TRAPPING MECHANISM OF DEBRIS FLOW BY STEEL OPEN DAMS

Nobutaka ISHIKAWA[1*], Joji SHIMA[2], Tomoo MATSUBARA[3], Hiroshi TATESAWA[4], Toshiyuki HORIGUCHI[5] and Takahisa MIZUYAMA[6]

1 Research Association for Steel Sabo Structures (2-7-5 Hirakawa-cho, Chiyoda-ku, Tokyo 102-0093, Japan)
2 Sabo and Landslide Techical Center (4-8-21 Kudan-minai, Chiyoda-ku, Tokyo 102-0074, Japan)
3 CTI Engineering, Co. Ltd. (1047-27 Onigakubo,Tsukuba, Ibaragi 300-2651,Japan)
4 Bousai Consultant Co.,Ltd.(3-41 Ogama-Fu-rin, Takizawa, Iwate 020-0757,Japan)
5 National Defense Academy (1-10-20 Hashirimizu, Yokosuka 239-8686, Japan)
6 Graduate School of Agriculture, Kyoto University (Kitashirakawa, Oiwake-cho, Sakyo-ku, Kyoto, 606-8502, Japan)
*Corresponding author. E-mail: cgishikawa@m4.dion.ne.jp

Many steel open dams have recently been constructed in Japan's mountainous areas. These structures consist of steel pipes, framed as a grid, allowing usually soil and small gravel flow to downstream through the gaps, but capturing large rocks when the debris flow has occurred. This paper presents experimental and computational approaches to examine the trapping mechanism whereby rocks in a debris flow are captured by a steel open dam. First, a model test was performed by using a flume to examine the mechanism whereby gravel in a debris flow is trapped by a steel open dam. Second, a three-dimensional distinct element method (3-D DEM) was developed to simulate the test results, assuming the gravel to consist of spherical elements. Finally, the final trapping state, the trapping process (riverbed height-time relationship), and the trapping ratio were compared with the test results.

Key words: trapping mechanism, steel open dam, debris flow, hydrodynamic test, 3-D DEM

1. INTRODUCTION

Abnormal weather has given rise to debris flow hazards in the mountainous areas in Japan. Since 1980, many steel open-type Sabo dams (referred to as "steel open dams," hereafter) have been constructed as defensive measures against debris flow hazards [Watanabe, et. al. 1980]. Figure 1 shows how such a steel open dam has trapped only the rocks in a debris flow on Rijiri island, Hokkaido, Japan [Steel Sabo Structure Committee, 2009].

To investigate the mechanism whereby only rocks in a debris flow are trapped, this paper presents both experimental and computational approaches that use a model test and a simulation analysis to study the trapping mechanism of a steel open dam.

Many studies [Asida and Takahashi, 1980, Mizuyama et al., 1988, Mizuno et al., 2000, Fukawa, et al., 2002, 2004 and Ishikawa, et al., 2004] have been conducted on the trapping mechanism whereby a debris flow is trapped by a steel open dam.

However, the aim of this study differs from those of previous studies as follows.

(1) To find the trapping process (riverbed height-time relationship) by using the hydrodynamic channel model test.

(2) To extend a three-dimensional distinct element method (3-D DEM) to simulate the performance whereby rocks in the debris flow are trapped.

(3) To examine the trapping and outflow ratios of gravels in the debris flow model.

To this end, a model test was first performed to examine the mechanism whereby gravel in the debris flow is trapped for time history using a flume and a steel open dam. Second, a 3-D DEM was developed by assuming the gravel to be made up of spherical elements and by proposing a water flow method for the trapping mechanism of the debris flow. Finally, the trapping and outflow ratios obtained by the 3-D DEM simulation were compared with those obtained by the model test.

Fig.1 Only rocks trapped by a steel open dam

2. HYDRODYNAMIC MODEL TEST

Many studies [Mizuyama, et al.1988,1995, Fukawa, et al., 2002, 2004] have been performed to examine the trap performance of steel open dams by using the hydrodynamic model test. In this study, the hydrodynamic model test was mainly conducted to measure the trapping process (riverbed height -time relation).

2.1 Outline of test

The model test was performed by using a channel with a width of 20 cm, a total length of 6.85 m, and a slope of 18°, as shown in Fig. 2.

2.2 Steel open dam model

The steel open dam model was constructed using steel pipes with a diameter of 1 cm, a height of 15 cm, and a pipe interval of 1.5 cm, which corresponds to 1.5 times the maximum diameter of gravel (95% of the gravel diameter distribution).

2.3 Debris flow model

The debris flow model consisted of 7760 pieces of gravel, which had been screened through a 1-cm sieve. The gravel was formed into a layer with a length of 1.85 m and a height of 5.0 cm, as shown in Fig. 2. Side and front views of the gravel layer on the bed are shown in Figs. 3(a) and (b), respectively.

2.4 Flow method

In the debris flow model, water flowed from an upper reservoir at a height of 5 m, against the steel dam model at a flow rate of 3.0 liter/s, as shown in Fig. 2. The flow velocity was 1.40 cm/s at the front of the steel open dam. The flow behavior in the test is illustrated in Fig. 4.

3. TEST RESULTS

3.1 Final trapping state

The final trapping state of the gravel was determined from the front and side views, as shown in Figs. 5 and 6, respectively. Although the slit interval of the steel dam was 1.5 cm, gravel with a diameter larger than 1.0 cm was trapped by the steel open dam. This phenomenon may be a result of the so-called "arch action."

3.2 Trapping and outflow ratios

The trapping and outflow ratios of the gravel obtained by the test were 99.2% (7000/7760) and 0.8% (60/7760), respectively.

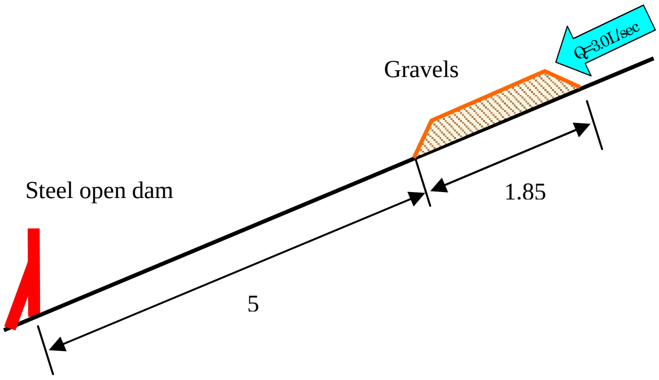


Fig. 2 Hydrodynamic model test (unit: m)

(a) Side view

(b) Front view

Fig. 3 Gravel arranged into a layer

Fig.4 Flow behavior in the test

Fig.5 Final trapping state (front)

Fig.6 Final trapping state (side)

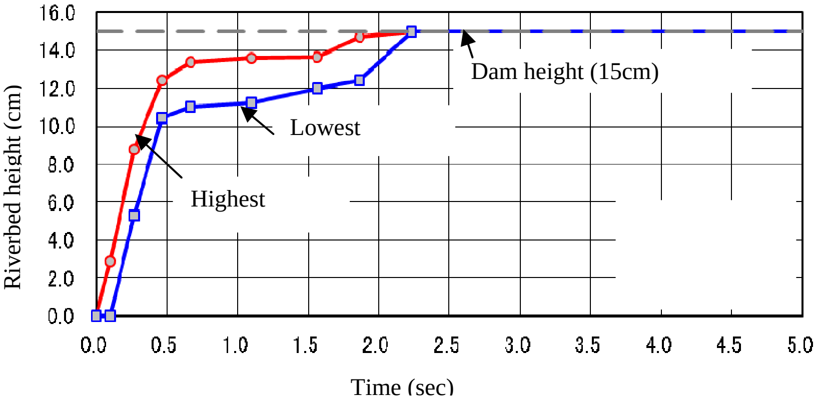


Fig.7 Riverbed height- time relation (Test)

3.3 Trapping process (Riverbed height-time relation)

Figure 7 shows the trapping process (riverbed height-time relationship) of the debris flow model for a slit interval of 1.5 cm. In Fig. 7, the lowest and highest heights of the entrapped gravel correspond to the lowest and highest levels of the captured gravel, respectively. It was discovered that the capturing height was approximately 10 to 12 cm for a time of 0.5 s. In this case, the sedimentation occurred very quickly. Therefore, once the first gravel had been trapped by the barrier (steel open dam), the following gravels quickly accumulated behind it.

4. SIMULATION BY 3-D DEM

In the 3-D DEM, the shape of each piece of gravel was assumed to be spherical.

4.1 Basic equations

In the 3-D DEM (Fukawa, et al., 2002, Ishikawa, et al., 2004, Shibuya, et al., 2011), the contact force is estimated by introducing a spring between elements i and j, as shown in Fig. 8, if the distance between the elements is satisfied by Eq. (1).

$$\left|\mathbf{L}_{Si}-\mathbf{L}_{Sj}\right| \le r_{Si}+r_{Sj} \qquad (1)$$

where, L_{Si}, L_{Sj} : central coordinates of spherical elements i and j, respectively, r_{Si}, r_{Sj} : radii of spherical elements i and j, respectively.

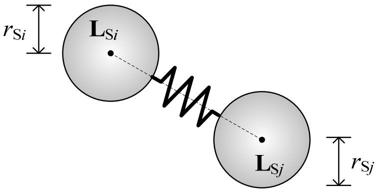


Fig. 8 Spring between elements i and j

The contact force between an element and a plane is calculated by introducing a spring, as shown in Fig. 9, provided Eq. (2) is satisfied.

$$l_{dij} \le r_{Si} \qquad (2)$$

where, l_{dij} **:** distance between an element and a plane, r_{Si} : radius of a spherical element.

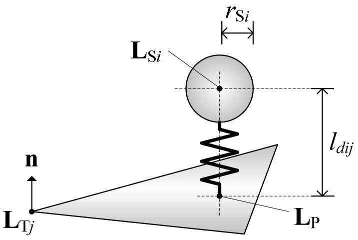


Fig.9 Spring between an element and a plane

Therefore, the equation of motion is expressed as follows.

$$\mathbf{M}\ddot{\mathbf{u}}(t)+\mathbf{D}\dot{\mathbf{u}}(t)+\sum \mathbf{f}_{\mathrm{K}}(\mathbf{u}(t))=\mathbf{f}_{\mathrm{ex}}(t) \qquad (3)$$

$$\mathbf{f}_{\mathrm{ex}}(t)=\mathbf{Mg}+\mathbf{f}_{\mathrm{W}}(t) \qquad (4)$$

where, M: mass matrix, D: damping matrix, f_K: equivalent force vector due to spring force, u: displacement vector, f_{ex}: sum of external force vector, g: gravity acceleration vector, f_W: fluid force vector.

However, the damping matrix was expressed as a proportional damping model which produces the equivalent damping force f_D by setting dash-pots between elements. Accordingly, Eq.(3) can be transformed into the following equation.

$$\mathbf{M}\ddot{\mathbf{u}}(t)+\left\{\sum \mathbf{f}_{\mathrm{D}}(\dot{\mathbf{u}}(t))+\sum \mathbf{f}_{\mathrm{K}}(\mathbf{u}(t))\right\}=\mathbf{f}_{\mathrm{ex}}(t) \qquad \mathbf{(5)}$$

Eq.(5) can be solved by using the central difference method as follows.

$$\ddot{\mathbf{u}}(t)=\frac{\mathbf{u}(t+\Delta t)-2\mathbf{u}(t)+\mathbf{u}(t-\Delta t)}{\Delta t^2} \qquad (6)$$

$$\dot{\mathbf{u}}(t)=\frac{\mathbf{u}(t)-\mathbf{u}(t-\Delta t)}{\Delta t} \qquad (7)$$

Therefore, the displacement of each element can be found by introducing Eqs.(6) and (7) into Eq.(5) as follows.

$$\mathbf{u}(t+\Delta t)=\mathbf{M}^{-1}\left\{\mathbf{f}_{\mathrm{ex}}(t)-\sum\mathbf{f}_{\mathrm{D}}(\dot{\mathbf{u}}(t))-\sum\mathbf{f}_{\mathrm{K}}(\mathbf{u}(t))\right\}\Delta t^2 + 2\mathbf{u}(t)-\mathbf{u}(t-\Delta t) \qquad (8)$$

Consequently, the movement of all the elements can be determined at any point in time

4.2 Water flow method

In this paper, the water was flowed by giving the flow velocity distribution,

The flow velocity was modeled as a linear shape in which the surface velocity was U_s and the bottom velocity was $0.8U_s$, as shown in Fig. 10. It was also assumed, from the test observation, that the flow was observed at a point 10 cm behind the front-most gravel. The flow volume was given as 3.0 liter/s which corresponds to a flow velocity of $U_s = 1.4$ m/s and a water depth of 1.07 cm.

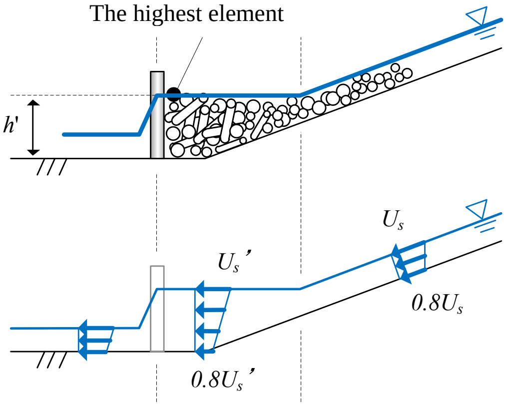


Fig. 10 Flow velocity distribution

The flow velocity has been changed from U_s to U_s' (< U_s) after the sediment was accumulated by trapping of steel open dam.

4.3 Simulation method

A 3-D DEM for simulating the trapping of the debris flow was performed by expressing the riverbed as a plane element, the grid steel dam as cylindrical elements, and the gravel as spherical elements. In this simulation, a riverbed with two sidewalls and a steel dam was expressed as three plane elements and eight steel pipes, respectively, as shown in Fig. 11.

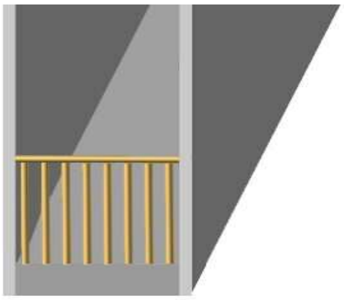


Fig. 11 Steel dam model

The computation was performed by changing the gravel diameter D = 1.0-1.5 cm at 0.1-cm intervals. This was done because the pieces of gravel used in the test (more than 1.0 cm) were not perfectly spherical in shape.

In the computation, the input data was used as shown in Table 1.

Table 1 Input data

Computational values	Spring constant	Normal direction K_n	1.0×10^6 N/m
		Tangential direction K_s	1.5×10^5 N/m
	Damping constant h		0.2
	Adhesive force c		0 N
	Friction angle $\tan\varphi$		0.404
Computational condition	Time interval Δt		1.0×10^{-7} s
	Total time		10s

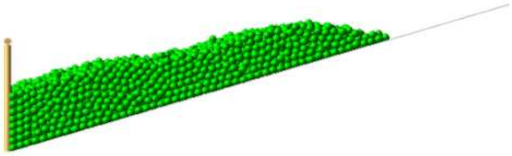
5. SIMULATION RESULTS

5.1 Final trapping states

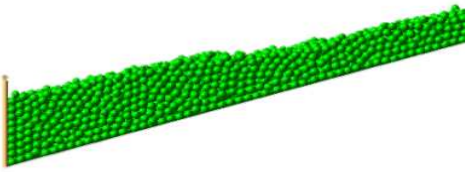
Figure 12 shows the final trapping states of gravel with diameters of 1 cm, 1.3 cm and 1.5 cm. From Fig.12(c), it was possible to determine that the computed result of D = 1.5 cm was in relatively good agreement with the test result, as shown in Fig. 6. It was recognized that a trapping mechanism is necessary to catch some gravel with the columns as a result of the arching action, as shown in Fig.13.

5.2 Trapping and outflow ratios

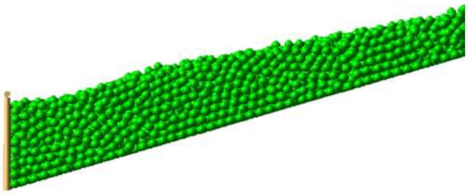
The trapping and outflow ratios were obtained by changing the gravel diameter (D) as listed in Table 2. It was found that the trapping ratio became



(a) Gravel diameter D=1.0cm

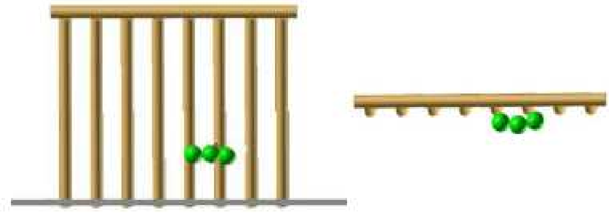


(b) Gravel diameter D= 1.3cm



(c) Gravel diameter D=1.5cm

Fig.12 Final trapping states (computed)



(a) from the upper-stream (b) from the top

Fig.13 Trapping mechanism by arch action

larger as the gravel size increased. A trapping ratio of D = 1.5 cm (97.7%) was nearly equal to that obtained in the test (99.2%). It was also confirmed that the outflow ratio of D = 1.5 cm was the smallest and closest to the test results.

5.3 Riverbed height- time relation

The riverbed height–time relationships for D = 1.0, 1.3, and 1.5 cm were computed as shown in Fig. 14, and were then compared with the test results. As the diameter of the gravel increased, the computed riverbed height–time relationship approached the test results. For a gravel diameter of D = 1.5 cm, the relationship was intermediate between the highest and the lowest. This was in good agreement with the test results.

This was because the pieces of gravel used in the test were of uneven shape, even though the gravel has been passed through a 1.0-cm screen.

6. CONCLUSIONS

The following conclusions can be drawn from this study.

(1) The experiments were able to model the trapping behavior of a debris flow by a steel open dam.

(2) The riverbed height–time relationship was determined from the test. This relationship provides a measure of the efficiency of the trapping performance of a steel open dam.

(3) The trapping and outflow ratios were obtained by counting the number of pieces of gravel either trapped or allowed to pass in the test.

(4) The final trapping states were photographed. These photographs are shown in Fig. 5 (front) and 6 (side).

(5) The 3-D DEM was developed to investigate the mechanism whereby a debris flow is trapped by assuming pieces of gravel to be spherical elements.

(6) The trapping and outflow ratios were computed by the 3-D DEM and were found to be in good agreement with the test results for a gravel diameter of D = 1.5 cm.

(7) The riverbed height–time relationship was examined by 3-D DEM. It was confirmed that the computed result for D = 1.5 cm was very close to the test result.

In the near future, the 3-D DEM should be extended to handle uneven elements so that each piece of gravel may be regarded as being an assembly element to examine the mechanism whereby a debris flow is trapped. It is also hoped that the actual trap state, as shown in Fig.1, would be simulated by the 3-D DEM.

ACKNOWLEDGMENTS

The authors are grateful to CTI Engineering, Co., Ltd. for the use of their hydrodynamic test facility.

Table 2 Trapping and Outflow ratios by gravel diameter (D)

Item	Test	D=1.0cm	D=1.1cm	D=1.2cm	D=1.3cm	D=1.4cm	D=1.5cm
Total No	7760	7760	7760	7760	7760	7760	7760
Trap No	7700	6903	7110	7332	7405	7409	7581
Outflow No	60	857	650	428	355	351	179
Trap ratio	99.2%	89.0%	91.6%	94.5%	95.4%	95.5%	97.7%

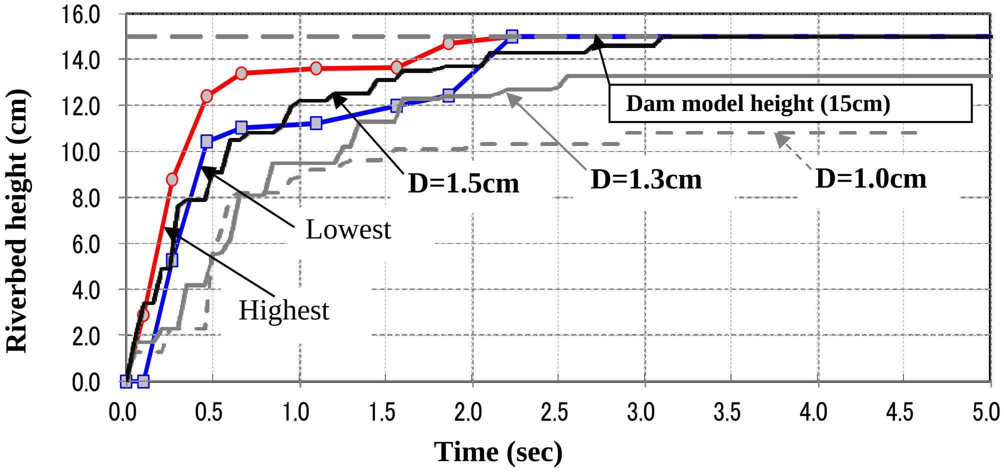


Fig.14 Riverbed height- time relation (Test and Analysis)

REFERENCES

Ashida, K. and Takahashi, T.(1980): Study on debris flow control-hydraulic function of grid type open dam, Annuals of Disaster Prevention Res. Ins. Kyoto Univ., Vol. 23B-2, pp. 433-441 (in Japanese with English abstract).

Fukawa, G., Katsuki, S., Ishikawa, N., and Yamada, T.(2002): Simulation and Stochastic Evaluation of Open Type Steel Check dam for Damming Up Performance, INTERPRAEVENT 2002, In the Pacific Rim-Matsumoto /Japan,Vol. 2, pp.751-760.

Fukawa, G., Katsuki, S., Ishikawa, N. and Yamada, T. (2004): A trap performance analysis of steel open-type dam by a 3D DEM, Proc. of JSCE, No.738/I-64, pp. 97-112 (in Japanese).

Ishikawa, N., Fukawa, G., Katsuki, S. and Yamada, T., (2004): Catch Effect of Debris Flow for Open Type Steel Check Dam by Physical and Numerical Modeling, INTERPRAVENT 2004, Band 3, pp. 153-163.

Katsuki, S. and Shibuya, H. (2010): The Distinct Element Method Simulation of Trap Performance of Check Dams used for Wood Contained Debris Flow, *Proceedings of The Tenth International Conference on Computational Structures Technology*, CD-ROM, pp.1-20, Valencia, Spain

Mizuno, H., Mizuyama, T., Minami, T., and Kuraoka, S. (2000): Analysis of Simulating Debris Flow Captured by Permeable Type Dam using Distinct Element Method, Journal of the Japan Society of Erosion Control Engineering, Vol. 52, No. 6, pp. 4-11.

Mizuyama, T., Kobashi, S., and Mizuno, H. (1995): Control of Passing Sediment with Grid-type Dams, Journal of the Japan Society of Erosion Control Engineering, Vol. 47, No. 5, pp. 8-13 (in Japanese with English abstract).

Mizuyama, T., Suzuki, H., Oikawa, Y., and Morita, A. (1988): Experimental Study on Permeable Sabo Dam, Journal of the Japan Society of Erosion Control Engineering, Vol.41, No. 2, pp. 21-25(in Japanese with English abstract).

Shibuya, H., Katsuki, S., Osumi, H., and Ishikawa, N. (2011): Trap performance analysis of woody debris structures by 3D DEM, Journal of the Japan Society of Erosion Control Engineering, Vol. 63, No. 6, pp. 13-22(in Japanese with English abstract).

Steel Sabo Structure Committee (2009): Design Manual of Steel Sabo Dam, Sabo and Landslide Technical Center, p.183 (in Japanese).

Watanabe, M, Mizuyama, T., Uehara, S.(1980): A study on Sabo facilities against countermeasure of debris flow, Journal of the Japan Society of Erosion Control Engineering, Vol. 32, No. 4, pp. 40-45(in Japanese).