INTRODUCTION

Woody debris has recently become a drainage bottleneck. This increasing tendency has been identified through on-site investigations, particularly over the past 10 years or so. For example, the 2014 Hiroshima landslide, the Izu-Oshima debris flow disaster (Typhoon Wipha), and the typhoon disasters in Kagoshima in 2016 and in northern Kyushu in 2017 involved large volumes of woody debris. In northern Kyushu, a large volume of driftwood accumulated in closed Sabo dams. Previously, debris flows or mud flows have been the main concern, but woody debris has now become the main type of ‘debris’ or ‘obstacle.’ This problem may be the result of a lengthy period of afforestation that was achieved through a tree-planting campaign to promote stable ground. The aim was to maintain living things and areas of preservation, but this concept has changed in the current age of forest management. Depopulation, felled trees, deforestation, and other issues may contribute. In contrast, planning and design previously differed between driftwood and debris flows based on the design standards for Sabo dam facilities, which have changed since 2000. Lately, renewal planning and design requires effective measures for both driftwood and debris flows [e.g., NILIM, 2007, 2016]. One countermeasure for open Sabo dams with steel pipes that are a countermeasure against woody debris and debris flows have been constructed. However, it is difficult for designers to select the optimum spacing between pipes. Therefore, the concept of general entrapment tends to employ smaller spacing intervals between pipes to protect downstream areas, which have a high expectation of security, although open Sabo dams gradually lose their function of routine sediment transport to pass through. Furthermore, in current design methods, the maximum grain size ($d_m$) is applied to determine the optimum spacing interval for entrapment, which does not take into account driftwood and roots. Thus, an effective method to evaluate the effects of woody debris is required to analyze the problems that arise due to trapping effects. We propose a novel method for evaluating the optimum spacing interval of open Sabo dams using a distinct element method. Moreover, the trapping mechanism of woody debris was investigated for open Sabo dams.

Key words: woody debris, open Sabo dam, distinct element method, trapping efficiency

1. INTRODUCTION

Woody debris has recently become a drainage bottleneck. This increasing tendency has been identified through on-site investigations, particularly over the past 10 years or so. For example, the 2014 Hiroshima landslide, the Izu-Oshima debris flow disaster (Typhoon Wipha), and the typhoon disasters in Kagoshima in 2016 and in northern Kyushu in 2017 involved large volumes of woody debris. In northern Kyushu, a large volume of driftwood accumulated in closed Sabo dams. Previously, debris flows or mud flows have been the main concern, but woody debris has now become the main type of ‘debris’ or ‘obstacle.’ This problem may be the result of a lengthy period of afforestation that was achieved through a tree-planting campaign to promote stable ground. The aim was to maintain living things and areas of preservation, but this concept has changed in the current age of forest management. Depopulation, felled trees, deforestation, and other issues may contribute. In contrast, planning and design previously differed between driftwood and debris flows based on the design standards for Sabo dam facilities, which have changed since 2000. Lately, renewal planning and design requires effective measures for both driftwood and debris flows [e.g., NILIM, 2007, 2016].
al. (2015) considered the optimal spacing interval with respect to the maximum boulder size. Furthermore, the trapping mechanisms have been used in experiments to examine open Sabo dams based on various flow models [e.g., Itoh et al., 2011; Hasegawa et al., 2003]. Discharge has a significant influence on open Sabo dams. Hiura et al. (2017) investigated the trapping functions of the vertical and horizontal members in an open Sabo dam. They reported some features that influenced the shape of the structure, and considered the optimal locations of the members.

In contrast, there have been many studies using smooth-particle hydrodynamics [Liu and Liu 2003] or moving-particle simulations [Koshizuka and Oka 1996] for fluid analysis, including the Lagrange model and Euler-Lagrange coupling model [Li and Zhao, 2018a, Kim et al., 2018]. These studies focused on the impact load, flow mechanisms of debris flows, and various other problems. However, the interaction between the fluid force and rigid bodies and interpretation of artificial viscosity terms make it hard to analyze complex multiphase flows composed of rigid bodies and fluid. Furthermore, the boundary conditions of interactions between elements are complex, and computational efficiency is insufficient for analyzing multiphase flows of woody debris. Few studies on the effects of woody debris have been conducted and it is essential to consider how woody debris becomes trapped.

Piton and Rocking (2015) and Piton et al. (2018) investigated the design of the spacing intervals of open Sabo dams. As the shape of the slits influences the trapping effect, the optimal shape of the slits against flowing materials was analyzed. Based on empirical data, the reproducibility was poor. Also, the trapping mechanisms for driftwood and boulders remain unknown. Shima et al. (2018) studied boulder trapping performance based on the blockage of an open Sabo dam that entrapped woody debris. The results indicated that the spacing intervals between pipes become blocked due to an arch effect. An experimental investigation of the trapping performance of an open Sabo dam was carried out, and a hydraulic test for an open Sabo dam was applied to evaluate the capture and height time relations, and the grain size distributions of outflow sediment with changes in the riverbed slope and slit interval. Furthermore, the proposed capture patterns were classified as “complete blockage”, “partial blockage”, and “control” types. These types express the allowable passage of gravel through a small amount of sediment. Therefore, it is necessary to consider when an open Sabo dam will become completely blocked by debris flow. However, the results of this experiment are uncertain under some conditions. Hence, a number of factors remain to be examined.

We previously studied the mechanisms that trapping woody debris in an open Sabo dam [Horiguchi et al., 2015], and used a distinct element method (herein, DEM) to assess the movement of driftwood necessary to prevent bridges from becoming blocked. However, verification of trapping efficiency in the event of large volumes of driftwood has been little examined, with a lack of observations and proper perspective. For performance assessment, it is important to investigate the features of the gravel that passes through open Sabo dams, and those of the gravel that is trapped. It is important to characterize trapped or passed gravel to evaluate the trapping efficiency. Therefore, a numerical method to evaluate trapping effects is needed.

In this paper, we propose a method for determining trapping efficiency based on the optimal pipe spacing for an open Sabo dam using a DEM. Furthermore, the trapping mechanism is investigated based on our experimental and analytical results regarding the passage of gravel through an open Sabo dam.

2. Applied DEM

2.1 Outline of the DEM

The DEM is basically a solid-body method. The method is used to model “distinct” bodies. Contact between elements is formulated as a two-body problem interaction and calculated based on Newton’s laws. If two elements come into contact, a spring force suddenly acts between the two. The spring force is calculated at every time step, and the elements should follow the calculated trajectory. The results of this analysis can easily determine the motion of each element. To interpret DEM results requires a confirmation analysis of trapping efficiency. We analyzed the behavior of the trapped boulders and driftwood, and used the method to obtain detailed information about each element.

Fluid force is used to analyze the interaction between water flow and the movement of driftwood and boulders. In this case, it is necessary to analyze how the fluid is influenced by the effect of woody debris on the trapping efficiency, and how the fluid flows through gaps between driftwood and gravel. Accordingly, there have been many numerical studies of fluid flow models for debris flows [Busnelli et al., 2005; Catella et al., 2005]. For example, computational fluid dynamics (CFD)-DEM or Lattice-Boltzmann and DEM coupling have been used to analyze solid-liquid mixed phase flows, and the behavior of the fluid was calculated accurately [Li and Zhao, 2016]. However, it is difficult to apply the parameter-decision method, and the cell size and stability of the analysis has a large influence on the
Accurate calculations impose high computational burdens. Therefore, the proposed model focuses on water velocity and discharge based on the data obtained from our experimental results. The individual behaviors of driftwood and gravel are investigated to evaluate trapping efficiency.

We omit many numerical formulas that have already been published [Katsuki et al., 2014 a; Horiguchi et al., 2015]. The proposed method reproduces the circumstances that cause bridge blockages and the motion of driftwood in real disasters, although the profile of the flow velocity was obtained from a preliminary experiment [Katsuki et al., 2014 b]. The objective of water-flow-distribution models is to facilitate analysis of fluid forces. Furthermore, our proposed method can be used to investigate how boulders and driftwood combine in trapping situations.

2.2 Equation for fluid force acting on woody

The proposed method is based on the fluid force acting on each element. The fluid force is calculated in terms of the relative velocity obtained from the velocity of each integration point using the Gauss divergence theorem for running water. The fluid force acting on a cylindrical element influences five points along the centerline of a cylindrical element, and the fluid force is obtained from the flow velocity between each Gaussian point, as shown in Fig. 1. Furthermore, the fluid force acting on the center of gravity of a cylindrical element is evaluated to generate a Gaussian integral formula [Shibuya et al., 2011 a].

First, the fluid force acting on integral point \( j \) is the local coordinate of element \( i \), which is evaluated based on the calculated flow velocity \( \mathbf{U}_i \) using the water-flow-distribution model.

\[
\mathbf{f}_{w_j} = \frac{1}{2} C_d \rho w \mathbf{A}_0 \begin{bmatrix} u_{x_i} \\ u_{y_i} \\ u_{z_i} \end{bmatrix} + \mathbf{f}_b
\]

where \( C_d \) is the coefficient of the drag force, \( \rho \) is the specific gravity of water, \( w \) is the weight of integral point \( j \), \( \mathbf{A}_0 \) is the projected area of the flow direction for integral point \( j \) of element \( i \), \( u_{x_i}, u_{y_i}, u_{z_i} \) are the \( x \)-, \( y \)-, and \( z \)-axial direction components for the relative velocity vector between the velocity of integral point \( j \) and the water velocity with respect to the local coordinate system of each element, \( \mathbf{u}_i \) is the translational direction velocity vector for the local coordinate system of element \( i \), \( u_{x_0}, u_{y_0}, u_{z_0} \) are the rotational velocity around the \( y \)- and \( z \)-axes for the local coordinate system of each element \( i \), \( l_{g0} \) is the position of integral point \( j \) with respect to a cylindrical element when the center point of an element is 0, \( l_2/2 \leq l_{g0} \leq l/2 \), \( l \) is the length of element \( i \), \( \mathbf{f}_b \) is the buoyancy vector for integral point \( j \) of element \( i \), \( V_i \) is the cubic volume of element \( i \), and \( g \) is acceleration due to gravity.

Furthermore, the cylinder model uses five integral points based on position \( l_{g0} \) and the weight of integral point \( w_j \), for integral point \( j \), as shown in Table 1. In the basic concept, the water-flow-distribution model is defined directly in terms of the center of gravity of each cylindrical element. However, the complex shape of the cylindrical model is not simply given because of a certain length from a first direction. The fluid point is defined in terms of a five-integral Gauss point, and the ratio of buoyancy and/or drag force and weight is used when integrating the Gauss value.

Considering the equilibrium conditions between the water and elements, the fluid force \( \mathbf{f}_i \) of local coordinate element \( i \) is defined as:

\[
\mathbf{f}_i = \sum_{j=1}^{N-1} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -l_{g0} \\ 0 & l_{g0} & 0 \end{bmatrix} \mathbf{f}_{w_j}
\]

2.3 Water-flow-distribution model

A woody debris is composed of accumulated driftwood and water. It is therefore necessary to integrate the proposed method, which affects the impact flow of open Sabo dams. The water flow

| \( j \) | Location \( l_{g0} \) | Weight \( w_j \) |
|-------|----------------|--------------|
| 1     | -0.90 \( l/2 \) | 0.12         |
| 2     | -0.53 \( l/2 \) | 0.24         |
| 3     | 0              | 0.28         |
| 4     | 0.53 \( l/2 \) | 0.24         |
| 5     | 0.90 \( l/2 \) | 0.12         |
velocity around driftwood varies due to interactions between them. The water-flow-distribution model adopts three domains, as shown in Fig. 2: the approach, trapping and watercourse domains.

An outline of the model is as follows.
1) The water-flow-distribution model is based on the flow velocity, which is varied with the water depth to fit the experimental flow.
2) The flow velocity is based on the center of gravity of each element. We use only cylindrical elements based on five Gaussian integral points, as indicated in Fig. 3(a), (b).
3) In the calculation of the flow velocity vector, we use unbalanced water movement; the hydraulic jump and accuracy of the turbulence are disregarded.
4) The water depth changes based on the experimental data for trapped driftwood. This model was considered to conserve discharge in the analytical case.

The behavior seen in the experiments was roughly reproduced by this model, although the flow velocity distribution differed from that of an actual debris flow.

### 2.3.3 Trapping domain

The water depth in the trapping domain increases proportionally when approaching an open Sabo dam, as shown in Fig. 2. The depth of woody debris is defined as the ratio of the area of the trapped woody debris, as indicated in Fig. 4, to the cross-sectional area of the channel, as follows:

\[ h' = k_r (\frac{\sum A_\alpha}{A_0} \leq 0.2) \] (6 a)

\[ h' = \frac{H - h_0}{1.3} \left( \frac{\sum A_\alpha}{A_0} - 0.2 \right) (0.2 \leq \sum A_\alpha/A_0 \leq 1.5) \] (6 b)

\[ h' = H \left( 1.5 \leq \sum A_\alpha/A_0 \right) \] (6 c)

where \( H \) is the height of the open Sabo dam, \( A_\alpha \) is the cross section of the channel \( (A_\alpha = BH) \), \( B \) is the channel width and \( A_0 \) is the total projected area of the trapped woody debris and the cross-sectional area of the channel.

Thus, the flow velocity decreases to retain continuous discharge as the water depth increases. The
trapping domain is determined based on the water depth of the trapped woody debris. The experimental observations obtained using a high-speed video camera show the changes in water depth around the open Sabo dam model.

The cross-sectional average velocity $\overline{U}$ at depth $h'$ is obtained based on the law of conservation of discharge, as follows:

$$\overline{U} = \frac{h_o}{h'} U_o$$  \hspace{1cm} (7)

The increment in the damming up of depth $\Delta h$ is defined as follows:

$$\Delta h = k_o \sin \theta_o \left( \frac{D}{W} \right) \frac{u_0^2}{2g}$$ \hspace{1cm} (8)

where $k_o$ indicates the section modules (e.g., $k_o$ of a steel pipe is 2.0), $\theta_o$ is the angle of vertical members relative to the bottom, $D$ is the diameter of the vertical members, $W$ is the interval of the vertical members, and $U_o$ is the upstream water velocity.

Furthermore, an experiment under supercritical flow conditions was conducted to observe the damming up of the open Sabo dam model. The afflux water depth is obtained as a random number from a normal distribution, as shown in Fig. 5. With regard to running water, the afflux water depth ($h_\alpha$) is assumed to be a stochastic variable influenced by a normal distribution, and is given a random number with a standard deviation of $\Delta h / 4$ and an average value of $h_\alpha$. The flow velocity in the trapping domain is calculated based on Eq. (5). The maximum, minimum, average, and standard deviations of $h_\alpha$ are $h_\alpha + \Delta h / 2$, $h_\alpha$, $h_\alpha + \Delta h / 2$, and $\Delta h / 4$, respectively.

A parameter is used to confirm the reproducibility of the water depth around the summit of the open Sabo dam model at a particular moment.

Because the flow direction of each piece of driftwood and gravel affects the trapping efficiency in a real flow, the water-flow-distribution model uses the probability distributions of the tangential velocity and the damming up depth around an open Sabo dam. The tangential direction velocity $U_{t\alpha}$ is obtained based on a random number from the normal distribution, taking into account the turbulence of the water flow, as shown in Fig. 6. The maximum, minimum, average, and standard deviations of $U_{t\alpha}$ are $0.1 U_{t\alpha}$, $-0.1 U_{t\alpha}$, $-0.05 U_{t\alpha}$, and $0.025 U_{t\alpha}$, respectively. The velocity $U_{t\alpha}$ is considered only in the case of supercritical flow, which is defined as follows:

$$\Delta h \leq h_\alpha = \sqrt{\frac{1}{g} (h_\alpha U_{t\alpha})^2}$$ \hspace{1cm} (9)

where $h_\alpha$ is the critical depth.

The changes in water depth with respect to the distance from the entrapment are shown in Fig. 3. In this calculation, preservation of the discharge must be considered. The value of the water velocity vector $|U_{t\alpha}|$ acting on each integral point is provided simultaneously by Eq. (5).

First, the location ($h' = h_\alpha$) indicated in Fig. 3 (a) is the same as the initial velocity. However, as the initial water depth $h_\alpha$ increases in the trapping domain, the change in the water depth should obey $\alpha$ and $\beta$ in the following equations:

$$\alpha = \alpha_0 - \gamma$$ \hspace{1cm} (10 a)

$$\beta = \beta_0 - \gamma$$ \hspace{1cm} (10 b)

The coefficient $\gamma$ is obtained using the following equation, based on the law of the conservation of discharge.

$$\gamma = \frac{1}{3} \left[ 1 - \frac{h_\alpha}{h'} \right] (\alpha_0 + \beta_0)$$ \hspace{1cm} (11)

Therefore, the water velocity is used to evaluate the coefficients $\alpha$ and $\beta$.

2.3.4 Water course domain

The water depth and the velocity of the entrapment operate inversely, and are nearly equivalent to the initial water depth and flow velocity. The model reproduces the decrease in the water depth from the principal axis of the entrapment to the initial water depth. The parameter is set to confirm the reproducibility with respect to the results of the
3. Trapping assessment experiment

An experiment using woody debris was carried out to investigate the trapping effect on the performance of an open Sabo dam at a scale of 1:50. The effect of driftwood using various spacing intervals was observed. In particular, the trapping efficiency and outflow of the gravel and wood models were investigated under various scenarios.

3.1 Channel used in experiment

Figure 7 shows a schematic of the channel slope. The experimental setup had a length of 4.35 m, a width of 0.3 m, and a height of 0.5 m. The side was made of glass so that the movement of the granular and wood materials could be observed from the side. We set the inclination angle of the slope to 15°. The inclination angle was determined based on the debris flow section of a Japanese dam design [NILIM, 2016]. The channel bed used a roughness model with a board set at a width of 10 mm, height of 5 mm, and installation interval of 20 mm. The roughness model and the relationship between the strip roughness spacing (λ) and roughness height (k) of the bed has been found to be equivalent to the roughness of sand [Adachi, 1964]. We used a value similar to that for a river bed. Furthermore, we set the debris flow segregation based on the article of Horiguchi et al. (2016).

Photo 1 shows the open Sabo dam model. The model used wood of diameter 12 mm, which corresponded to a steel pipe of 60 cm. The interval was set to (W =25 mm) to the four cases, with applied ratios with respect to the interval and maximum boulder sizes (dv), W/dv, of 1.0, 1.5, 2.0, and 2.5, respectively. The empirical model is principally intended to use in investigating the effect of driftwood on the trapping effect. These cases are the same as the analytical cases investigated.

3.2 Granular material and wood model

The woody debris model used in this experiment was constructed based on both granular and wood material, as shown in Photo 2. The granular material was made of coal ash. The density was 1.9, and the shape of the granular material was roughly spherical to allow simplification. Each material was gray, green, yellow, or red, and four grain sizes were used so that we could easily observe the motion of the wood debris. The grain size distribution of the granular models is shown in Fig. 8. A grain size of dv =25 mm and a wood model size of 6 φ × 120 mm were used.

3.3 Outline of the experiment

During the experiment, the woody debris model was located in the channel slope, and the water (Q =4.4 l/s) flowed from the back of the apparatus. The experimental cases are summarized in Table 2. We varied the wood volumetric ratio and took the average of five results in each case. It has been reported that the wood volumetric ratio is approximately 20% in a real woody debris flow, and the ratios used in the experiment were 10%, 20%, and 30% [Osanai et al., 1998]. Here, the wood volumetric ratio was defined as follows:

\[
K_w = \frac{V_w}{V_g + V_w} \times 100 \% \tag{12}
\]

where \(V_g\) is the volume of the granular material, and \(V_w\) is the volume of the wood model.

The volume of the granular material (number of grains : 8,996) is constant, as shown in Table 2, and the volume of the wood varied throughout the experiment.
3.4 Experimental results

Figure 9 shows the relationship between the trapping efficiency and wood volumetric ratio with respect to the spacing interval. The experimental results are summarized below.

1. For a wood volumetric ratio of $K_w = 10\%$ and $20\%$, an interval parameter ($W/d_{ws}$) from 1.0 to 2.5 resulted in a granular material or driftwood trapping efficiency of approximately 100%. However, for an interval parameter of $W/d_{ws}=2.5$, the results of a wood volumetric ratio of $K_w = 10\%$ achieved granular material and wood trapping efficiencies of approximately 80% and 70%, respectively.

2. For a wood volumetric ratio of $K_w = 30\%$, if the interval parameter of $W/d_{ws}=2.5$ was applied, the granular and driftwood trapping efficiency was 98%. Although this was an extreme case of the current design, the effect of driftwood was sufficient to yield an improvement in the trapping efficiency.

3. For a wood volumetric ratio of $K_w = 0\%$, an interval of $W/d_{ws}=1.5$ achieved a trapping efficiency of approximately 0% under the experimental conditions tested. The concept of the present design is slightly different, for the following reasons.

The granular shown in Photo 2 are quasi-spherical in shape, and the inter-locking effect between the granular makes it difficult to generate the trapping functionality. For example, the front elevation for only the granular results ($W/d_{ws}=1.0$) is shown in Fig. 10 (a). However, the gray model cannot be trapped in the intervals in the case of $W/d_{ws}=1.5$. This is because the arch effect is difficult to achieve, as shown in Fig. 10 (b). The inter-locking is easily loosened when using a gravel frame structure. Under these experimental conditions, the water continues flowing until the granular material stops moving. As a reference, in the case of natural gravel, an experiment in which gravel was entrapped has already been carried out for an interval parameter of $W/d_{ws}=1.5$ [Ishikawa et al., 2014].

4. Analysis

4.1 Analysis procedure

We now present an analysis that reproduces the woody debris model in which the fluid force is defined in terms of a water-flow-distribution model. First, the initial positions of the elements are specified using a drooping method, because the elements are arranged irregularly [Hakuno, 1997]. The movement of the elements stabilizes at approximately 1 mm/s or less. The granular distribution during the experiment and analysis was fitted simultaneously, as shown in Fig. 11. The parameters of the water-flow-distribution model were determined after measuring the afflux depth and water velocity, based on experimental data [Shibuya et al., 2011 b, Horiguchi et al., 2015].

4.2 Conditions of analysis

Table 3 shows the parameters used in the analysis. The channel slope and element conditions were equivalent to the experimental conditions. The initial velocity, $U_i$, and initial water depth, $h_i$, were set based on experimental data. The coefficient of the drag force...
was \( C_p = 1.0 \), from a range from \( Re = 1.0 \times 10^3 \) to 1.0 \( \times 10^5 \). The normal direction of the spring constant, \( K_n \), was determined based on a loading test and the relationship between the load and displacement. The shear direction of the spring constant \( K_s \) was set as follows. The relationship between the normal and shear spring constants was represented by the following equation, which applies the pulse wave propagation of an elastic wave from a linear approximation method, as in wave theory.

\[
G = \frac{E}{2(1+\nu)}, \quad \lambda = \frac{E\nu}{(1+\nu)(1-2\nu)} \tag{13}
\]

\[
V_p = \sqrt{\frac{\lambda+2G}{\rho}}, \quad V_s = \sqrt{\frac{G}{\rho}} \tag{14}
\]

\[
K_n = \frac{1}{4\pi\rho}V_p^2, \quad K_s = \frac{1}{4\pi\rho}V_s^2 \tag{15}
\]

where \( G \) and \( \lambda \) are Lamé constants, \( E \) is Young’s modulus, \( \nu \) is the Poisson ratio, \( V_p \) is the primary wave (or longitudinal wave) velocity, \( V_s \) is the secondary wave (or transverse wave) velocity, and \( \rho \) is the density of the element.

From Eqs. (13) – (15), the ratio \( (K_s/K_n) \) of the shear -direction spring constant \( (K_s) \) and the spring constant in the normal direction \( (K_n) \) is as follows.

\[
K_s = \frac{G}{\lambda+2G} = \frac{1-2\nu}{2(1-\nu)} \tag{16}
\]

In general, the Poisson ratio of wood is \( \nu \approx 0.4 \), with \( K_s/K_n = 0.15 \) [Hakuno, 1997]. Each spring constant was determined. Contact between elements in water rather than air is thought to cause a large damping force.

Accordingly, the damping effect generated by the relative velocity between elements and water was evaluated using Eq. (17). We suppressed the vibration generated and stabilized the damping force (herein, dash-pot) in the numerical simulation in which each of the elements experiences some contact. The instability arises due to the fluid force. Therefore, the damping constant is \( h = 0.2 \), and the attenuation coefficient is calculated as:

\[
C = 2h \sqrt{\frac{m_1m_2}{m_1+m_2}} K_s \tag{17}
\]

where \( m_1 \) and \( m_2 \) are the masses of the elements in contact.

Furthermore, the adhesive force and friction were determined based on another experiment to be \( e = 0 \) N and \( \tan \phi = 0.404 (\phi = 22^\circ) \), respectively.

The time step \( \Delta t \) is calculated as follows:

\[
\Delta t \leq \frac{m}{\sqrt{K_s}} \tag{18}
\]

where, \( m \) is the mass of each element.

### 4.3 Analytical results

The analytical results are equivalent to the experimental results, as shown in Table 2. The analytical model was based on the experimental parameters and reproduced the experimental dimensions, as shown in Fig. 11.

#### 4.3.1 Relationship between trapping efficiency and interval (Wo.)

Figure 12 shows the relationship between trapping efficiency (solid line) and interval (dotted line). We compare the results. The analytical trapping efficiency is roughly the same as the experimental value, within a margin of error of 5% or less. Therefore, the proposed method is reliable for analyzing open Sabo dams based on the relationship between the interval \( (W) \) and wood debris. It is thought that the optimal spacing interval can be determined in a reproducible manner, although a

| Table 3 Analysis parameters |
|-----------------------------|
| **Channel**                 |
| Inclination angle \( \theta \) (°) | 15 |
| Length (m)                  | 3.5 |
| Width (m)                   | 0.3 |
| **Flow**                    |
| Water velocity (m/s)        | 1.1 |
| Water depth (mm)            | 50 |
| Drag force coefficient \( c_d \) | Sphere: 0.49 | Cylinder: 1.0 |
| **Element**                 |
| Sphere (number)             | 8996 |
| Cylinder (number)           | 0.200 | 450.721 |
| **Density**                 |
| Sphere \( \rho \) (kg/m³)   | 1900 |
| Cylinder \( \rho \)         | 950 |
| **Constant spring parameter** |
| Normal spring constant \( K_n \) (N/m) | 1.0×10⁴ |
| Shear spring constant \( K_s \) (N/m) | 1.5×10⁷ |
| Damping constant \( h \)     | 0.8 |
| Viscosity \( c_v \) (N)     | 0 |
| Friction coefficient \( \tan \phi \) | 0.404 |
| **Time step**               |
| Calculation condition \( \Delta t \) (s) | 1.0×10⁻⁶ |

Fig. 11 Outline of the analytical model: the analytical slope is the same as in the experiment, and the Sabo dam model uses a cylindrical element as the right side. The roughness model also used a cylindrical element.
simple spherical model was used in both the experiment and the analysis. Also, regardless of the initial positions of the granular and driftwood models, the results of the analysis confirm the reproducibility of the front part of the concentration mechanism for woody debris.

4.3.2 Woody debris trapping mechanism

Figure 13 shows some of the final shapes when only granular material is considered. The deposition depth of the experiment on the slightly upstream side of the open Sabo dam model was greater than the analytical value. This was because the model cannot express complex water flow. However, almost all of the final shapes were generally reproduced by the analysis. Large amounts of granular (gray or green) material blocked the spacing intervals and were concentrated in the front part of the debris flow. These results indicate the arch action effect and inter-locking between the blocked spacing intervals. These results also indicate that jamming of the intervals of an open Sabo dam is governed by the equilibrium forces between the spherical elements. The effect of blockage was reproduced even though the analysis used spherical material.

Figure 14 shows the final shapes of the woody debris. The final deposition shape obtained from the analysis was not completely consistent with the experimental results. In the water-flow-distribution model, each element is specified in terms of the fluid force acting on the center of gravity, and the fluid force continuously pushes in the direction of the water flow. Therefore, the final shape according to the analysis deviates from the experimentally observed shape. The results mainly indicate a volumetric ratio of $\alpha = 10-30\%$; the interval parameter was compared based on the influence of the driftwood. When a large amount of driftwood was clearly concentrated in front of woody debris, the spaces became blocked. The driftwood interrupted the granular material, most of which thus had difficulty passing between the pipes. Furthermore, as shown on the downstream side of Fig. 14, large amounts of granular material disappeared due to the effect of the accumulated driftwood, which acted as a wall. However, the driftwood was concentrated at the front, and the results of our experiments and the analyses were equivalent in terms of the trapping effect. Accordingly, a small amount of driftwood has a large influence on the blockage of intervals. The entrapped driftwood increases the effect of the trapping by acting as a reticulated mass, as shown in Fig. 15.

In a real disaster, it has been reported that driftwood becomes broken or deformed. The results of our analysis are generally similar to the trapping circumstances of real woody debris. Therefore, we conclude that the proposed method can express the effects of driftwood on trapping efficiency.

4.3.3 Passing of granular material through intervals

Figure 16 shows the amount of granular material passing through the dam in all cases applied in the experiments and analyses, and shows the relationship between the experimental and analytical results. However, the types of granular materials that flowed out differed slightly. In Fig. 16, red indicates a comparatively large amount of granular material passing through the dam in the experiment, whereas green indicates a larger amount according to the analysis. The difference occurred because the analysis concentrates on large granular materials. Namely, the larger particles in the analysis are more easily concentrated at the front part than those in the experiments. However, the analysis and experimental results show that granular materials can pass through if they are smaller than $d_{50}$, and gravel is comparatively small. Granular materials pass through only when they are transported individually.
Therefore, the proposed method can be used for safety assessments based on possible downstream outflow. The woody debris was completely trapped until the interval reached $w_{n}=2.0$.

5. Conclusion

We proposed a method for evaluating trapping efficiency to optimize the interval of an open Sabo dam using DEM. The results of this study are as follows.

1) Experiment

The woody debris was completely trapped for intervals less than $d_{n} \times 2.0$. The volume of driftwood had a large influence on the changes in and/or increases in the trapping efficiency.

2) Analysis

The applied DEM generally reproduced most of the experimental results, and could reproduce some of the trapping efficiency of the open Sabo dam model. Also, the proposed method could be used for safety assessments in terms of the possibility of downstream outflow. However, we used a linear water-flow-distribution model, and the experiment may have been performed without sufficient bed roughness, because the granular material did not become stuck between the rough parts of the bed after passing through the...
Therefore, it is necessary to use a more appropriate flow velocity distribution when applying the proposed method to other conditions.

3) Trapping mechanism
The experimental and analytical results indicate that the flow process becomes jammed in the spacing intervals of Sabo dams due to an arch action effect. We also observed that driftwood jammed other granular materials and increased the trapping efficiency.

4) Future agenda
i) In this paper, the water depth and velocity obtained from our experiment were used in our analysis. At a real scale, the water depth and velocity should be estimated using the Manning formula, equation of continuity and the channel section of an open Sabo dam, based on estimated debris flow peak discharge. The proposed method can be used to evaluate trapping efficiency based on the calculated water depth and velocity. The applicability of our method should be confirmed based on analysis of past disasters. Moreover, the driftwood and boulder trapping mechanisms should be considered so that micromechanics can be applied when assessing the blockage mechanism in crevice areas.

ii) The proposed method should be improved with respect to the estimated discharge and the behavior of individual pieces of driftwood. Also, there are many factors that influence trapping efficiency, so it would be useful to investigate the effects of maximum boulder size ($d_m$), length of wood, and inclination angle in the near future.

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