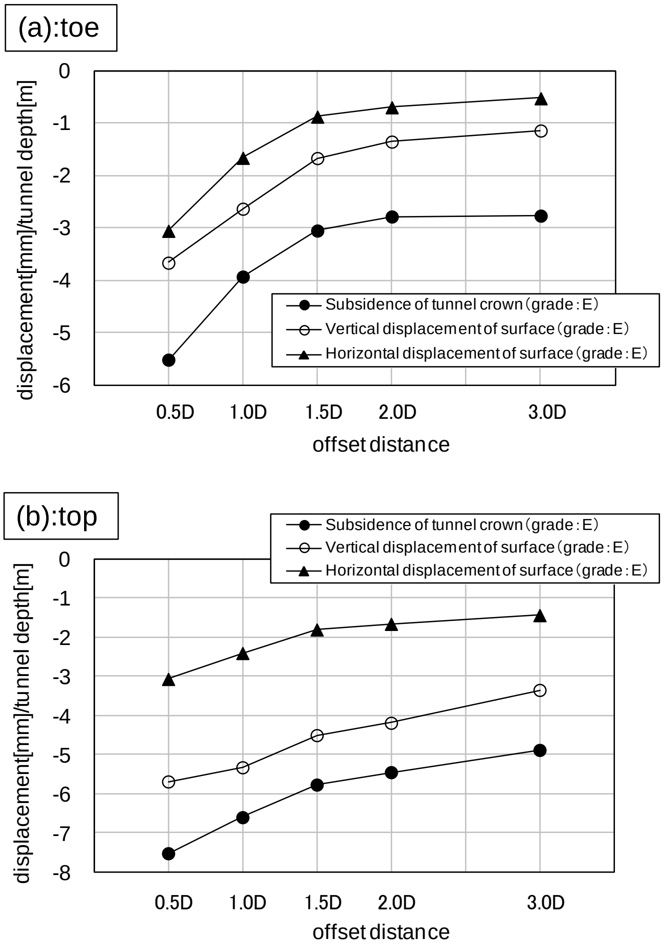


Fig. 9. Relationship between offset distance and vertical and horizontal displacement when the tunnel position is at (a) the toe and (b) the top of the landslide and the ground material property type is set to E.

In the current technical standard, the offset distance is 2.0D, but the above results show that the required offset depends on the ground condition around the tunnel and the position of the tunnel relative to the landslide. Therefore, both of these factors must be considered when examining a tunnel route, and the use of numerical analysis that can take account of ground condition appears to be an effective method for doing so.

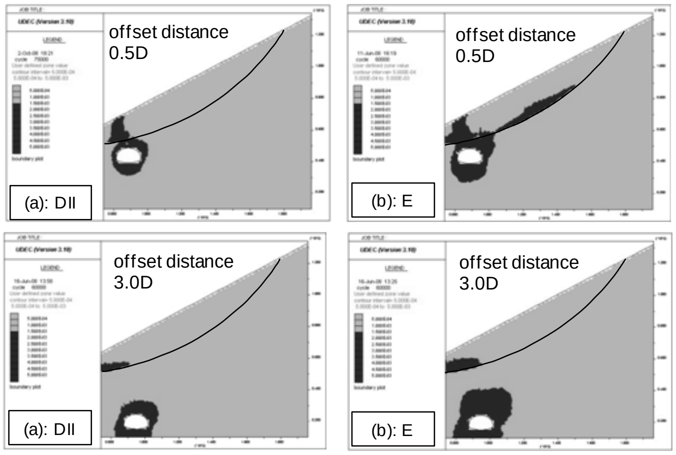


Fig. 10. The distribution of maximum shear strain after tunnel excavation when the tunnel position is at the toe of the landslide and the ground material property type is set to (a) DII and (b) E.

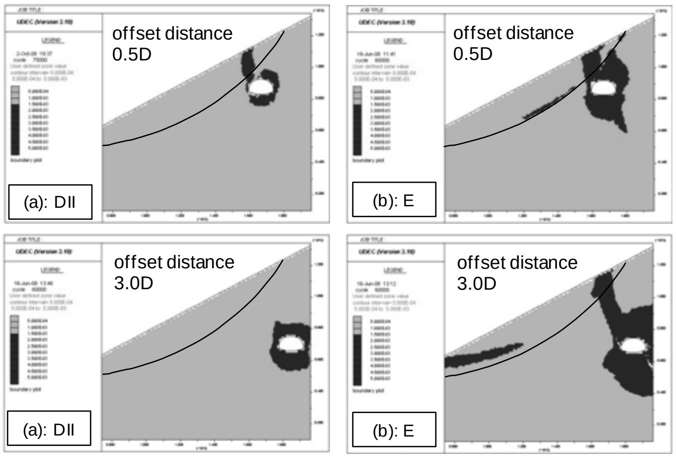


Fig. 11. The distribution of maximum shear strain after tunnel excavation when the tunnel position is at the top of the landslide and the ground material property type is set to (a) DII and (b) E.

EFFECT ON TUNNEL IF THE LANDSLIDE MOVES AFTER TUNNEL EXCAVATION

Before section deal with the tunnel route selection after the landslide has already moved, but it is also necessary to consider the influence of the landslide if it moves after tunnel construction. Therefore, most of the displacement in the previous analysis did not include any movement of the landslide. Figure 12 shows the displacement after tunnel excavation when the landslide moved prior to tunnel excavation. This figure shows that the landslide moving mass is not sliding along the sliding surface.

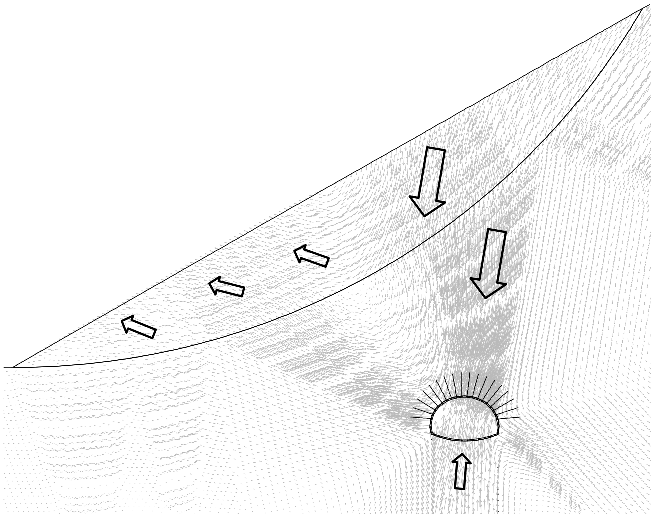


Fig. 12. The displacement when the landslide moved before tunnel excavation.

If the potential landslide was not identified prior to the tunnel excavation, and moved after tunnel excavation, the moving mass should be built into the analysis model after tunnel excavation. We assumed the landslide moved after tunnel excavation and indicated the influence on the tunnel of the landslide moving.

Method of analysis

We examined the influence on the tunnel of landslide moving after tunnel excavation by conducting the analysis for six different offset distances, 0.5(D), 1.0(D), 1.5(D), 2.0(D), 3.0(D), and 3.5(D) shown in Fig. 13. The properties of the ground material were set as Table 1, and the material of the bedrock I around the tunnel was set to grade DII.

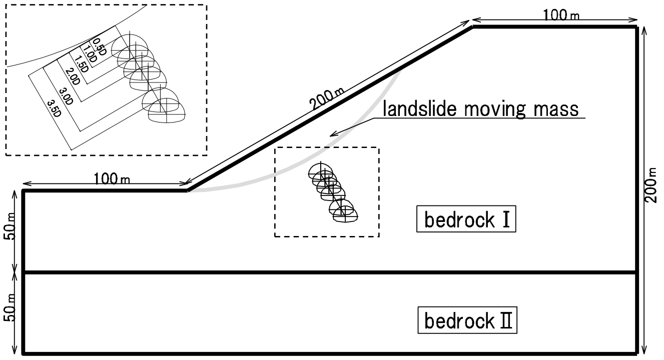


Fig. 13. The model used for analysis.

Results of analysis

Figure 14 shows the amount of subsidence of the tunnel crown for the landslide moving after excavation and that for the landslide having moved before tunnel excavation. This subsidence is the combined displacement after the tunnel lining structures are completed (which can in practice be measured) and the displacement during tunnel construction (which cannot in practice be measured, but can be estimated by numerical analysis).

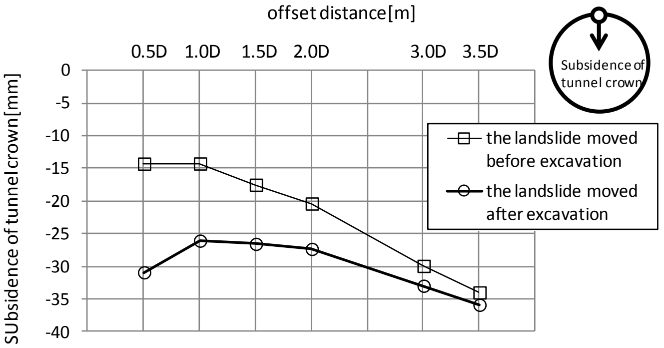


Fig. 14. The subsidence associated with each offset distance.

From 0.5(D) to 1.0(D), the amount of subsidence decreased when the landslide moved after construction and remained the same for when the landslide had moved prior to construction. After that though, in both models the amount of subsidence increased with offset distance. The amount of subsidence was greater when the landslide moved after the tunnel was constructed, but the difference between the two models decreased as the offset distance increased (Fig. 15).

Figure 15 shows the displacement caused by the landslide moving after tunnel construction used from this analysis. It shows that the direction of movement of the sliding mass is towards the toe of the slope and the movement has affected the tunnel.

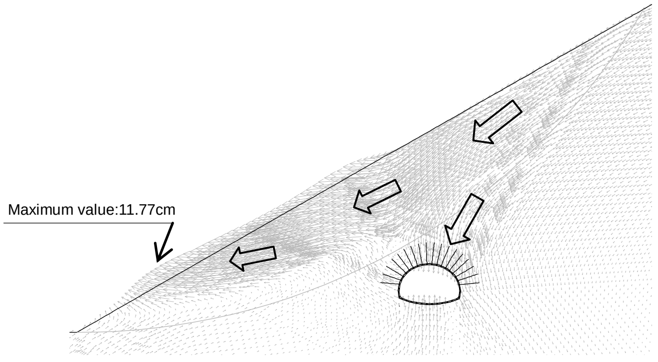


Fig. 15. The displacement of the landslide moving after tunnel excavation.

Comparison with results of when the landslide moved before excavation

Figure 14 shows the difference in displacement between the cases when the landslide movement is assumed to occur before tunnel excavation versus after tunnel excavation. The difference in the amount of subsidence of the tunnel crown in each case shows the importance of the assumptions on the conditions of each site. The implications of the comparison of the results of displacement when the landslide moved before and after excavation are discussed below.

The subsidence of the tunnel crown occurred by displacement after the tunnel support structures had been completed, and this is the only displacement when the landslide moves before tunnel excavation. But in the case where the landslide moves after tunnel excavation, the displacement includes both that triggered by the landslide movement and that of the crown subsidence following completion of the tunnel support structures. Therefore the displacement of this analysis is larger than the previous. Figure 16 presents this diagrammatically.

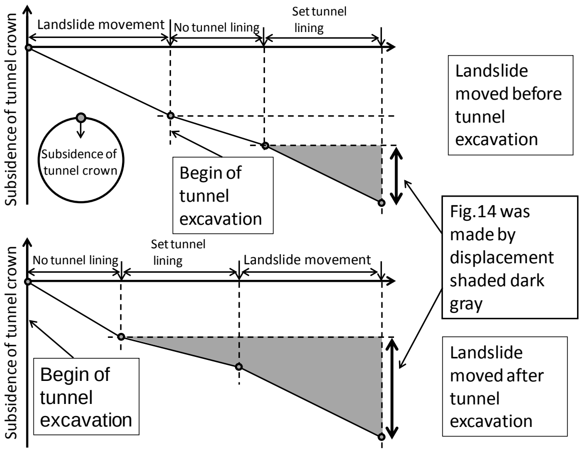


Fig. 16. Diagrammatic representation of the difference in sequence of events and displacement when the landslide occurs before or after tunnel construction.

In the beginning of this chapter, we discussed how the route of a tunnel should be designed to consider the distance from a landslide to avoid any adverse influence on the tunnel. So it is necessary to decrease the displacement that occurs when the landslide moves after tunnel excavation closer to that when it moves before tunnel excavation (Fig. 17).

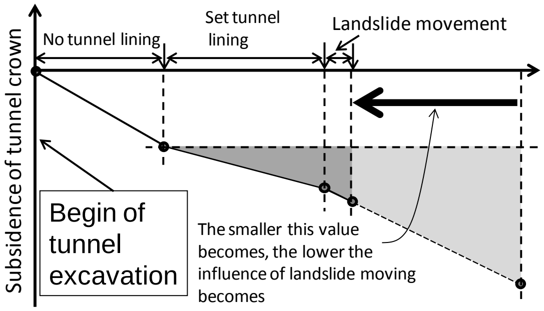


Fig. 17. The case which the displacement by landslide reduced.

The subsidence of the tunnel crown obtained in this analysis approximated that of when the landslide had moved before excavation, which indicates that the landslide moving after tunnel excavation did not have a large influence on crown subsidence. When the offset distance of the both results is the same, the offset value that should be adopted is the value of offset distance for the case of the landslide moving after tunnel excavation.

Figure 14 shows that the offset distance in both analyses almost agrees at 3.5(D), which is the safe offset distance in this case. In the previous results, the safe offset distance was 2.0(D) at material property type DII. Therefore, when we assume that the landslide occurs after tunnel excavation, the safe offset distance is larger than when the landslide occurs before tunnel excavation. Thus, when landslide movement can be expected after tunnel excavation, based on the site assessment, the offset distance should not be determined using an analysis that assumes the landslide occurs before tunnel construction.

In addition, this results show that the safe offset distance depends on the assumed mechanism of the landslide movement with tunnel excavation, so sufficient consideration needs to be given to the landslide mechanism for setting the offset distance.

SUMMARY OF RESULTS

Numerical analysis indicated the effect of a landslide on a nearby tunnel by parametric analysis. The results of the analysis can be summarized as follows:

1. As the offset distance increased, the rate of change in subsidence of the tunnel crown relative to the tunnel depth and the maximum displacement of the landslide moving mass decreased. This indicated that when the rate of change is large, particular caution is required when the tunnel route is being examined, and that the rate of change in displacement divided by the tunnel depth (relative displacement) was a meaningful measurement for determining the appropriate offset distance.
2. When the ground condition around the tunnel was set to type DII, a sufficient offset distance between the tunnel and the landslide was 2.0(D) or greater. However, when the ground condition around the tunnel was set to type E, the rate of change in displacement did not converge on a constant value over 2.0(D). The offset distance in the current technical standard is 2.0(D). The results indicated that the offset distance actually needs to be determined according to the ground condition.
3. The distribution of strain after tunnel excavation depended on the offset distance, and that inside the landslide moving mass was determined by the offset distance.
4. The results of the analysis for the case when the landslide occurred after tunnel excavation showed that the required offset distance depended on the model conditions.

FUTURE DIRECTIONS

In order to model the mechanism of when the landslide moved again after tunnel excavation, it is necessary to use numerical analysis to take into consideration the effect of tunnel excavation on the reduction in strength of the sliding surface from the ultimate equilibrium situation. This analysis also needs to consider in detail the influence of the tunnel support structures on the tunnel displacement and landslide movement. The mechanism of landslide movement by tunnel excavation is complex at each site. Numerical analysis modeling can be further developed by applying the characteristics of each site condition.

REFERENCES

Express Highway Research Foundation of Japan. [1981]. *"The research report for countermeasure of landslide and collapse around tunnel pit"*. (In Japanese)

Japan Road Association. [2010]. "*Road Earthwork Standard – Cutting Slope and Slope Stability*". (In Japanese)

Japan Society of Civil Engineering [2006a]. "*Tunnel Standard Manual — Mountain Tunneling".* (In Japanese)

Japan Society of Civil Engineering [2006b]. "Model Experiments and Numerical Analyses in Mountain Tunneling". *Tunnel Library, No.16.* (In Japanese)

Nippon Road Public Corporation. [1998]. *"Design method series No.1"*. (In Japanese)

Okuzono, S. [1997]. "Approach to stability analysis conditions in preventive measures for landslide of a tunnel pit mouth". *Landslide Technical Journal, Vol.23, No.3.* (In Japanese)

Public Works Research Institute [2010]. "Evaluation technique of landslide on tunnel by numerical analysis". *Public Works Research Institute data No. 4163.* (In Japanese)

Test and Research Center of Nippon Road Public Corporation. [1998]. "Numerical analysis for tunnel manual". *Test and Research Center Technical Data No.358.* (In Japanese)