Protection by Steel Open-Type Sabo Dams against Unexpected Debris Flow

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1.Introduction

In order to protect people and houses and to mitigate the damage against debris flow, many steel open-type Sabo dams (hereafter, steel open dams) have been constructed in Japan. Recently, due to torrential local downpours of unusual weather, steel open dams have partially collapsed by unexpected debris flow including gigantic rocks as shown in Figs.1 and 2 [Central Regional Development Bureau, 2014].

Fig.1 Steel open dam trapped rocks

Fig.2 Steel open dam was partially collapsed by large rocks

This paper presents two computational approaches on the structural protection by using a three dimensional (3D) elastic-plastic analysis and an impact FEM analysis to demonstrate the effects of unexpected debris flow load and rock impact. First, the structural integrity is evaluated for steel open dams against unexpected flow loads from the viewpoints of (1) redundancy (reserved strength for the undamaged structure) and (2) robustness (remaining strength for the damaged structure), respectively[Ishikawa, et.al, 2013]. Second, the impact FEM analysis is conducted to investigate the damage of a steel open dam against rock impact by using the software of ANSYS AUTODYN [Beppu,et.al.2015].

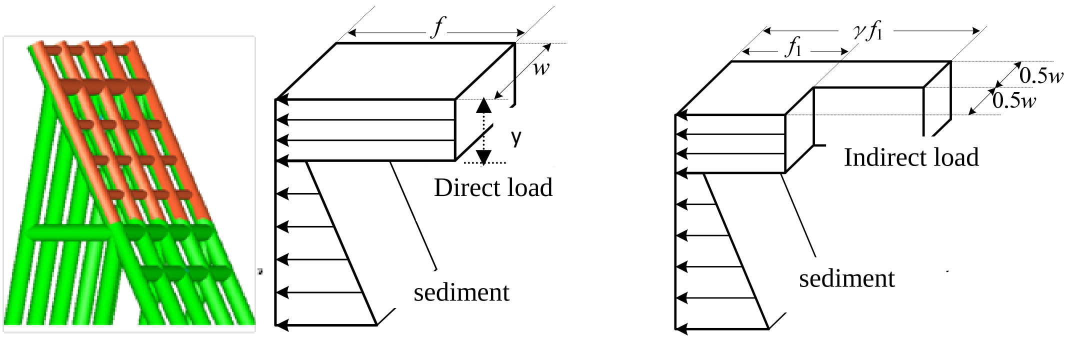
2. Unexpected Debris Flow

Unexpected debris flow is defined as the debris flow unexpected in the design process and is the debris flow diverted through unexpected means, causing unexpected damage. That is to say, the unexpected debris flow means the huge direct and indirect (diverted) debris flows[Katade and Katsuki, 2010] as shown in Fig. 3(b) and 3(c), respectively. Although the debris flow is actually an impulsive fluid load, it has been dealt with as a quasi-static load as shown in Fig. 3.

The indirect debris flow was assumed as a diverted load in the right hand side of the steel dam as shown in Fig.3(c). In case of direct debris flow in Fig.3(b), the debris flow load F_1 is expressed as follows [Steel Sabo Structure Committee,2009] ;

$$F_1 = f\,w\,y \qquad (1)$$

where, f: the length of direct debris flow load, w: the width of direct debris flow load, y: the depth of debris flow load.



(a) Steel open dam (b) Direct debris flow (c) Indirect debris flow

Fig.3 Direct and indirect (diverted) debris flow loads

In case of indirect debris flow in Fig.3(c), the indirect debris flow load which is the same one as direct flow is expressed as follows;

$F_2 = 0.5w\gamma f_1 y + 0.5wf_1 y = 0.5wf_1 y(\gamma + 1)$ (2)

where, f_1: the uniform length of indirect debris flow load, γ: the diverted ratio of the length of indirect debris flow load ($\gamma \geq 1.0$). Therefore, the uniform length of indirect debris flow load is obtained by equating Eq.(1) and Eq.(2) as follows.

$$f_1 = \frac{2f}{\gamma + 1} \quad (3)$$

If γ =1.0, then it means the direct debris flow load. If γ =2.0, then it represents the maximum indirect debris flow load.

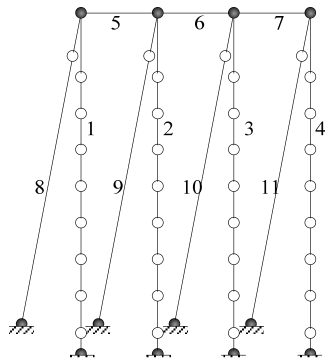


Fig.4 A steel open dam model

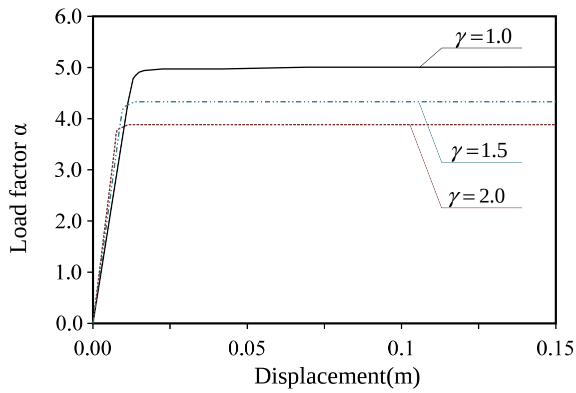


Fig.5 Load factor- displacement relation

3. Redundancy analysis

3.1 Definition

Redundancy is defined as the reserved strength for the undamaged structure. Therefore, redundancy analysis means to examine how much safety margin the undamaged structure has. That is to say, the redundancy is evaluated by the structural safety factor R_1 from the design load factor (α=1) to the collapse load factor ($\alpha=\alpha_c$) and the reserved strength R_2 as the ratio between collapse load factor (α_c) and elastic limit load factor (α_e) as follows.

$R_1=\alpha_c/1.0$ (4) $R_2= \alpha_c/\alpha_e$ (5)

where, R_1:structural safety ratio (collapse load factor /design load factor), R_2:reserved strength ratio(collapse load factor /elastic limit load factor), α_c: collapse load factor, α_e: elastic limit load factor.

Therefore, the redundancies R_1 and R_2 can be found by performing the 3D elastic-plastic analysis [Katsuki,S.(1998)] for steel open dams against the direct and indirect (diverted) loads, respectively.

3.2 Computational results

First, the redundancies R_1 and R_2 against the direct load (γ=1.0) and indirect load (γ=2.0) for a steel open dam model in Fig. 4 were obtained as shown in Fig.5 and Tab.1, respectively. It should be noted that the load factor R_1 =5.0 (γ=1.0) for direct load decreases to R_1 =3.8(γ=2.0) for indirect load, and R_2=1.16(γ=1.0) for direct load to R_2 =1.09(γ=2.0) for indirect load as shown in Fig.5 and Tab.1. This means that the dam has a small reserved strength when a dam subjected to indirect load (γ=2.0).

Tab.1 Redundancy of a steel open dam as shown in Fig.3

	Direct load(γ=1.0)		Indirect load(γ=2.0)	
Redundancy	$R_1= \alpha_c$	$R_2=\alpha_c /\alpha_e$	$R_1=\alpha_c$	$R_2=\alpha_c /\alpha_e$
Value	5.0	1.16	3.8	1.09

4.Robustness analysis

4.1 Definition

Robustness means the remaining strength for the damaged structure by removal of one or two members from a steel dam against the direct or indirect loads. Therefore, robustness analysis is to investigate how much remaining strength of the damaged structure has.
Robustness index, i.e., the remaining strength ratio is expressed as follows:

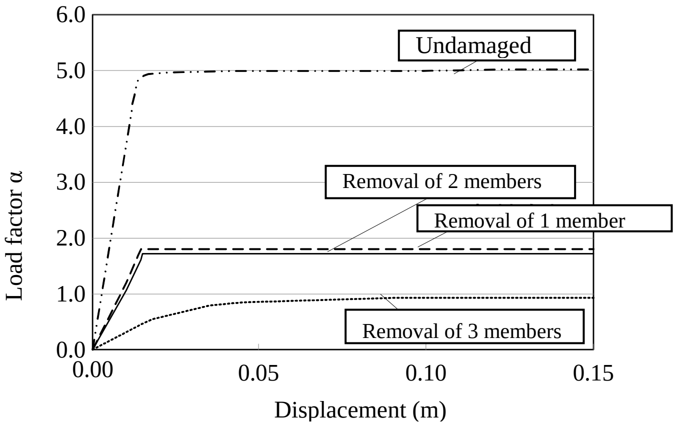


Fig.6 Effect of removal of members against direct load

$$\beta_i = \frac{\alpha_{ci}}{\alpha_{c0}} \qquad (3)$$

where, α_{ci} : the maximum load factor of the damaged structure by removal of i number of member, α_{c0}: the load factor of undamaged structure.

4.2 Computational results

The remaining strength is decreased by removal of a member against direct or indirect load. For example, the relationship between load factor α and displacement is obtained against direct load as shown in Fig.6. It was obvious that the remaining strength ratios ($\beta_i = \alpha_{ci} / \alpha_{c0}$) decreased β_1=0.36(=1.8/5.0), β_2=0.34(=1.7/5.0) and β_3=0.20(=1.0/5.0) less than the undamaged dam by removing the 1, 2 and 3 members, respectively. It was also found that the remaining strength ratio against the indirect load was generally decreased than the one against the direct load.

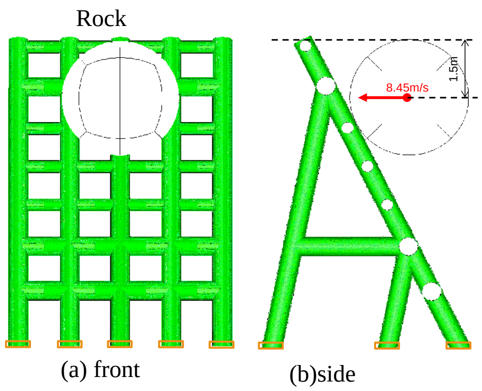


Fig.7 Steel open dam against a rock impact

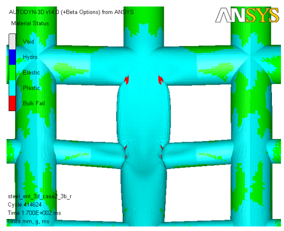


Fig.8 Local deformation of front struck by rock impact

5. Impact FEM analysis

An impact FEM analysis was conducted against a huge rock by using ANSYS AUTODYN in order to confirm the integrity of a steel open dam, as shown in Fig.7. The steel open dam model with the height of 8m and the width of 5.2m which was connected by the joints between the thick pipe of 508mm with the thin pipe 318mm or joints between thick pipes is shown in Fig.7.

Fig.8 illustrates the local deformation of the pipe members at the impact point. It was obviously recgonized that the rock impact energy was only absorbed by the limited pipe members at the impact point. Therefore, the steel open dam was not entirely collapsed against a rock impact with diameter of 3.0m and velosity of 8.45m/s.

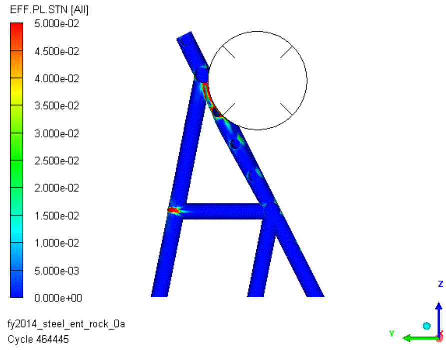


Fig.9 Damage by a rock impact

Fig.9 illustrates the damage of the side of the steel open dam against a rock impact. It was recognized that the damage was only limited at the impact point, and it propagated to the joint between the diagonal member and cross beam. The maximum plastic strain (5%) has occurred at the impact point and the joint. Therefore, the damage was very large, but the whole structure was not collapsed against a huge rock.

6. Conclusions

The following conclusions were drawn from this study.

(1) The unexpected debris flow was defined as the huge direct and indirect (diverted) debris flows.
(2) Redundancy was evaluated by 3D elastic-plastic analysis against the direct and indirect loads.
(3) Robustness was computed by removing one or two members.
(4) Structural integrity has decreased against indirect load rather than the direct load.
(5) The impact FEM analysis against rock impact indicated that the damage of the steel open dam was only limited at the impact points and the structure was not collapsed.

References

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