IMPACT FORCE ASSESSMENT OF FLEXIBLE DEBRIS-FLOW BARRIERS USING SMALL-SCALE MODEL TEST

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Abstract— The impact forces applied on a closed-type erosion control dam and a ring-net were assessed using a small-scale model test. The experimental results demonstrated that the debris-flow behaved similar to fluids. The debris-flow impact force applied on the back of the closed-type erosion control dam was measured to be the largest at 4.14 kN on the lower part, followed by 3.66 kN on the middle part, and 1.66 kN on the upper part. The ring-net test results also demonstrated that the impact force was the largest on the lower part and decreased toward the upper part (from 2.28 kN to 1.95 kN and then, to 1.49 kN), similar to the results of the closed-type erosion control dam. When the mechanism of absorption of the debris-flow impact force by the flexible debris-flow barrier was analyzed using numerical analysis results, the actual horizontal force acting on the structure was equal to that obtained by the theoretical formula. This is because the closed-type erosion control dam resists the horizontal force using the stiffness of the structure similar to a concrete retaining wall. However, in the case of the ring-net, which utilizes the elastic stretching of the strand and particle transmission to the net front, the impact force was lower by up to 45% than the result of the erosion control dam.

Index Terms—Debris-flow, flexible debris-flow barrier, erosion control dam, ring-net, debris-flow impact force

I. INTRODUCTION

As a foundational study to reduce damages from debris-flows, a debris-flow model test was conducted to analyze the barrier behavior characteristics and impact absorption mechanism following a debris-flow impact. The barriers used in this study were flexible debris-flow barrier and ring-net. The performance evaluation results for each barrier are presented based on the test results.

II. RESEARCH METHOD

A. Small-scale model test

Considering economy and efficiency of experiment, the behavior of each of the barriers under a debris-flow dynamic load was evaluated using a small-scale model test based on the actual debris-flow scale instead of a mock-up test or centrifuge test, which require substantial time and resources.

B. Debris-flow system

A small-scale model test was performed by fabricating a debris-flow device with a tilted section of length 5.0 m and a tilt angle range of 0–50° (adjustable), as illustrated in Fig. 1. For the flexible debris-flow barrier, a 1.6 cm thick steel plate (weighing approximately 62.4 kg) was used as the closed-type erosion control dam, and a net made by connecting rings of diameter 50.0 mm was used as the ring-net. Then, steel wires were attached to the sides of each barrier, and the barriers were fixed to the debris-flow device. In addition, a strain gauge was attached to the steel wires to analyze the impact force applied on the barriers.

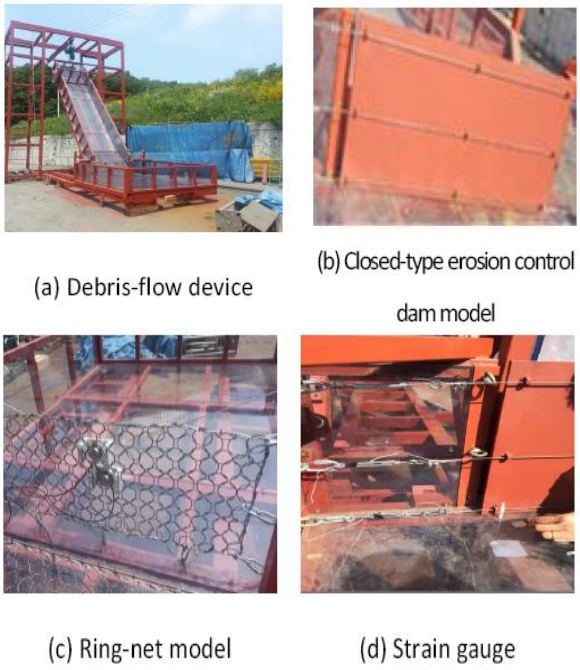


Fig. 1. Debris-flow device

C. Debris-flow sample

Wendeler and Volkwein (2015) reported their experimental result wherein the optimum debris storage capacity was manifested at a ring diameter corresponding to 90% of the cumulative pass-through percentage. To simulate the debris-flow in the present study, a sample mixture produced by mixing standard sand, fine aggregates, and coarse aggregates in the volume ratio 2:2:1 was used. Considering the ring diameter used in the ring-net model, the coarse aggregate used had a maximum diameter of 60 mm. Table 1 lists the debris-flow mixing ratio and the weights of each component of the mixture.

Table 1. Debris-flow mixing ratio

Category	Sand	Fine crushed rock	Coarse crushed rock
Mixing ratio	2	2	1
Volume (m^3)	0.12	0.12	0.06
Unit weight (t/m^3)	1.8	2.2	2.4
Weight (ton)	0.216	0.264	0.144

III. MODEL TEST RESULTS FOR IMPACT FORCE OF FLEXIBLE DEBRIS-FLOW BARRIER

D. Test results of closed-type erosion control dam model

Figure 2 illustrates the behavior characteristics of the closed-type erosion control dam under the debris-flow impact force at 40° tilt angle of the debris-flow device. It was observed that the debris-flow sample of the closed-type erosion control dam first conveys the impact force to the bottom of the erosion control dam and then gradually conveys the impact force to the upper part over time. Because the erosion control dam does not permit the passage of debris-flow to the front of the structure, the debris-flow impact force was analyzed to be completely conveyed to the barrier.

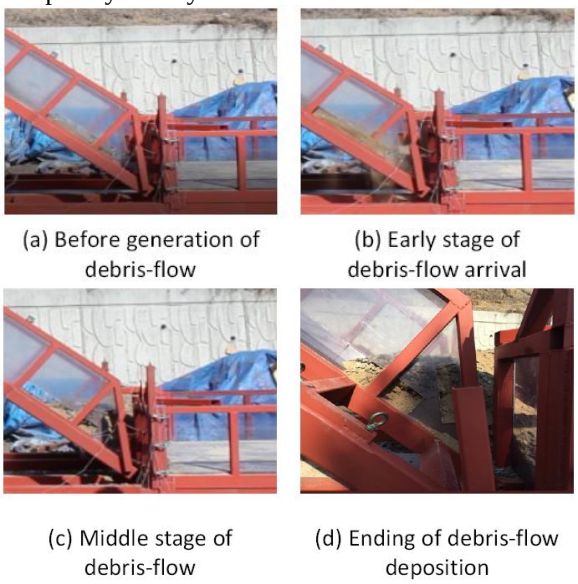


Fig. 2. Behavior characteristics of the closed-type erosion control dam

E. Ring-net model test results

Figure 3 illustrates the ring-net behavior characteristics under the debris-flow impact force at 40° tilt angle of the debris-flow device. Dissimilar to the erosion control dam that does not permit the passage of debris-flow, a portion of the fine sands and aggregates smaller than the ring diameter were observed to pass through the ring-net after conveying the impact force to the structure. The aggregates larger than the ring diameter did not pass through the ring-net and were deposited at the back of the ring-net after conveying the impact force to the ring-net.

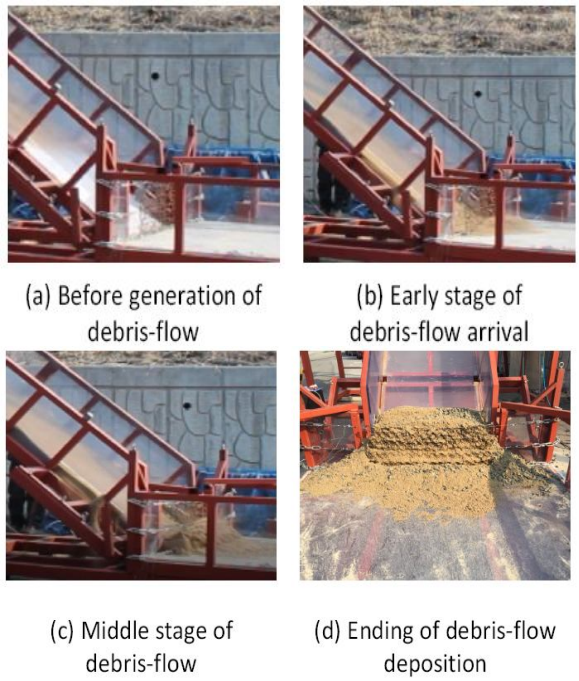
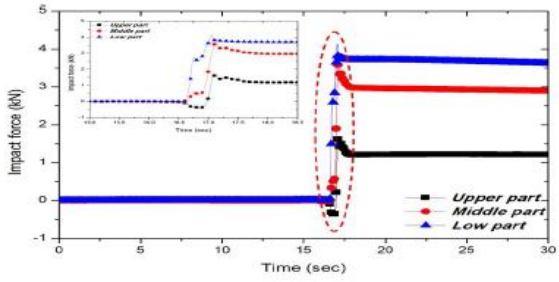


Fig. 3. Ring-net behavior characteristics

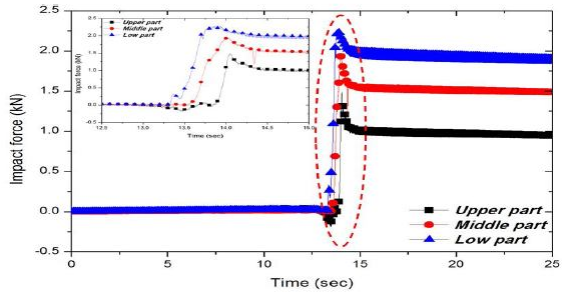
F. Comparison of the impact force of flexible debris-flow barriers

Figure 4 presents the analysis results of the strain gauge measurements. The impact force acting on the erosion control dam was the highest (4.15 kN) in the lower part, followed by 3.66 kN in the middle part, and 1.66 kN in the upper part. The impact forces acting on the ring-net were 2.28 kN in the lower part, 1.95 kN in the middle part, and 1.49 kN in the upper part.

Table 2 presents the impact forces that were applied on each part of the back of the closed-type erosion control dam and ring-net. The impact force applied to the ring-net was lower by up to 45% compared to the results of the erosion control dam, depending on the particle penetration and structure deformation by the impact force.



(a) Impact force applied to the erosion control dam



(b) Impact force applied to the ring-net

Fig 4. Impact forces applied to the erosion control dam and ring-net

Table 2. Comparison of debris-flow impact force between ring erosion control dam and ring-net

Part structure	Lower Part (kN)	Middle Part (kN)	Upper Part (kN)
Erosion control dam	4.14	3.66	1.66
Ring-net	2.28	1.95	1.49

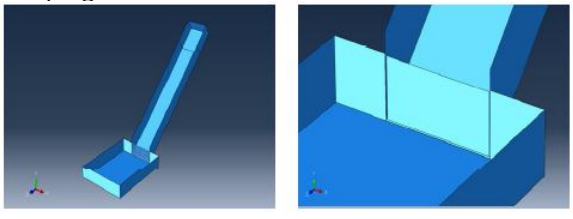
IV. ANALYSIS OF THE IMPACT FORCE ABSORPTION MECHANISM OF FLEXIBLE DEBRIS-FLOW BARRIER USING NUMERICAL ANALYSIS METHOD

G. Introduction

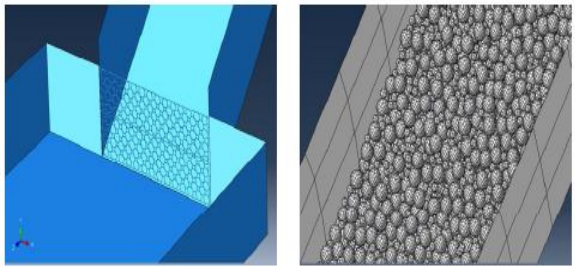
In this study, the behavior of the debris-flow and the behavior and impact force absorption mechanism of the barriers were analyzed by applying numerical analysis. The analysis code used in this study simulated the debris-flows and barriers using the Standard/Explicit Module of ABAQUS/CAE, Ver. 6.14, which is a finite element analysis application.

H. Analysis modeling

Figure 5 illustrates the modeling of the debris-flow device and sample using ABAQUS. The debris-flow device and flexible debris-flow barrier were modeled with dimensions and stiffness identical to those of the actual test. The debris-flow sample was modeled using a circular rigid body. Although approximately two million particles are to be used for the debris-flow sample, 4700 particles were used here considering the technical limitations of the computer analysis system and program.



(a) Debris-flow device modeling (b) Erosion control dam model

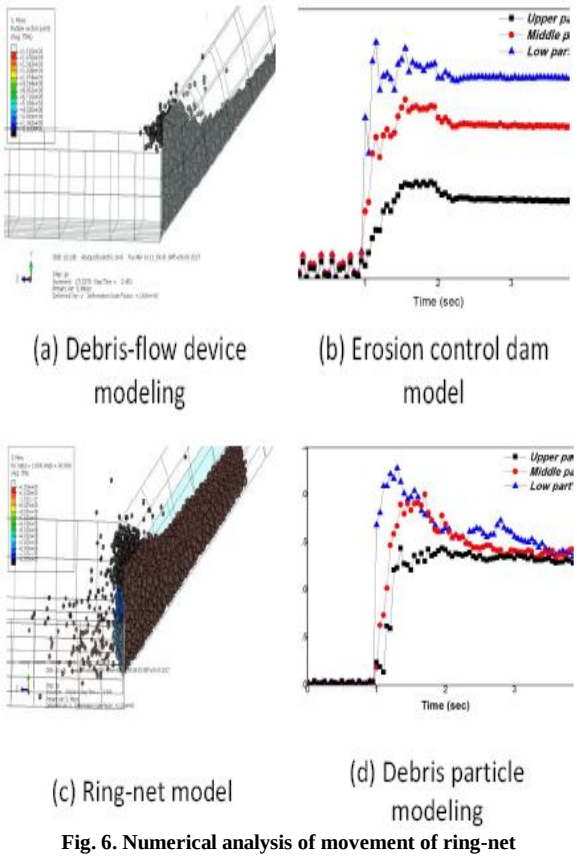


(c) Ring-net model (d) Debris particle modeling

Fig. 5. ABAQUS modeling results for the small-scale model test of debris-flow

I. Comparison of flexible debris-flow barrier impact force using numerical analysis results

Figure 6 illustrates the numerical analysis results; analysis of these results revealed that impact forces of 4.38 kN, 3.32 kN, and 1.78 kN were applied on the lower, middle, and upper parts of the erosion control dam. In the case of the ring-net, impact forces of 2.28 kN, 2.00 kN, and 1.44 kN were applied to the respective sections. Table 3 illustrates a comparison of the model test results and numerical analysis results of the impact forces applied to each section of the barriers. With regard to the accuracy of the numerical analysis, the results obtained from the numerical analysis were consistent with the model test results by 90% or higher.



(a) Debris-flow device modeling (b) Erosion control dam model

(c) Ring-net model (d) Debris particle modeling

Fig. 6. Numerical analysis of movement of ring-net

Table 3. Comparison of debris-flow impact force between the results of numerical analysis and small-scale test

Category		Lower Part (kN)	Middle Part (kN)	Upper Part (kN)
Closed-type erosion control dam	Test results	4.14	3.66	1.66
	Numerical analysis results	4.38	3.32	1.78
Ratio		**1.06**	**0.91**	**1.07**
Ring-net	Test results	2.28	1.95	1.49
	Numerical analysis results	2.28	2.00	1.44
Ratio		**1.00**	**1.03**	**0.97**

V. Comparison of Results between the Proposed Equation of Debris-Flow Impact Force and the Debris-flow Closed-type Erosion Control Dam Model

Equation (1) is a prediction equation of the debris-flow impact force applied on the back of the closed-type erosion control dam, proposed by the Ministry of Land, Infrastructure, Transport and Tourism of Japan. In the present study, the impact force applied to the back of the erosion control dam was examined using this equation. When the widely used impact coefficient of 1.0 was applied to this equation, an impact force of up to 1.93 kN was determined to be applied on the back of the erosion control dam. The model test results demonstrated that the maximum impact force applied on the back of the erosion control dam at a 40° tilt angle was 4.14 kN. Thus, compared to the model test result, the proposed equation underestimated the impact force applied on the back of the erosion control dam. The impact coefficient α is an empirical constant determined by the composition of particles. The higher the composition of gravel, the higher the impact coefficient tends to be. For materials in which the weight of fine and coarse aggregates accounts for over 65% of the total composition, such as the debris used in this study, results similar to those of the model test results were obtained when the impact coefficient of 2.15 was applied. Therefore, the impact coefficient is to be determined considering the domestic debris-flow conditions.

$$F = \alpha \cdot \frac{\gamma_d}{g} \cdot D_d \cdot V^2 \quad (1)$$

Here,
- F : debris-flow impact force per unit width (kN/m)
- γ_d : Unit weight of debris; 21 kN/m^3 was applied.
- V : debris-flow rate; 3.0 m/s was applied.
- g : Gravitational acceleration; 9.8 m/s^2
- α : Impact coefficient of debris-flow (1–3)
- D_d : Depth of debris-flow; 0.10 m was applied.

CONCLUSION

A model test and a numerical analysis were performed on closed-type erosion control dam and ring-net, which are flexible debris-flow barriers. Based on the results, the performances of the two structures were evaluated, and the impact force absorption mechanism was analyzed. The key observations of this study are as follows:

1) A debris-flow device, a closed-type erosion control dam, and a ring-net model structure that simulated the debris-flow were fabricated to evaluate the performance of flexible debris-flow barriers. The debris-flow device was produced with a 5.0 m tilt section at 40° tilt angle, the erosion control dam with a 16 mm thick steel plate, and the ring-net with 50 mm diameter rings.
2) The small-scale test results demonstrated that the debris-flow behaved similar to fluids, and the impact forces applied on the erosion control dam were 4.14 kN, 3.66 kN, and 1.66 kN on the lower, middle, and upper parts, respectively. Furthermore, the impact forces acting on the ring-net were 2.28 kN, 1.95 kN, and 1.49 kN in the lower, middle, and upper parts, respectively. These values are smaller by up to 45% compared to the results of the erosion control dam. The analysis revealed the reason for this to be that the ring-net uses the elastic stretching of the strand and the particle penetration through the front of the net.
3) The impact force applied on the back of the model barrier obtained from the numerical analysis was consistent with the actual model test results by 90% or higher.

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