THE EFFECTS OF LOW VELOCITY IMPACT ON CONCRETE DAMS

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ABSTRACT

There have been recent examples of collapse of some concrete dam wings. This was because large rocks were carried in the debris flow, as shown in Figure 1. Firstly, in order to investigate the collapse mechanisms of a concrete dam wing, a model test of a reinforced concrete (RC) slab was conducted along the horizontal direction using an impact apparatus. The impact load and deformation were measured on low velocity impact tests. Secondly, a computational model simulation approach was adopted using the AUTODYN, in combination with the CAPROUS model for concrete. Thirdly, this method was applied to estimate the impact load of the concrete dam wing following a rock collision. The collapse mechanisms were also examined by subjecting the dam wing to a large rock impacts with velocities within the range of 2m/s – 10m/s. It was found that the concrete dam wing collapsed due to tension at its bottom part. Finally, a computer simulation was run, with an impact load that involved rocks in a debris flow against a concrete dam, using a newly developed MPS-DEM in which the particle method (MPS) was combined with a Distinct Element Method (DEM).

Figure 1. Collapse of concrete dam wing

KEYWORDS

Low velocity impact, concrete dam wing, rock impact, AUTODYN, CAPROUS model, MPS-DEM method.

INTRODUCTION

Recently, some concrete dam wings have collapsed due to rocks in the debris flow, as shown in Figure 1. These disasters may have resulted due to torrential downpour as a result of unusual weather conditions. Theses sediment-related disasters may have been caused by debris flow, landslide and slope failure. The debris flow is divided into three types (Takahashi 2004): the gravel cobble flow including large rocks, the mudflow or turbulent flow including volcanic debris, and the immature debris flow without gravel.

In order to prevent such disasters caused by debris flow, many concrete dams have been constructed in the mountainous area of Japan. Current design codes for concrete dams exposed to debris flow are conducted at two different loads (Mizuyama 1979 and Ministry of Construction 2000). One is the fluid force in which the dynamic pressure due to jet stream is replaced with the static load, and the other is the impact load induced by rock collisions onto the concrete dam.

Many studies have been devoted to the investigation of impact load by rock collisions (Mizuyama, et.al. 1985, Shimoda,et.al.1996, Ishikawa,et.al. 2005). However, the effects of the impact velocity and the size of the impacting rocks on the concrete dam have not been sufficiently investigated thus far.

To this end, this paper presents experimental and computational approaches relevant to the collapse mechanisms of concrete dam wings, in order to examine the effects of the impact velocity of a rock in debris flow. First, the low velocity impact test was performed against reinforced concrete (RC) slabs in order to investigate the dam's dynamic characteristics, including the impact load and local deformation by using an impact apparatus along the horizontal direction (Miwa,et.al. 2010). Herein, the relationships between the impact load-time and the deformation-time were quantified by changing the impact velocity. Second, an impact analysis was conducted to simulate the impact behavior of RC slabs based on low velocity impact tests, using the AUTODYN (Katayama, M. et.al.2007) in which the CAPROUS model (Itoh, et. al. 2013) was incorporated. Third, this computational approach was applied to the study of the impact load and failure mechanism of a concrete dam wing, in order to examine the effects of impact velocity and the size of impacting rocks. Finally, a new MPS-DEM method (Goto, et al. 2003, Ishikawa, et.al. 2009) was developed to estimate the impact load due to debris flow that contained rocks.

HORIZONTAL IMPACT TEST

Outline of Test

A horizontal impact test was performed to examine the effect of impact velocity on the dynamic responses of a RC slab using the horizontal impact apparatus with a maximum velocity of 20m/s and a mass of 100kg, as shown in Figure 2. Acceleration was measured using an acceleration meter attached to the impact body. The impact load was estimated by multiplication of measured acceleration with the mass of impact body. Local deformation was estimated as the outcome of the double integration of the acceleration. The total deformation was also estimated by tracking a set mark point on the impact body using a high-speed camera.

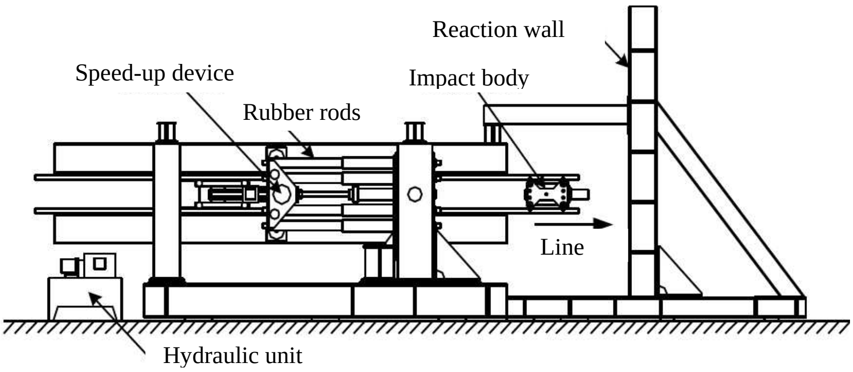


Figure 2. Impact test apparatus

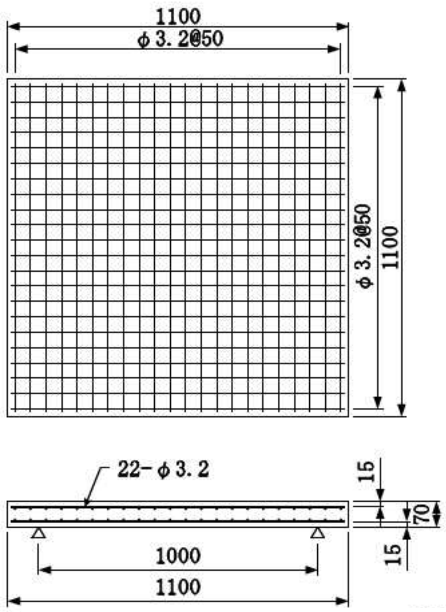


Figure 3. RC slab (unit:mm)

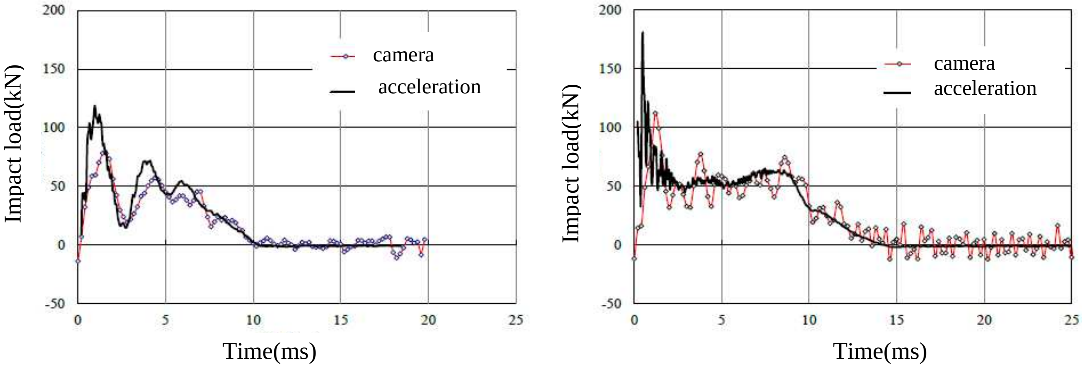
Impact body and RC plate

The impact body with a mass of 100kg was equipped with an acceleration meter (capacity of 1,000G and a sampling time of 50kHz) placed inside a spherical head with a diameter of 10cm. Impact velocity was measured by a high-speed camera with a maximum frame-rate of 5,000 frames/sec. The doubly reinforced RC slab had a longitudinal length of 110cm, a width of 110cm, and a depth of 7cm, and was fixed at four sides, as shown in Figure 3. The compressive strength was 33.5N/mm^2 and the rebar ϕ=3.2mm, placed at an interval of 5cm, corresponding to a reinforcement ratio of 0.25%. The concrete cover depth was 1.5cm.

Test Results

Load-time relation

Figure 4 (a) and (b) illustrate the impact load-time relations at the impact velocities of 3m/s and 5m/s, respectively. In these plots, reference to "camera" implies that the impact load was obtained by multiplying the acceleration (computed by double differentiation of the deformation obtained experimentally using high-speed camera tracking based on the set mark on impact body) with the mass of the impact. Correspondingly, "acceleration" refers to the impact load, estimated by the acceleration meter of the impact body, multiplied by the mass. The first peak value of "acceleration" is larger than the corresponding peak from the "camera", because the acceleration meter sensitivity is larger than the camera sensitivity. It was also confirmed that the first peak load at an impact velocity of 5m/s (180kN) was about 1.5 times larger than its corresponding value at an impact velocity of 3m/s (120kN).



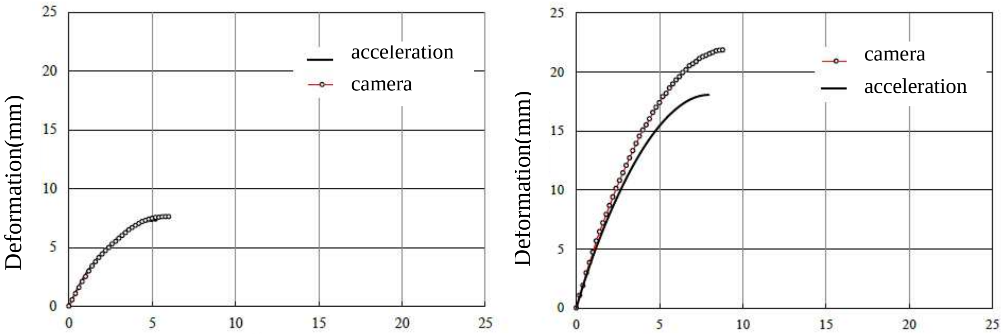
(a) Impact velocity of 3m/s (b) Impact velocity of 5m/s

Figure 4. Impact load – time relation

Deformation- time relation

Figure 5 (a) and (b) show the deformation-time relations at impact velocities of 3m/s and 5m/s, respectively. The total deformation (δ) is divided into the local (δ_L) and global (δ_G) deformations, and is expressed as $\delta = \delta_L + \delta_G$. The total deformation δ can be measured based on the mark tracking of the impact body using the high speed camera. The local deformation (δ_L) is measured by integrating twice the measured acceleration of the impact body. Therefore, δ_G can be found by $\delta_G = \delta - \delta_L$.

In case of an impact velocity of 3m/s, it was observed that the total deformation coincides with the local deformation ($\delta = \delta_L = 7.5mm$), that is, there is no global deformation ($\delta_G = 0$). This is because of the slow impact velocity of 3m/s. In the case of an impact velocity of 5m/s, $\delta = 22.5$mm and $\delta_L = 17.5$mm, and, therefore, the plate deformation δ_G =5mm. This was caused by the increased velocity. Note also is the fact that the total deformation (22.5mm) at 5m/s was about three times larger compared to its corresponding value (7.5mm) at 3m/s.

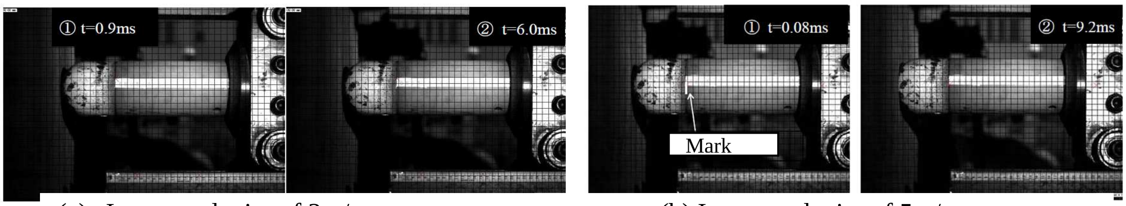


(a) Impact velocity of 3m/s (b) Impact velocity of 5m/s

Figure 5. Deformation-time relations

Profile of impact moment

Figure 6 (a) and (b) show typical profiles at the moment of contact between the impact body and the RC slab at the impact velocities of 3m/s and 5m/s, respectively. It was confirmed that the local deformation at an impact velocity 5m/s [Figure 6 (b)-②] was greater than the corresponding one at 3m/s [Figure 6 (a)-②].



(a) Impact velocity of 3m/s (b) Impact velocity of 5m/s

Figure 6. Impact moment between impact body and RC slab

(①:moment at the maximum impact load, ②: moment at the maximum deformation)

IMPACT ANALYSIS

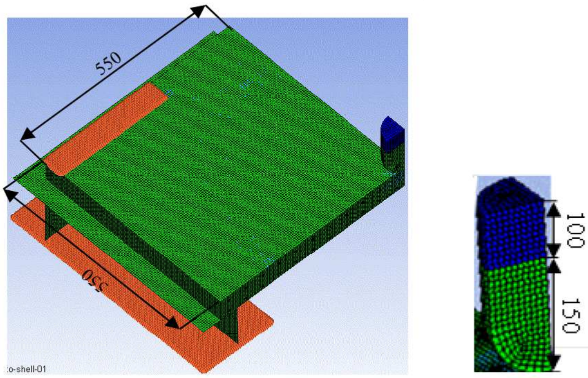
The low velocity impact analysis was conducted by using the AUTODYN software in which the CAPROUS model for concrete was introduced. Herein, the applicability of the AUTODYN is assessed for low velocity impacts, although this software is usually suitable for simulations at the high impact velocity.

Concrete material model

The concrete material model uses the CAPROUS model considering a dynamic, nonlinear constitutive law, the yield condition model, and the spall failure criterion. This model considers only four parameters, namely, the density, the Young's modulus, the Poisson ratio, and the static compressive strength of concrete.

RC plate model and impact body model

The RC slab and the impact body were modeled at 1/4 of their actual sizes in the simulation of the impact test, as shown in Figure 7. The mesh elements were 5mm in size and the 50mm×300mm RC slab was fixed at its periphery where the boundary conditions were defined. The head and posterior part of the impact body were assumed as elastic and rigid bodies, respectively, as shown in Figure 7 (b).



(a) RC plate model (b) Impact body model

Figure 7. Computational model (1/4 model)

Material	Item	Data
Concrete	Density (g/cm^3)	2.35
	Young's modulus (N/mm^2)	2.53x10^4
	Yield stress(N/mm^2)	33.5
	Poisson ratio	0.2
	State equation	Non-linear model
	Yield condition	Bi-linear model
	Failure criterion	Spall criterion
	Spall pressure (MPa)	6.0
Steel	Density (g/mm^3)	7.83
	Young's modulus (N/mm^2)	2.0x10^5
	Yield stress(N/mm^2)	1130
	Poisson ratio	0.3
	State equation	Linear model
	Yield condition	Johnson Cook
Impact body	Density (g/mm^3)	7.83
	Young's modulus (N/mm^2)	2.0x10^5
	Yield stress(N/mm^2)	1130
	Poisson ratio	0.3
	State equation	Linear model
	Yield condition	Elastic model

Computational Results

The input data was used for the horizontal impact test as shown in Table 1.

Load-time relation

Figure 8 shows the relationship between the impact load and time at an impact velocity of 5m/s.

The non-linear model is in good agreement with the experimental test results ('camera' and 'acceleration'), although the peak value of the non-linear model differs from the experimental test value. However, the linear model differs significantly from the test curve. Particularly, the second load

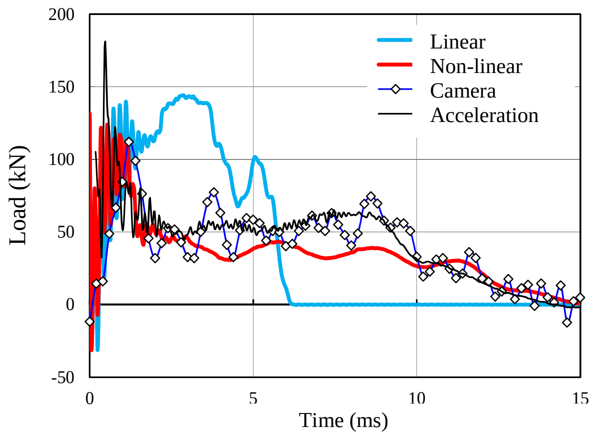


Figure 8. Load-time relation
(Impact velocity of 5m/s)

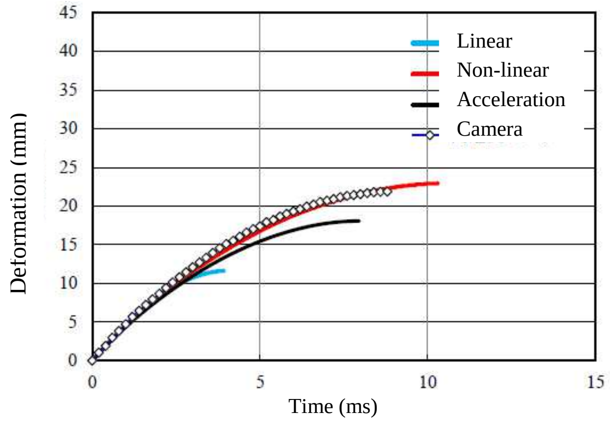


Figure 9. Deformation-time relation
(Impact velocity of 5m/s)

peak depicted in the linear model data was not seen in the experimental test results. The non-linear model is a well-suited model for simulating the experimental conditions. On the contrary, the linear model did not match well the test curves.

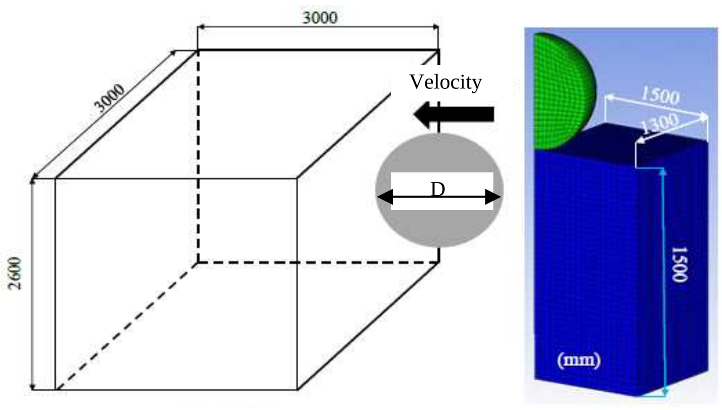
Deformation-time relation

Figure 9 represents the relationship between the deformation and time at the impact velocity of 5m/s. The non-linear model matched well one of the experimental test curves ('camera'). On the contrary, the linear model did not match the experimental test curves ('camera' and 'acceleration'). Therefore, the non-linear model is well suited for simulating the experimental deformations.

APPLICATION OF IMPACT ANALYSIS TO CONCRETE DAM WINGS

Computational Model

In order to examine the effect of impact velocity and rock size on the impact behavior of a concrete dam wing, an impact analysis was performed using the AUTODYN, as shown in Figure 10. The input data used for the simulation are shown in Table 2.

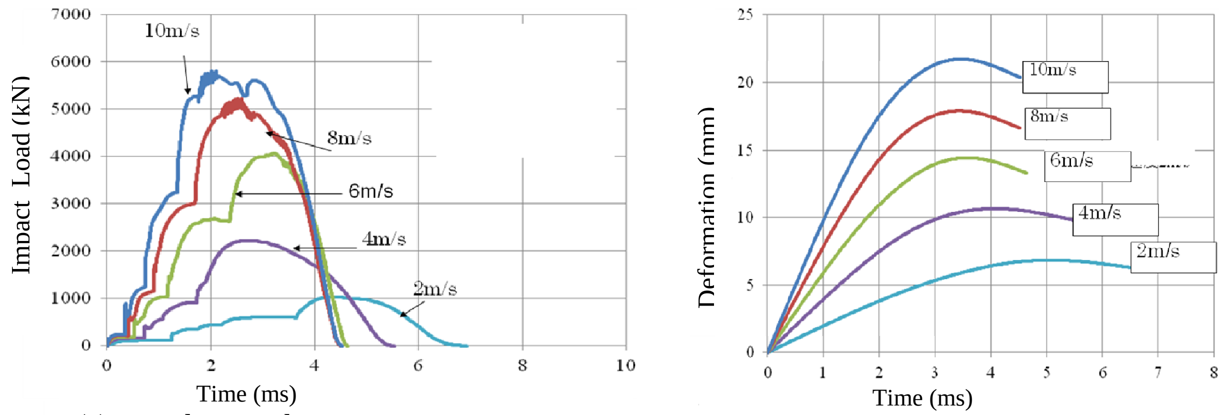


(a) Concrete dam wing model (b) 1/4 model
Figure 10. Analytical model

Table 2. Input data for concrete dam wing

Material	Item	Data
Concrete	Density (g/cm^3)	2.3
	Young's modulus (N/mm^2)	2.2x10^4
	Yield stress(N/mm^2)	18
	Poisson ratio	0.23
	State equation	Non-linear model
	Yield condition	Bi-linear model
	Failure criterion	Spall criterion
Rock	Density (g/mm^3)	2.6
	Young's modulus (N/mm^2)	4.9x10^4
	Poisson ratio	0.23
	State equation	Linear model
	Yield condition	Elastic model

Computational Results



(a) Load-time relation (b) Deformation-time relation

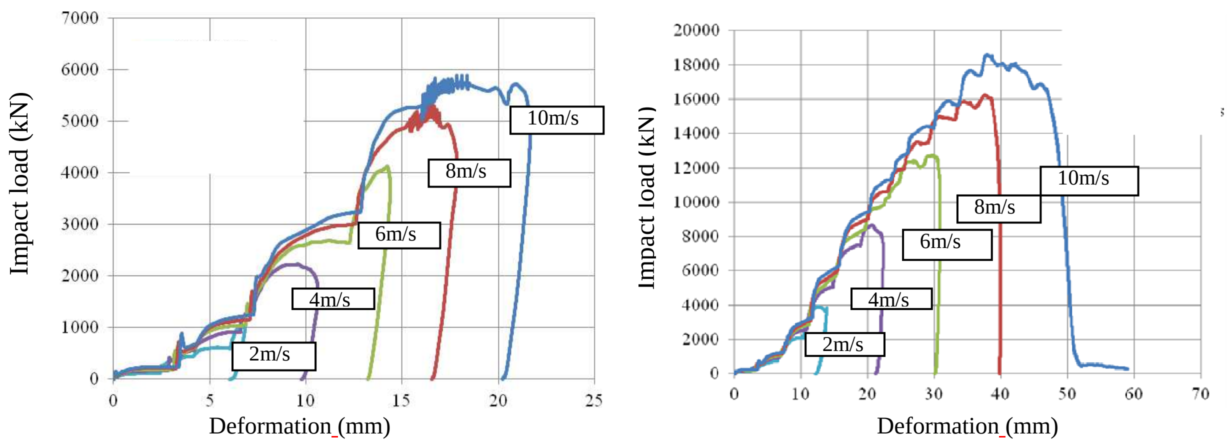
Figure 11. Concrete dam wing characteristics for an impacting rock with a diameter of 1m

Impact load-time and deformation-time relations

Figure 11 (a) and (b) show the load-time and the deformation-time relations of the concrete dam wing, respectively, for an impacting rock diameter of 1m at various impact velocities. Figure 13 (a) shows that the elicited maximum load (6,000kN) at an impact velocity of 10m/s is about six times larger than the corresponding load value (1,000kN) at 2m/s. This shows that the effect of the impact velocity on the impact load is significant. On the contrary, based on Figure 11 (b), the elicited maximum deformation (22.5mm) at 10m/s is about three times larger than the corresponding deformation value (7.3mm) at 2m/s.

Impact load-deformation relation

Figure 12 (a) and (b) depict the relationships of the impact load and local deformation at impacting rock diameters of 1m and 2m, respectively. Based on these results, the elicited maximum impact load (18,000kN) for an impacting rock with a diameter of 2m at 10m/s is about three times larger than the corresponding impact load value (6,000kN) for a rock with a diameter of 1m. Correspondingly, the maximum deformation (45mm) for an impacting rock with a diameter of 2m is about two times larger than the corresponding deformation value (22.5mm) for a rock with a diameter of 1m.



(a) Impacting rock diameter of 1m (b) Impacting rock diameter of 2m

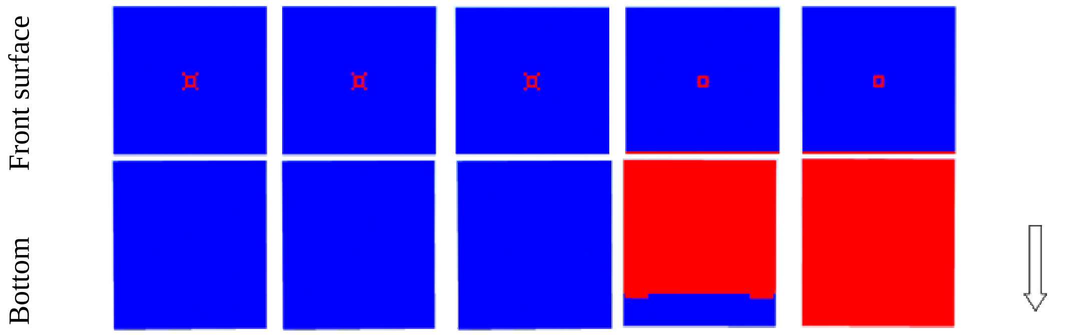
Figure 12. Impact load- deformation relation

Spring constant

The spring constants were obtained from the slopes of the load-deformation curves of Figure 12 (a) and (b) and were estimated to be 250–300kN/mm and 400–450kN/mm, respectively.

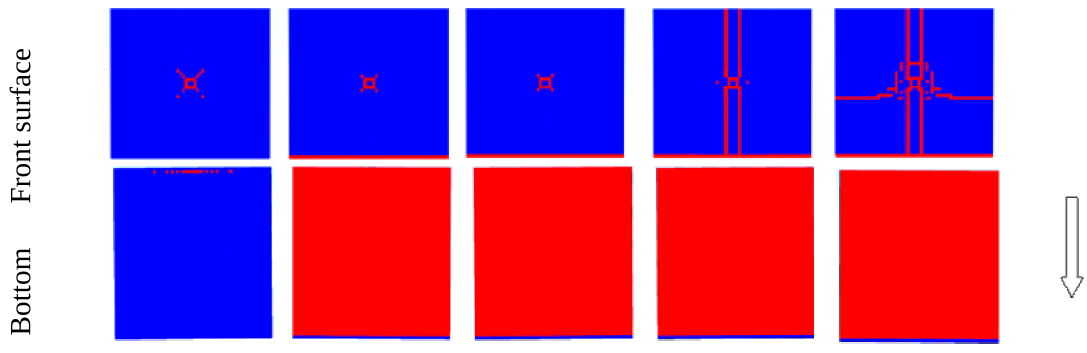
Failure mechanism

Figures 13 and 14 depict the failure mechanisms of the concrete dam wings subjected to impacting rocks with respective diameters of 1m and 2m, at various impact velocities within the range of 2m/s to 10m/s. In the case of an impacting rock with a diameter of 1m, the tensile failure occurred at the bottom of the concrete dam wing at an impact velocity of 8m/s, as shown in Figure 13 (d). Correspondingly, the tension failure at the bottom of the concrete dam wing started at an impact velocity of 4m/s in the case of an impacting rock with a diameter of 2m, as shown in Figure 14 (b). This shows the significant effect of the impacting rock size on the failure mechanism.



(a) 2m/s (b) 4m/s (c) 6m/s (d) 8m/s (e) 10m/s

Figure 13. Failure mechanisms of concrete dam wing
(Impacting rock diameter of 1m)



(a) 2m/s (b) 4m/s (c) 6m/s (d) 8m/s (e) 10m/s

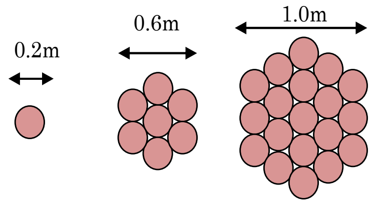
Figure 14. Failure mechanisms of concrete dam wing
(Impacting rock diameter of 2m)

IMPACT LOAD EFFECTS DUE TO DEBRIS FLOW

In order to examine the effects on the impact load due to debris flow that includes rocks, a new MPS-DEM method was developed by combining the MPS method with a DEM.

Debris flow model including rocks

Three kinds of rocks with diameters of 0.2, 0.6, and 1.0m, shown in Figure 15, were incorporated into the debris flow model expressed by the MPS method (Koshizuka, 2005), as shown in Figure 16. In this configuration, a debris flow with a velocity of 3m/s, a water depth of 1.9m and a strike length of 10m to the concrete wall were chosen. At the moment of rock



(a) Small (b) Medium (c) Large

Figure 15. Size of rocks incorporated in the debris flow

impact (Figure 17), the local spring constant between the rocks and the concrete wall was assumed to have a constant value (270kN/mm), despite the different sizes of impacting rocks on the concrete wall.

Impact load – time relation

Figure 18 shows the impact load-time relation due to the impacting rocks in the debris flow. The peak load was approximately 7,700kN, reached at the moment of rock collision at the impacting velocity of 3m/s.

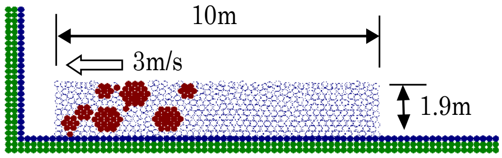


Figure 16. Debris flow model with rocks

CONCLUSIONS

This paper has presented the results for a low velocity impact test for RC slabs and the corresponding computer simulation using the AUTODYN. The method was applied to a concrete dam wing, and the effects of the impact velocity and the size of impacting rocks were investigated based on the impact load characteristics and failure mechanisms. Finally, a new MPS-DEM was developed to study the impact load of rocks contained in the debris flow.

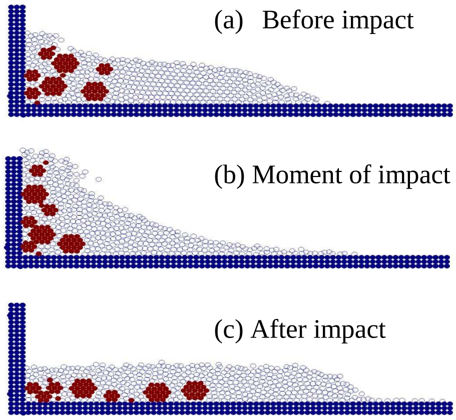


Figure 17. Impact of rocks included in the debris flow onto the dam's concrete wall

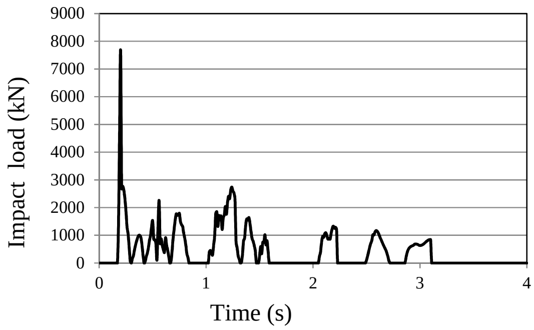


Figure 18. Impact load – time relation

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