A Numerical Investigation for Rock Fall Impact Behavior of Pithead of Tunnel with Falling Weight Impact Loading

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Abstract

In order to establish a rational impact resistant design procedure for Arch type rock-shelter based on not only allowable stress design but also on ultimate state design and/or performance based design method, impact resistant capacity and/or maximum input impact energy for the RC structures must be clearly estimated. At present, the RC structures have been designed statically based on allowable stress design method. Here, maximum input impact energy for reaching ultimate state was numerically estimated by means of three-dimensional elasto-plastic finite element method for existing real arch-type RC rock-shelters with sand-cushion and EPS layer under falling heavy-weight impact loading. In this numerical analysis, solid elements were employed for concrete, falling heavy-weight and sand-cushion, and beam elements for rebar. Drucker-Prager and rebar yield criteria were used as material constitutive law for concrete and rebar, respectively. Cracks were estimated by allowing tensile stress cut-off at reaching at the tensile strength. In this paper, weight impact force, total axial force at the side-walls, displacement wave at the loading point, and crack patterns of the shelter at the time occurring of the maximum displacement are output. The results obtained from this study are as follows; 1). About twice the bending moment are generated at the edge as compare to the centre of falling weight in the direction of road axis. 2) It was observed that maximum response generation time of the bending moment and shear force is different. 3) When three layer buffer structure is set up in the tunnel pithead part, the sectional force can be decreased to about 1/2 to 1/5 in the mid-span compared with the case for sand cushion.

***Keywords**: Pithead of tunnel; Three-layered absorbing system; Transmitted impact force; elasto-plastic response*

Introduction

In Japan, many reinforced concrete (RC) arch shelters have been constructed connecting to road tunnel to protect vehicles and people's lives from falling rocks [1,2,3]. However, usually those shelters have been designed without considering impact loads due to falling rocks. In order to establish a rational impact resistant design procedure for arch type RC rock-shelter based on not only allowable stress design but also ultimate state design and/or performance based design method, impact resistant capacity and/or maximum input impact energy for the RC structures must be clearly estimated. At present, the RC structures have been designed statically based on allowable stress design method.

Here, maximum input impact energy for reaching ultimate state was numerically estimated by means of three-dimensional elasto-plastic finite element method for existing real arch-type RC rock-shelters with sand-cushion and three-layered absorbing system under falling heavy-weight impact loading [4]. To effectively absorb and disperse the impact forces caused due to a rock falling, authors have developed a three layered absorbing system (TLAS) which is composed of

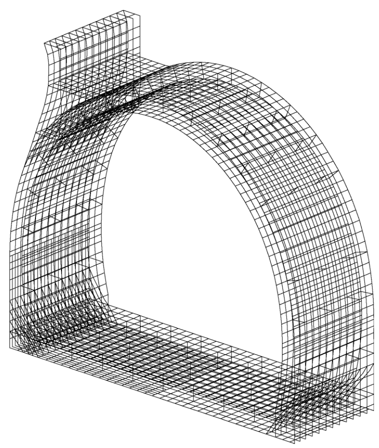
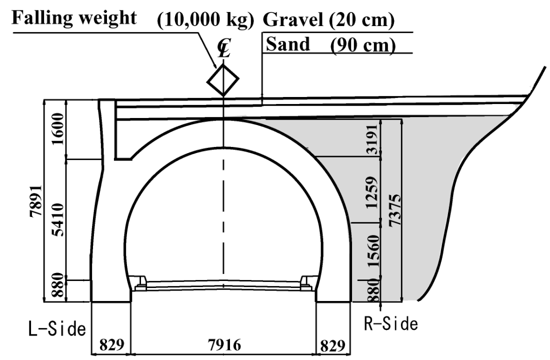
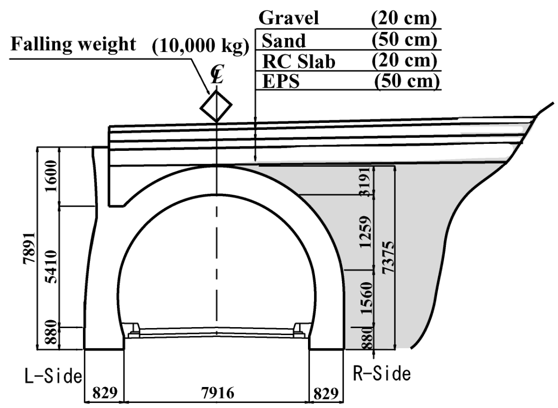


Figure 2. Rebar arrangement of tunnel



(a) Absorbing system with sand cushion

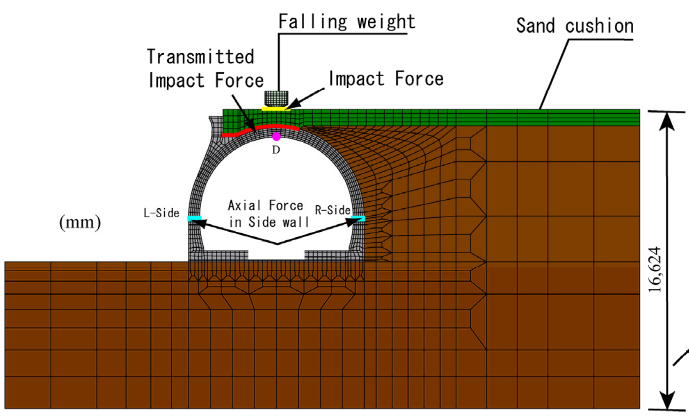


(b) Three layer absorbing system

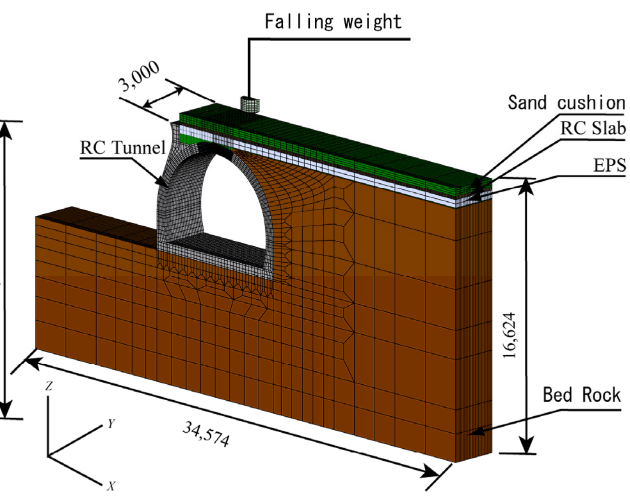
Figure 1. RC Tunnel with two absorbing System

Material Type	**Density**	**Elastic Coefficient**	**Poisson's Ratio**
	ρ (kg/m³)	***E* (GPa)**	***ν***
RC	2,500	25	0.2
Sand	1,600	10	0.06
Concrete	2,350	25	0.167
Rebar	7,850	210	0.3
EPS	20	0.0022	0
Foundation	2,000	0.042	0.45
Falling weight	3,054	210	0.3

Table 1. Material Properties of two absorbing system



(a) Case applying sand cushion



(b) Case applying TLAS

Figure 3. FE mesh model in cases applying two absorbing system

50 cm thick sand layer (top), 20 - 30 cm thick Reinforced Concrete (RC) slab (core) and 50 - 100 cm thick Expanded Poly-Sterol (EPS) block (bottom) layer. For numerical analysis, LS-DYNA® was used [5]. The dimensions of the RC arch tunnel for numerical analysis are of 5,037 mm in inner radius, 7,891 mm in height of side-wall and 6,000 mm in length along the road which is one block of tunnel. 10,000 kg heavy-weight was used as falling weight. In this paper, falling height of heavy-weight was set as 20 m high. In this numerical analysis, solid elements were employed for concrete, falling heavy-weight and sand-cushion, and beam elements for rebar. Drucker-Prager and von Misses yield criteria were used as material constitutive law for concrete and rebar, respectively. Cracks were estimated by using smeared crack model by cutting-off the tensile stress at zero level when average tensile stress in element reaches at the tensile strength. In this paper, weight impact force, transmitted impact force to the roof of the tunnel, total axial force at each side wall, and displacement wave at the crown, and crack patterns of the shelter at the maximum displacement are output.

The results obtained from this study are as follows; 1) transmitted impact force is decreased to a half of impact force by applying TLAS; 2) it was observed that maximum response times of the impact force and displacement are different; 3) when TLAS is set up on the tunnel pithead part, the displacement can be decreased to about 3/4 at the crown compared with that the case setting sand cushion.

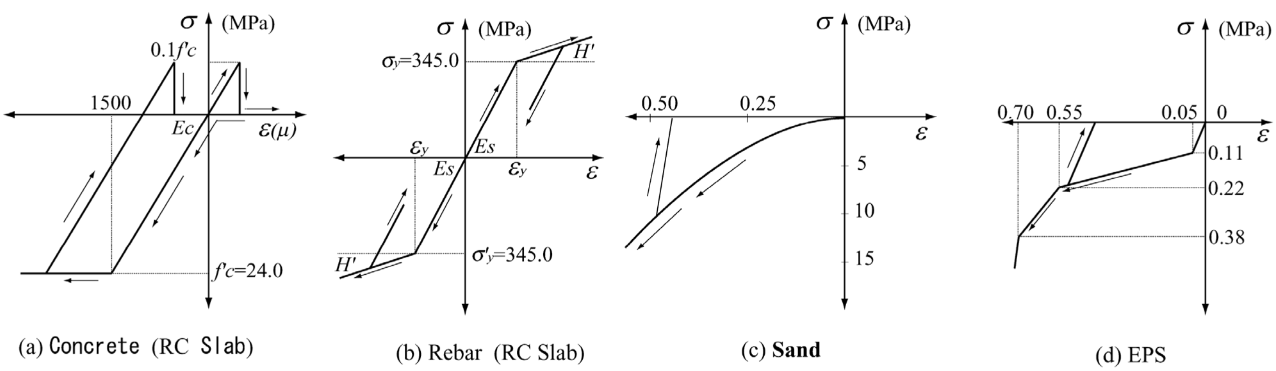


Figure 4. Stress strain relationships of material constitutive models

Outline of Prototype Arch Shape Type Rock Shelter and Absorbing System

The cross-section and absorbing system of the RC arch are shown in Fig. 1. In this figure, the D13 rebars for upper and lower axial ones are arranged taking 100 mm concrete cover. The shear rebars were not arranged. Material properties for each component for two absorbing system; sand cushion and TLAS, are listed in Table.1

Analytical Overview

The objective of this research is to establish an analytical technique that can appropriately simulate the impact behavior of three layer absorbing system of prototype RC arch type shelter. In this analysis method, the same material constitutive laws for concrete and rebar with those in case of analyzing large scale type RC girders were applied [7]. For these investigations, LS-DYNA code (ver.970) was used [5].

FE models

An example of FE numerical analysis model is shown in Fig. 3. Only half of RC arch tunnel model, foundation, a falling heavy-weight, absorbing system: sand cushion; and TLAS were modeled with FE meshes considering symmetrical axis. Six and/or eight node solid elements were applied for all of these FE models except axial rebars. Total number of nodes and elements of the RC arch tunnel model of two absorbing systems shown in Fig. 3 are 60,470 and 63,389 for the case using sand cushion and 70,954 and 75,451 for the case using TLAS. The rebar arrangement of the RC arch tunnel is shown in Fig. 2.

Numerical analyses models were precisely formed for each component based on the dimensions of the RC arch tunnel model used in the real prototype structure.

However, axial rebars have been simplified as a square element equivalent to an actual cross-sectional area.

Contact surface is defined between striking face of heavy-weight and the upper surface of the absorbing system, in which sliding with contact and separation can be considered in this contact surface applied here. All nodes between concrete and rebar were assumed to be perfectly bonded with each other. Impact force is numerically surcharged against the RC arch tunnel model due to adding a predetermined impact velocity to all nodes of falling heavy-weight which is set on the surface of absorbing system. Impact response analysis for RC arch tunnel model was performed up to 300 ms from the beginning of impact. The time increment for numerical analysis is almost equal to 0.6 ms which is determined based on Courant stability condition.

Modeling of materials

Figure 4 shows the stress-strain relations for each material: concrete; rebar; sand; and EPS block. Neither strain rate effects of all materials nor softening phenomenon of the post peak of concrete were considered for this elasto-plastic impact response analysis. However, to accurately simulate a damped free vibration of the RC arch tunnel model after a heavy-weight rebounded, damping constant h was considered. The constitutive law for each material characteristics is briefly outlined below:

(1) Concrete

Stress-strain relation of concrete was assumed by using a bilinear model in compression side and a cut-off model in tension side as shown in Fig. 4(a). Namely, 1) yielding stress is equal to compressive strength f'_c; 2) compressive strain at the yielding point is equal to 1500 μ strain; 3) the tensile stress is steeply decreased to zero when an applied pressure reaches the ultimate tensile strength and its value is $1/16^{th}$ of the compressive yielding stress. von Mises yield criterion was applied as the yielding condition in concrete. LS-DYNA material model MAT_SOIL_AND_FOAM_FAILURE was used to model the concrete elements.

(2) Rebar

For main rebar and shear rebar, an elasto-plastic model with isotropic hardening was applied as shown in Fig. 4(b). Here, plastic hardening modulus H' was assumed as 1% of elastic modulus E_s (E_s: young's modulus). Yielding condition was judged based on von Mises yield criterion. LS-DYNA material model MAT_PLASTIC_KINEMATIC was used to model main and shear rebar.

(3) Falling heavy weight

The other elements (falling steel weight, supporting apparatus and anchor plate) were modeled as elastic body based on experimental observations. Young's modulus and Poisson's ratio were assumed as E = 206 GPa and ν_s = 0.3 respectively. LS-DYNA material model MAT_ELASTIC was used to model them.

(4) Sand cushion

Figure 4(c) shows the constitutive model for sand cushion. To rationally analyze in stress behavior of sand cushion when a heavy-weight collides on the cushion, second order parabolic stress-strain relation for sand cushion was assumed in which the constitutive relation is described in the following expression [6].

LS-DYNA material model MAT_CRUSHABLE_FOAM was used to model the Sand cushion.

$$\sigma_s = 50\ \varepsilon_s^2 \tag{1}$$

(5) Expanded Poly-Sterol (EPS) Block

Based on the concept as shown in Fig. 4 (d), it is assumed that the EPS layer will one-dimensionally behave against a collision of a falling rock in an effective area. The stress-strain relation of the EPS layer is multi-linearly modeled based on the curve obtained from the static loading test with 10 mm/min loading speed. In this paper, the maximum design strain of the EPS layer is limited to 0.55 to ensure an absorbing capacity of the TLAS and to keep some safety margin [4]. LS-DYNA material model MAT_CRUSHABLE_FOAM was used to model the Expanded Poly-Sterol (EPS) Block.

(6) Strain rate effects and viscous damping constant

Neither strain rate effects of all material considered here nor softening phenomenon at post-peak of concrete were considered for impact response analysis of the RC arch tunnel models. In addition, to accurately simulate impact response characteristics of the models, a viscous damping constant h was considered. The value was assumed as $h=0.005$ for the lowest natural vibration mode.

Overview of Analytical Results

Time histories of impact force and displacement at crown

The numerical analysis results for time histories of impact force (P), transmitted impact force, estimated summing of response axial force at left and right hand side of wall and displacement at the crown (D) of the RC tunnel model are compared between two cases of applying absorbing systems shown in Fig. 5. The impact force (P) obtained from the numerical analysis was estimated by summing the contact reaction forces in the vertical direction caused in the contact interface elements of falling heavy-weight.

From these figures, it can be observed that the impact force wave (P) is superposed of two waves: a triangular wave having 50 ms duration time; and a half-sinusoidal wave with 100 ms duration time for the case applying sand cushion; and an incidental triangular wave having 25 ms duration time and a half-sinusoidal wave with 100 ms duration time for the case applying TLAS as absorbing system. The configurations of the wave are almost similar for both absorbing systems. By comparing the response reaction forces at the side wall of left and right hand sides,

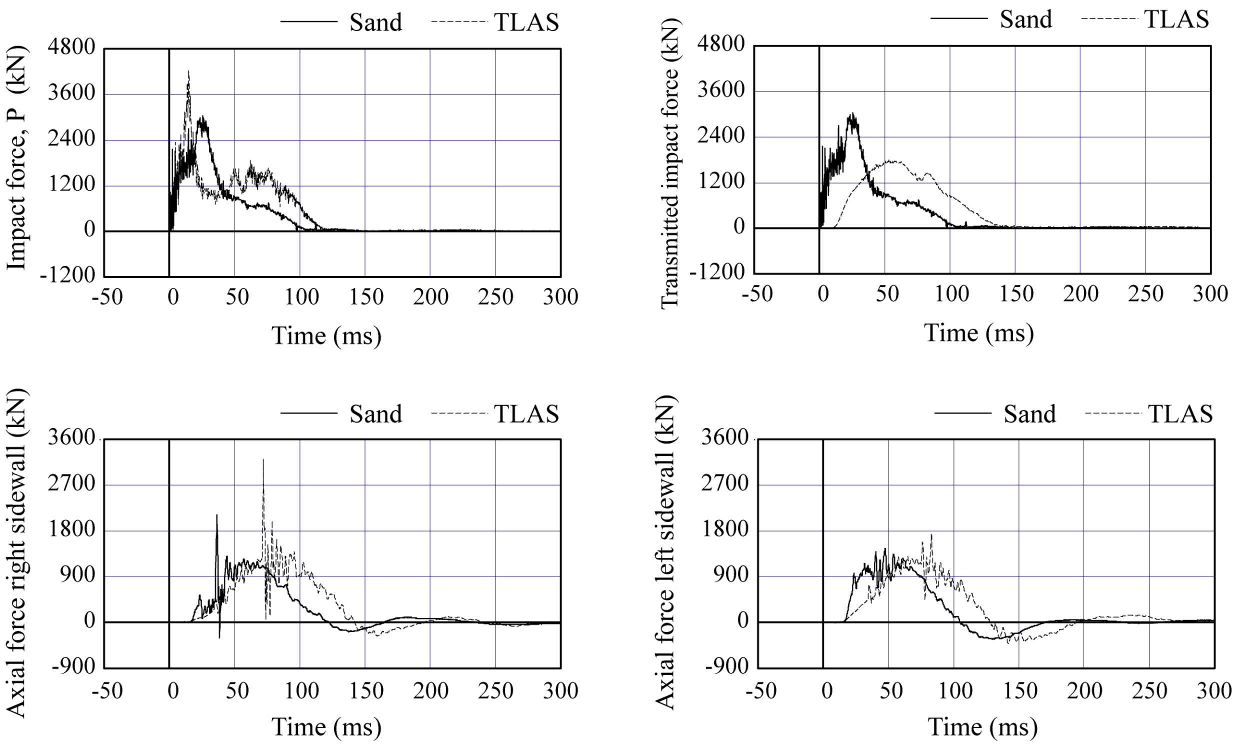


Figure 5. Comparison between two absorbing systems

it is observed that the two waves are almost similar to each other but higher frequency components are excited in the right hand side wall.

In addition, when paying attention to the transmitted impact force after falling weight collides, it is observed that maximum impact force in case applying sand cushion is 1.6 times larger than that of TLAS; and duration time of TLAS is about 50 ms longer than that of the case using sand cushion. By comparing the maximum response values of impact force and transmitted impact force, it is observed that the transmitted impact force is decreased to half and less of the impact force by using the TLAS and sand, respectively.

Focusing on the displacement (*D*) shown in Fig. 6, it is seen that the vibration period after reaching maximum amplitude and the damping characteristics are a little different between sand cushion and TLAS. However, wave configurations from the beginning of impact through the maximum value are almost similar to each other, irrespective of absorbing system. The maximum displacements for sand cushion and TLAS are about 13 and 11 mm, respectively.

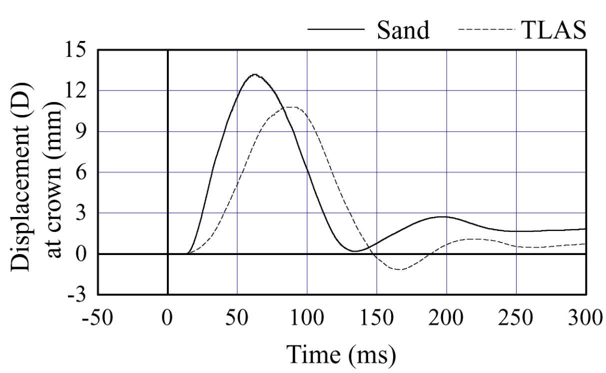


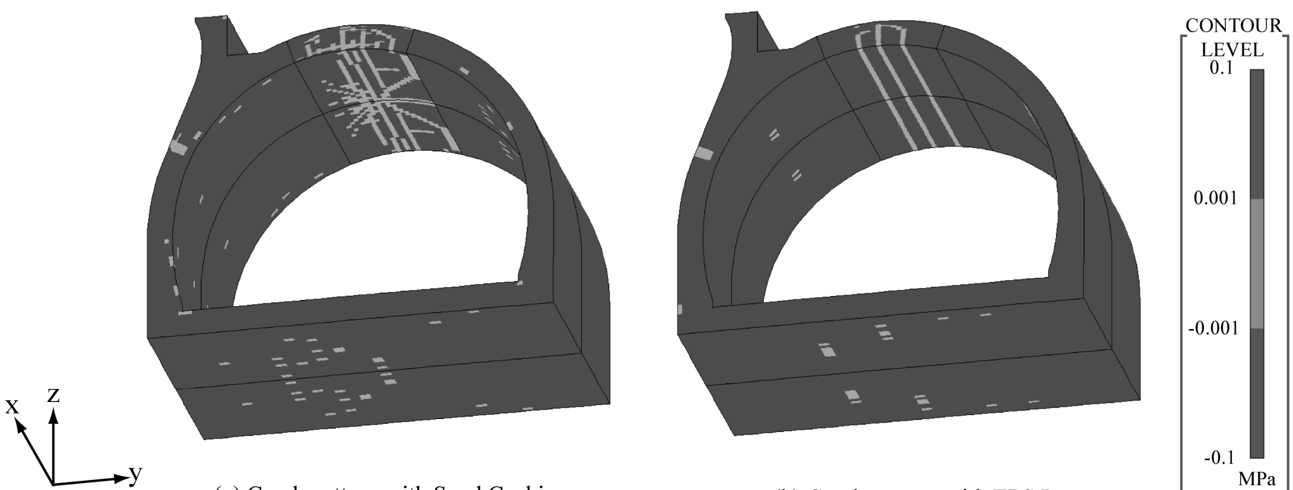
Figure 6. Dislplacement (D) at crown of Tunnel

The RC tunnel model with TLAS vibrates with smaller residual displacement. On the other hand, it is observed that the RC tunnel models vibrate with larger residual displacement and high damping after suffering severe damages in case of sand cushion. The residual displacements for sand cushion and TLAS are about 2 and 1 mm, respectively. The main reasons may be that in case of applying sand cushion, impact force will be concentrically loaded near the crown, but in case applying TLAS, the force will be depressively loaded over the whole of the tunnel.

Crack patterns at maximum response displacement

Based on a constitutive law model assumed for concrete elements earlier, stress applied in the concrete elements will be converted to zero when the applied pressure in an element reaches the tension cut-off value. In other words, it is understood that the element with zero stress has a potential for crack occurring. Here, crack patterns can be predicted based on this concept.

Figure 7 shows the comparisons between the contours of the maximum principal stress at the maximum displacement for applying two absorbing systems. In those figures, white color stress contour means that the elements are around zero stress and crack will be occurred. From those comparisons, it is observed that in case applying sand cushion, cracks are occurred near the loading points and that area was severely damaged; and in case applying TLAS, just three through crack along the tunnel axis were generated. From these results, it is confirmed that impact resistant capacity of the RC arch tunnel can be significantly upgraded apply TLAS as absorbing system.



(a) Crack pattern with Sand Cushion (b) Crack pattern with EPS Layer

Figure 7. Crack Pattern of two absorbing system

Conclusions

An applicability of the proposed FE technique was investigated for two absorbing system by performing the falling-weight impact loading simulation of prototype RC arch tunnel and by comparing with both results. The results obtained from this study are as follows:

1. Transmitted impact force is decreased to a half of impact force by applying TLAS;
2. It was observed that maximum response times of the impact force and displacement are different;
3. When TLAS is set up in the tunnel pithead part, the displacement can be decreased to about 3/4 at the crown compared with that the case setting sand cushion.

4. From the crack pattern, it is confirmed that impact resistant capacity of the RC arch tunnel can be significantly upgraded applying TLAS as absorbing system.

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