Numerical Simulation of Debris Flow Model by using DEM-MPS Method

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This paper presents an analytical approach on impact and dynamic loads due to debris flow including water, sand and large rocks. In order to describe complicated behavior of multiphase flow of the debris flow, a numerical model coupled with the Distinct Element Method (DEM) and the Moving Particle Semi-implicit method (MPS) methods is proposed. In the numerical simulation, impulsive fluid load is calculated with the MPS method and impact load caused by rocks is simulated with the DEM method. An accurate spring constant in the DEM modeling which describes local response between a rock and a dam structure is vital to simulate the impact load. In this study, the spring constant between a rock and a concrete dam structure is derived based on FEM analyses with a high-fidelity constitutive model of concrete material and contact algorithm. The parameters of the analysis are mass (diameter) and impact velocity of a rock. The proposed model could simulate the dynamic fluid load and the impact load simultaneously.

Key words: debris flow, Distinct Element Method, Moving Particle Semi-implicit method, impact load

1. 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.

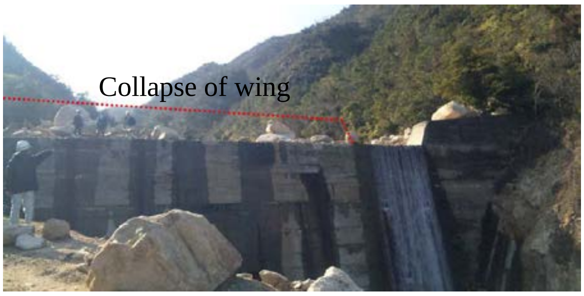
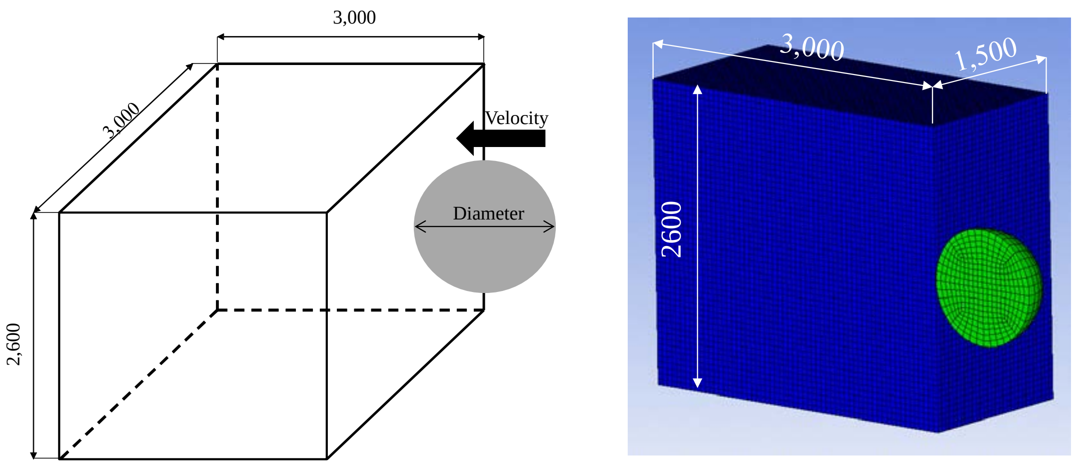


Figure 1 Collapse of concrete dam wing

Many studies have been devoted to the investigation of impact load by rock collisions (Mizuyama 1979, 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 computational approaches relevant to the collapse



(a) Concrete dam wing model (b) 1/2 model

Figure 2 Analytical model

mechanisms of concrete dam wings, in order to examine the effects of the impact velocity of a rock in debris flow. First, an impact analysis was conducted to simulate the impact behavior of concrete dam wings using the AUTODYN (Katayama, M. et.al.2007) in which the CAPROUS model (Itoh, et. al. 2013) was incorporated. In this part, impact load and failure mechanism of a concrete dam wing were discussed, in order to examine the effects of impact velocity and the size of impacting rocks. Secondly, 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.

2. IMPACT ANALYSIS TO CONCRETE DAM WINGS

2.1 Computational Model

The impact analysis of concrete dam wings was conducted by using the AUTODYN software in which the CAPROUS model for concrete was introduced. Herein, the applicability of the AUTODYN was assessed for low velocity impacts (Shibata et al. 2014), although this software is usually suitable for simulations at the high impact velocity. The concrete material model uses the CAPROUS model considering a dynamic nonlinear equation of state, constitutive law, and the spall fracture criterion. A rock model was modeled as elastic material.

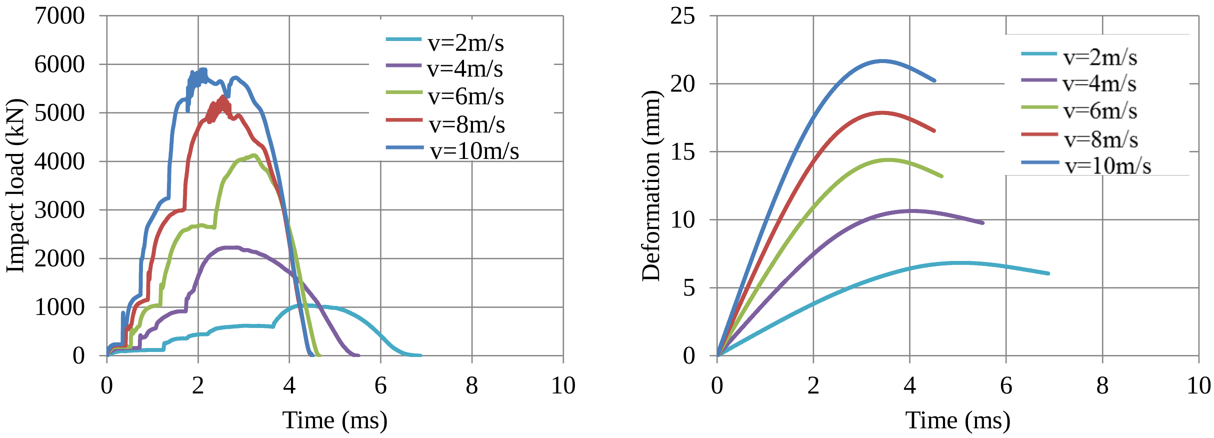
In order to examine the effect of impact velocity and rock size on the impact behavior of a concrete dam wing, an impact analysis was performed using the AUTODYN, as shown in Figure 2. The dimension of the concrete dam wing is 3000mm in length, 3000mm in width and 2600mm in height. In the analysis, the diameter of a rock model was 1m or 2m, and the impact velocity of the rock was varied between 2m/s and 10m/s. The input data used for the simulation are shown in Table 1.

Table1 Input data for concrete and rock

Material	Item	value
Concrete	Density (g/cm^3)	2.3
	Young’s modulus (GPa)	22
	Compressive stress (MPa)	18
	Poisson’s ratio	0.23
Rock	Density (g/cm^3)	2.6
	Young’s modulus (GPa)	49
	Poisson’s ratio	0.23

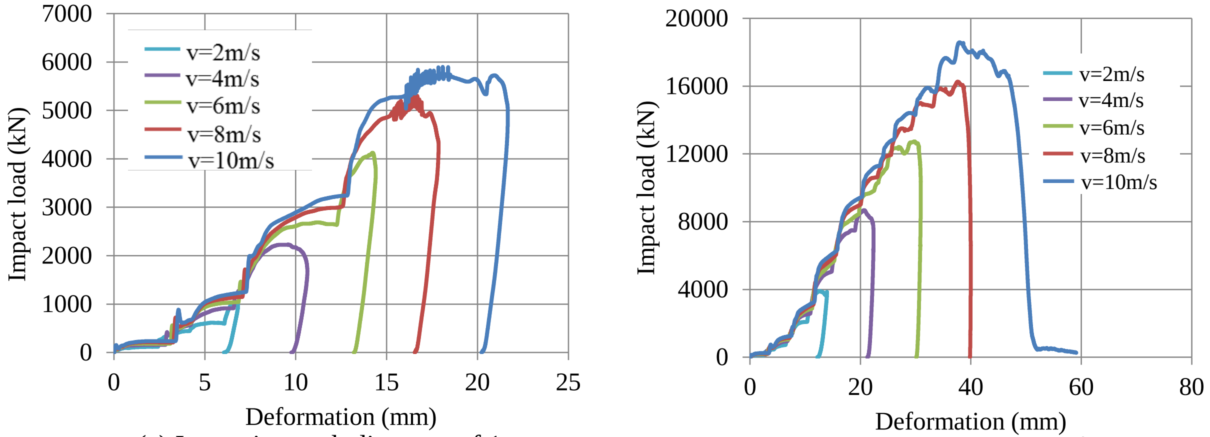
2.2 Computational Results

Figure 3 (a) and (b) show the load time history and the deformation time history of the concrete dam wing, respectively, for an impacting rock diameter of 1m at various impact velocities. Figure 3 (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. The duration of the impact load was between 4.5ms and 7ms. On the contrary, based on Figure 3 (b), the elicited maximum deformation (22.5mm) at 10m/s is about three times larger than the



(a) Load time history (b) Deformation time history

Figure 3 Concrete dam wing characteristics for an impacting rock with a diameter of 1m



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

Figure 4 Impact load-deformation relation

corresponding deformation value (7.3mm) at 2m/s.

Figure 4 (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.

The local resistant stiffness of impacted area can be obtained from the slopes of the load-deformation curves of Figure 4 (a) and (b) and were estimated to be between 250kN/mm and 300kN/mm and between 400kN/mm and 450kN/mm, respectively. This result indicated that the larger impacting rock diameter induces the higher local resistant stiffness. This stiffness can be used as a spring constant in the DEM analysis, as it is shown in the latter section.

2.3 Failure mechanism

Figures 5 and 6 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 5 (d). This tensile failure was induced by the bending deformation of the concrete dam wing.

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 6 (b). For the impact velocity of 2m/s, one should notice that the tensile failure occurred at the bottom of the front surface. This shows the significant effect of the impacting rock size on the failure

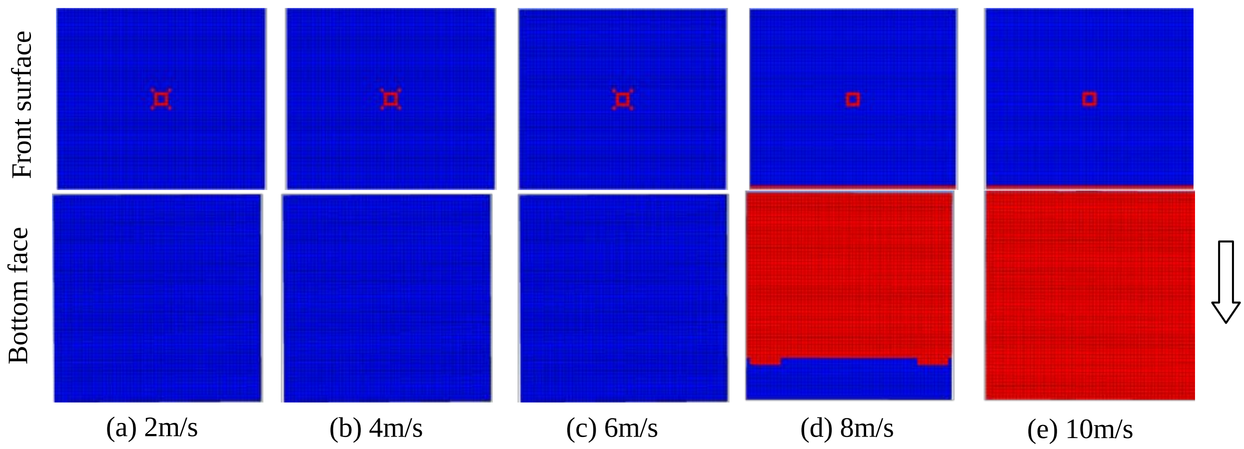


Figure 5 Failure states of concrete dam wing (Impacting rock diameter of 1m)

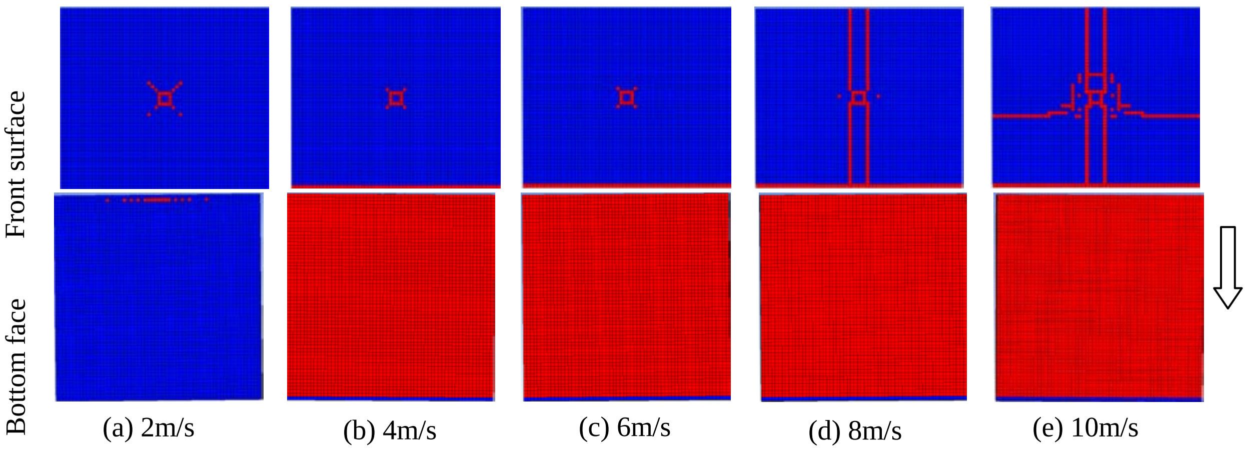


Figure 6 Failure states of concrete dam wing (Impacting rock diameter of 1m)

mechanism.

3. LOAD ASSESSMENT OF DEBRIS FLOW MODEL INCLUDING ROCKS

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 (Moving Particle Semi-implicit) method with the DEM (Discrete Element Method). In general, the MPS method and DEM are applied for incompressible fluid and discrete bodies, respectively. In this part, a new coupling procedure using the MPS and DEM is proposed and load of debris flow including rocks is valuated.

Three kinds of rocks with diameters of 0.2m, 0.6m, and 1.0m, shown in Figure 7, were made by consisting of several rigid particles. The rock models were incorporated into the debris flow model expressed by the MPS method (Koshizuka, 2005), as shown in Figure 8. In this configuration, a debris flow with a velocity of 3m/s, a water depth of

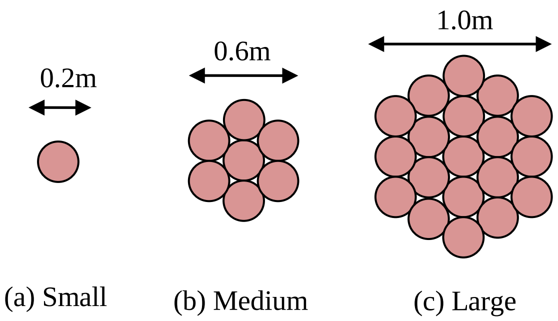


Figure 7 Size of rocks incorporated in the debris flow mode

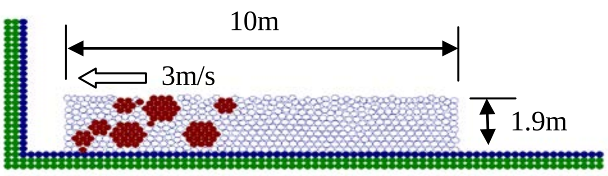
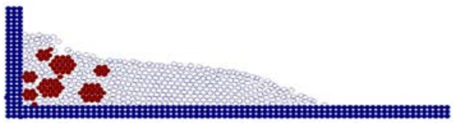
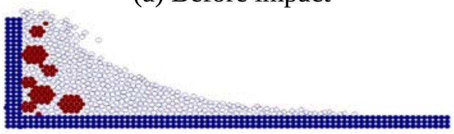


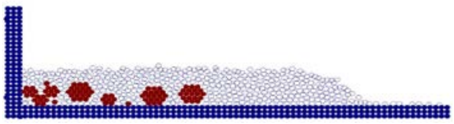
Figure 8 Debris flow model with rocks



(a) Before impact



(b) Moment of impact



(c) After impact

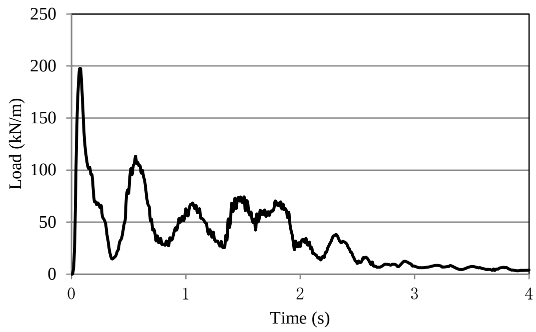
Figure 9 Impact of rocks included in the debris flow onto the dam’s concrete wall

1.9m and a strike length of 10m to the concrete wall were chosen. At the moment of rock impact (Figure 9), 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. Figure 9 shows that the rocks collided with the wall and were flowed back due to the back flow.

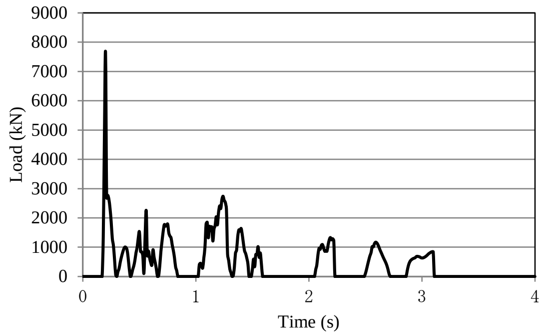
Figure 10 shows the load time histories of the fluid load and impact load of rocks in the debris flow. The fluid load was determined by integrating the fluid pressure over the wall and the impact load was calculated from DEM procedure with the spring constant. It is seen from Figure 10(a) that the fluid load per unit length rapidly rose to the peak load of about 200kN/m. The impact load generated about 0.2s behind the arising of the fluid load and showed the peak impact load of approximately 7,700kN, reached at the moment of rock collision at the impacting velocity of 3m/s. The impact load showed several sinusoidal waves due to the impacts between rocks and the wall.

4. CONCLUSIONS

This paper has presented the failure behavior of a concrete dam wing by the computer simulation using the AUTODYN. 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.



(a) Fluid load per unit length



(b) Impact load

Figure 10 Load time history

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