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Field falling impact test and numerical study for constituting impact resistant design of arch type RC structures

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ABSTRACT: In this paper, a falling-weight impact test using real arch type RC structures was conducted to verify a proposed impact response analysis method. An applicability of the numerical analysis method was confirmed comparing with the experimental results. And an applicability of the current impact resistant design procedure to the performance based design procedure was investigated using the proposed numerical analysis method. From this study, it is confirmed that applying the current impact resistant design procedure, performance based impact resistant design with enough safety margin may be performed for the arch type RC structures.

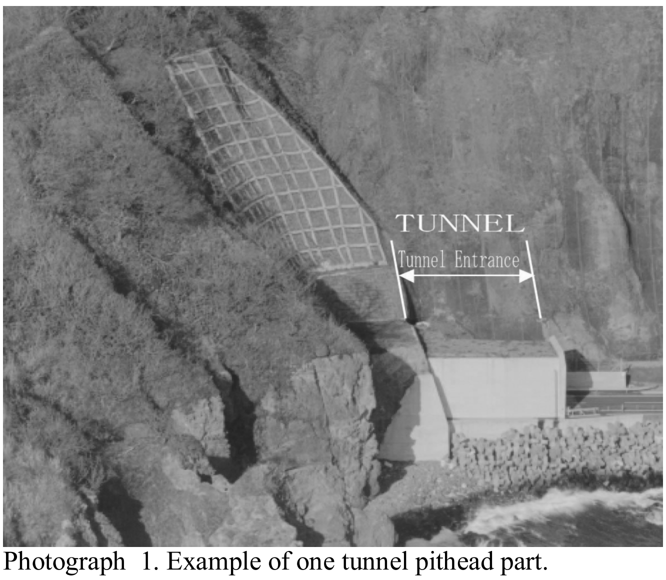
1 INTRODUCTION

The terrain in Japan presents the geographical features that it is narrow, long and slender where the road and the railway are planned unavoidably and constructed along the rapid cliff slope. Moreover, tunnels are constructed when making road plan to secure traffic safety in such restrictions. The entrance of tunnel comes to shoulder the slope as shown in Photograph-1. There is no danger concerning the slope disaster such as falling rocks because enough examination is performed for safety when the route plan is finalized.

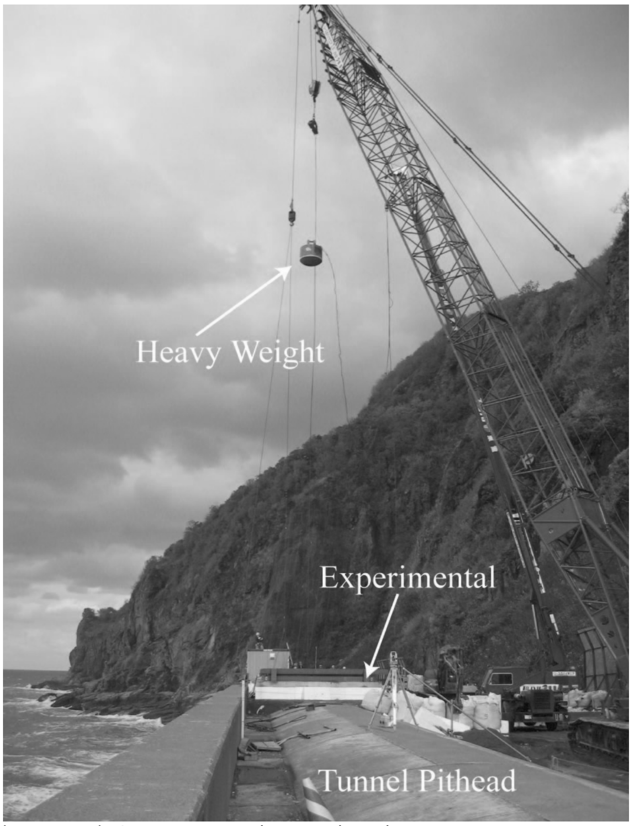
In Japan, many reinforced concrete (RC) arch shelters have been constructed connecting to road tunnel to protect vehicles and people's lives from falling rocks. However, usually those shelters have been designed without considering impact loads due to falling rocks. In order to establish a rational impact 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 and experimentally estimated by means of three-dimensional elasto-plastic finite element method for existing real arch-type RC rock-shelters with sand-cushion under falling heavy-weight impact loading.

For numerical analysis, LSDYNA code was used. In numerical analysis, solid elements were employed for concrete, falling heavy-weight and analysis technique concerning the arch made of RC structure is executed. It was assumed that the applicability of the method for analyzing was verified by numerical analysis when the impact response analysis technique of real scale RC beam



Photograph 1. Example of one tunnel pithead part.



Photograph 2. Two experiment situation.

that authors also examined in past research was applied to the arch made of RC structure, and comparing it with the outcome of an experiment. As a result, it is assumed that both experimental and the numerical results show a brittleness destruction property.

2 EXPERIMENTAL OVERVIEW

2.1 *Experimental methodology*

In Photograph 2 the experimental condition is shown. The experiment does a heavy weight that imitates the falling rock by lifting up through the detaching device, dropping from prescribed height freely, and making it collide with an arch crown central point by the crawler crane. The heavy weight used by the actual experiment was 10,000 Kg mass because it caused big impact energy.

2.2 *Outline of Real Tunnel Pithead Part*

In Figure 1 the shape size and bar arrangement is shown 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 6,000mm 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. In Table 1: The list of an experiment and an analytical case is shown. It is guessed that the damage of the concrete of the arch made of RC structure is negligible as compared to buffer material at the heavy weight collision position in the actual experiment. The height of the fall was increased gradually to attempt good use of the efficiency of the examination block and therefore, it repeated, and it experimented repeatedly. However, buffer material was laid and assumed to exclude the influence by the repetition. As the experiment case four cases are executed about the numerical analysis shown in Table 1.

Table 1. One Experiment and Analytical Case List.

Experimental Case	Impact Load Method	Mass of heavy weight (Kg)	Height of Fall (m)	Concrete strength (MPa)
S-H 2.5			2.5	
S-H 5	Iterative	10,000	5	27.5
S-H 10			10	
S-H 20			20	

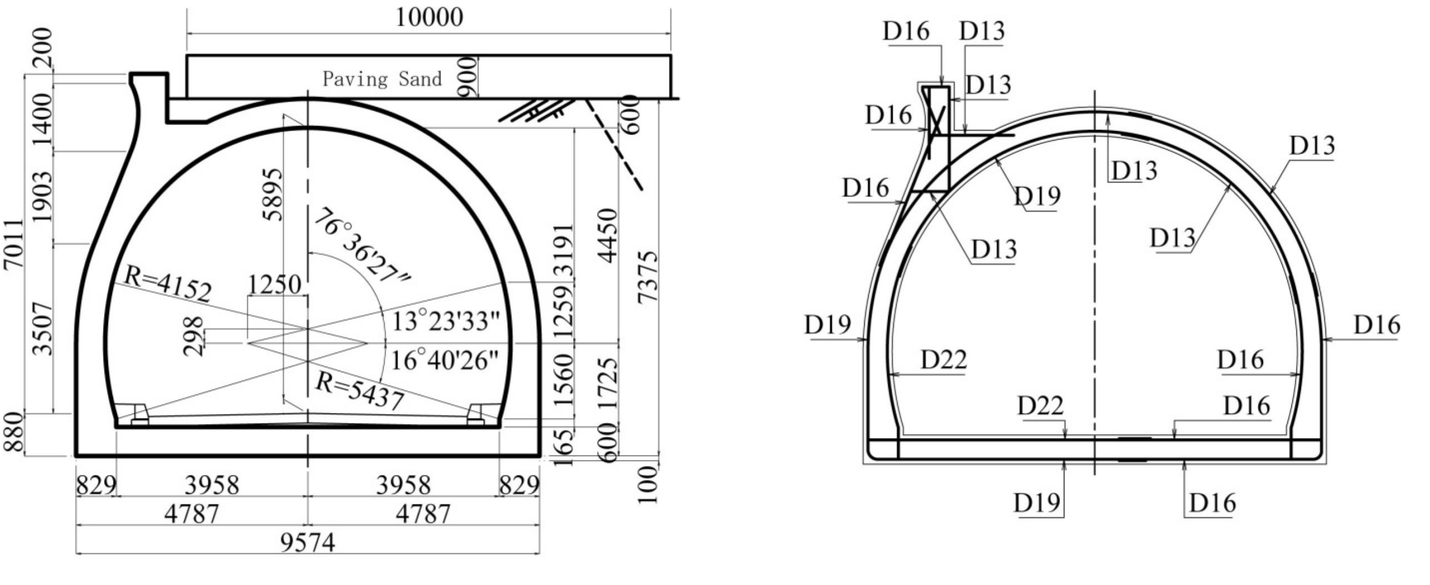
2.3 *Measurement method*

The contactless laser displacement sensor measures the horizontal displacement in perpendicular direction is installed at inner surface of the arch. Load cell for the impact stress measurement also installed, Figure 2 (b).

3 ANALYTICAL ASSUMPTION

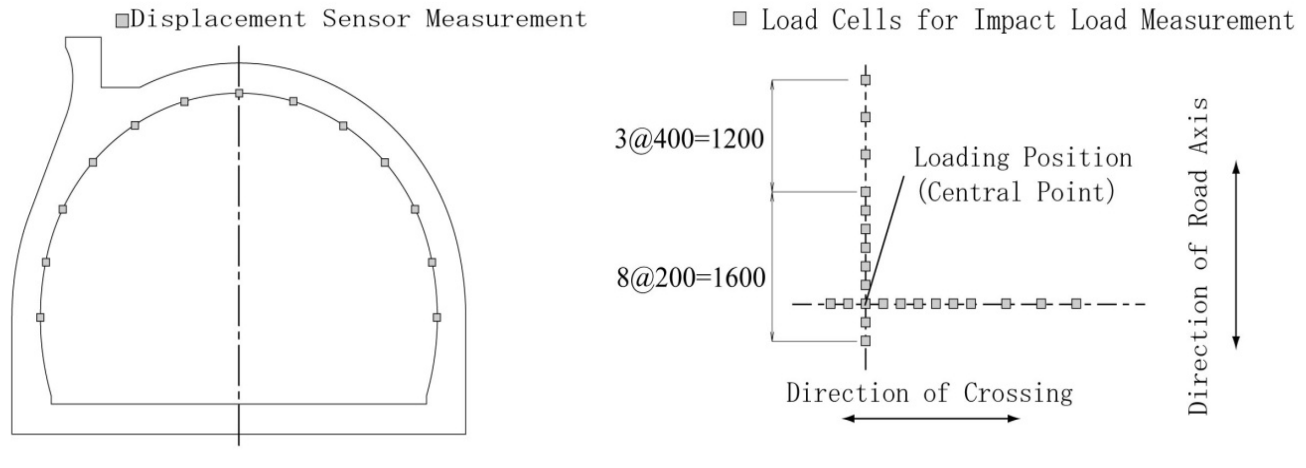
3.1 *Numerical analysis model*

The objectives of this research are 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. For these investigations, LSDYNA code was used. An example of FE numerical analysis model is shown in Figure 3. Only half of RC arch tunnel model, foundation, a falling heavy-weight, absorbing system: sand cushion 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 with absorbing system shown in Figure 3 are 60,470 and 63,389 for the case using sand cushion .The rebar arrangement of the RC arch tunnel is shown in Figure 1(b). 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



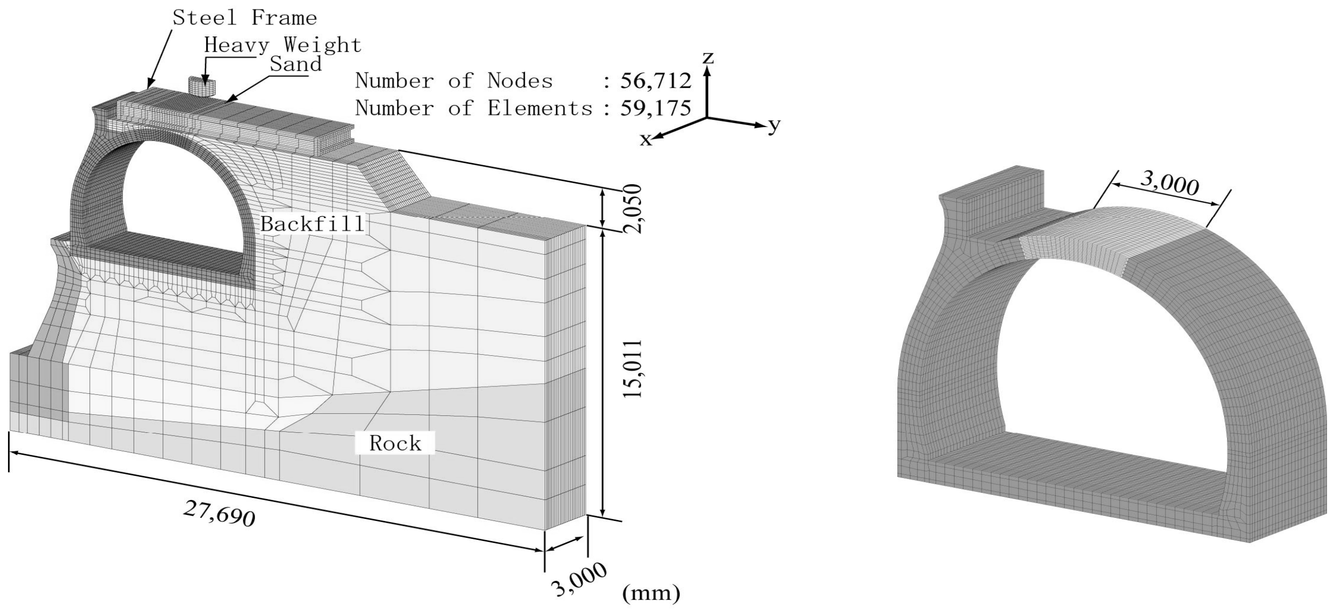
(a) Shape Size (b) Bar Arrangement Situation

Figure 1. Shape size and bar arrangement situation of one real examination body.



(a) Displacement Sensor Measurement (b) Transmission Impact Stress Measurement, plane location map

Figure 2. Measurement Position.



(a) Analytical Modal (b) Arch

Figure 3. Analytical Model.

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.

3.2 *Material physical properties model*

Figure 4 shows the stress-strain relations for each material: concrete; rebar and sand. 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 characteristic is briefly outlined below.

3.2.1 *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 Figure 4(b). 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 1/16th 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.

3.2.2 *Rebar*

For main and shear rebar, an elasto-plastic model with isotropic hardening was applied and plastic hardening modulus *H'* was assumed as 1% of elastic modulus *Es* (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.

3.2.3 *Sand cushion*

Figure 4(a) shows the constitutive model for sand cushion. To rationally analyze stress behavior of sand cushion when 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. LS-DYNA material model MAT_CRUSHABLE_FOAM was used

$$\sigma_{sand} = 50\varepsilon^2_{sand} \quad (1)$$

3.2.4 *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.

3.3 *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.

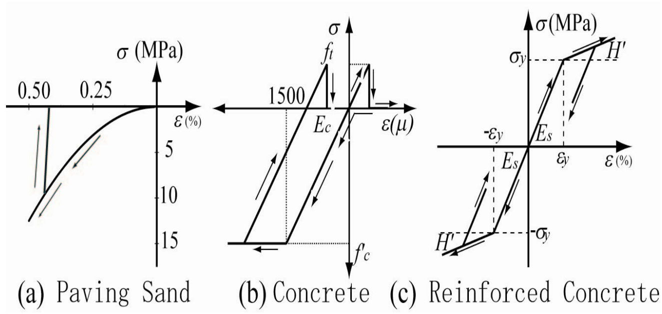


Figure 4. Material physical properties model.

Table 2. Physical properties value list used for two analyses.

Material	Density ρ (kg/m3)	Stiffness coefficient *E* (GPa)	Poisson Ratio ν
Concrete*	2,350	25.0	0.167
Paving Sand	1,600	10.0**	0.060
Reinforced concrete	7,850	206.0	0.300
Backfill soil	2,000		0.68

*When designing, a concrete density and the stiffness coefficient are the values.
**Stiffness coefficient at no load.

4 VERIFICATION OF ACCURACY OF NUMERICAL ANALYSIS

Here, the analytical accuracy of the numerical

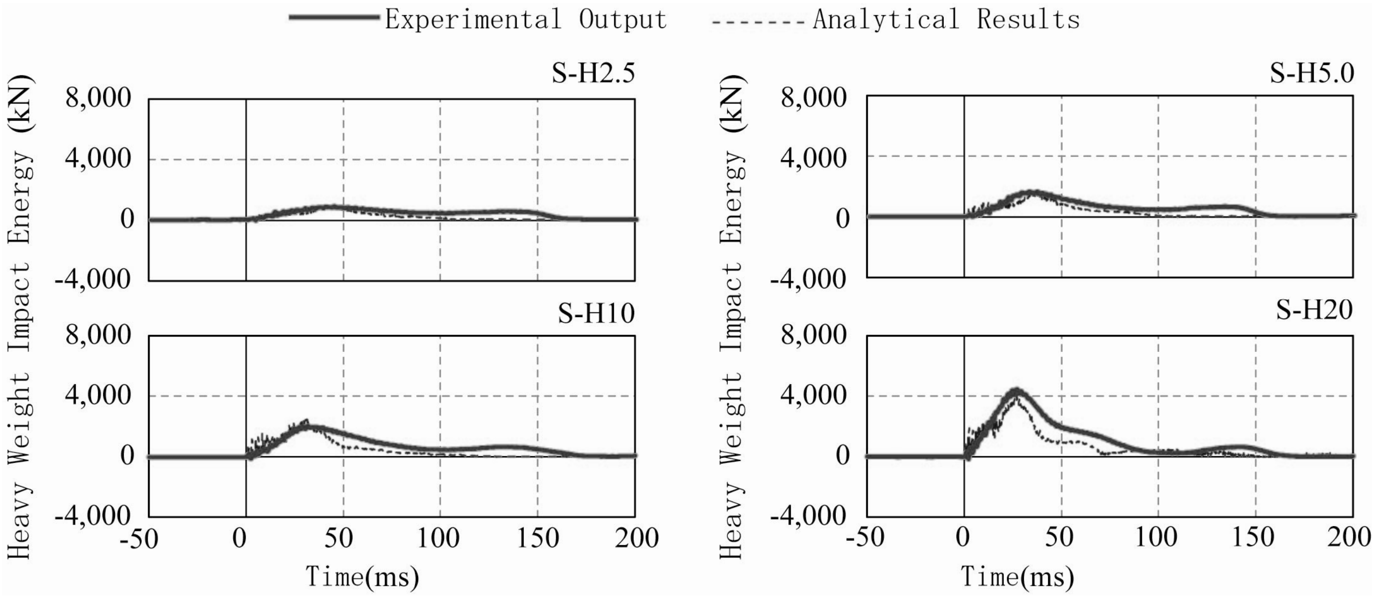


Figure 5. Heavy weight impact.

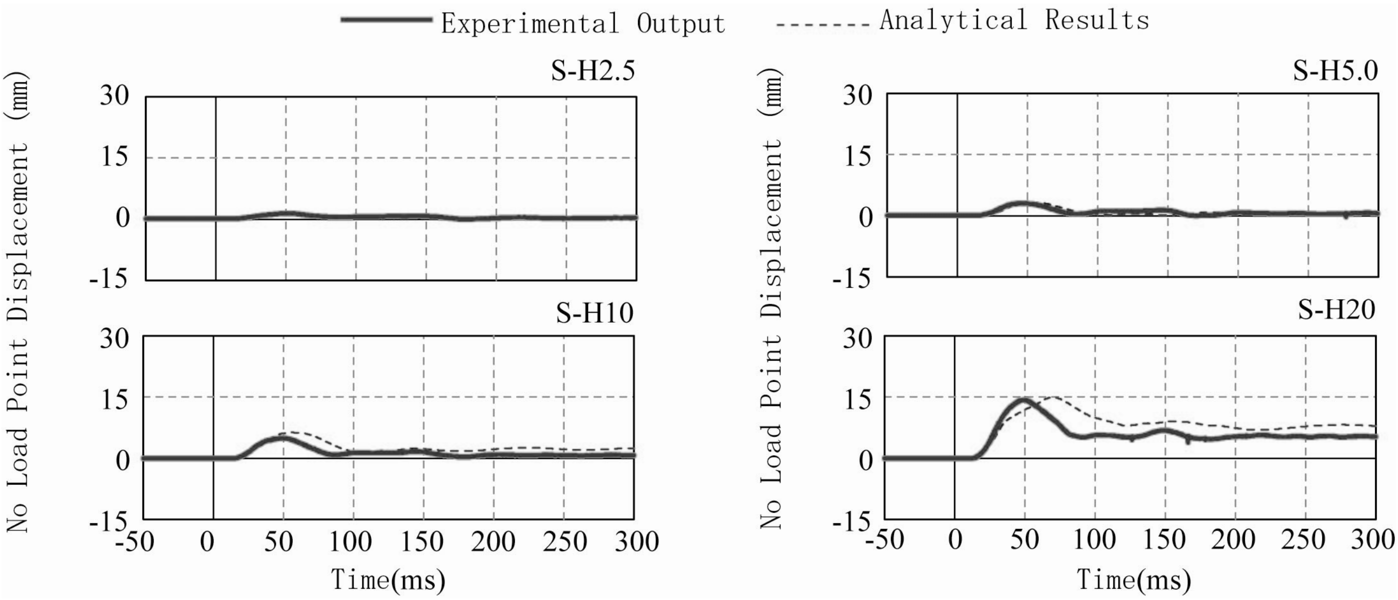


Figure 6. Point Displacement Wave Shape.

analysis technique for executing it is examined by comparing the outcome of an experiment with the numerical analysis result, and the applicability is discussed. Each data obtained by the experiment is sequentially examined.

4.1 *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 system shown in Figure 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. By comparing the response reaction forces at the side wall of left and right hand sides,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 applying more absorbing systems and duration time of three layered absobing systems 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 three layers system and sand, respectively. Focusing on the displacement (*D*) shown in Figure-6, it is seen that the vibration period after reaching maximum amplitude and the damping characteristics are almost similar for both experimental as well as analytical irrespective of absorbing system.

5 SUMMARY

In the present study, the applicability of the method for analyzing was verified by doing the numerical analysis when the impact analysis technique of real scale RC beam was applied to the shock analysis on the arch made of RC structure executing, and unifying the heavy weight fall impact experiment that used the real tunnel pithead part aiming at the establishment of the impact response analysis technique concerning the arch made of RC structure, and comparing it with the outcome of an experiment. As a result,

(1) Accuracy's turning over and being able to reproduce effect in both heavy weight impact power and the transmission impact power even when the impact analysis technique of real scale RC beam used by this examination was a shock analysis etc. on the arcuate type made of RC became clear.

(2) The outcome of an experiment was able to be reproduced in an excellent outline though some differences were generated in the residual displacement for the displacement response properties. Moreover, applicability when it was falling defensive and it covered and applied the design approach to the arch made of RC structure so far was examined by using the method for analyzing of the examination as a base of the performance check type design

(3) When a static, analytical result of applying a past design method was compared with the impact response analysis result, the impact response analysis result's showing an equal to a static, analytical result or a small response became clear. Moreover, it is thought that a similar tendency is shown for the structure at the real scale level.

(4) The impact-proof's being able to design by applying a past design method to the arch made of RC structure became clear.

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