Safety Verification of Sabo Dams Against Large Scale Debris Flow

Nobutaka ISHIKAWA[1*], Joji SHIMA[2], Ryo MATSUZAWA[3]
and Takahisa MIZUYAMA[4]

[1]Research Association for Steel Sabo Structures (2-7-4 Hirakawa-cho, Chiyoda-ku, Tokyo102-0093,Japan)
[2] Sabo & Landslide Technical Center (4-8-21 Kudan-Minami, Chiyoda-ku, Tokyo102-0074, Japan)
[3] ITOCHU Techno-Solutions Corporation (3-2-5 Kasumigaseki, Chiyoda-ku,Tokyo100-6080, Japan)
[4]National Graduate Institute for Policy Studies (7-22-1 Roppongi,Minato-ku, Tokyo106-8677, Japan)
*Corresponding author. E-mail: cgishikawa@m4.dion.ne.jp

Recently concrete and steel open-type Sabo dams (hereafter, steel open dam) have been damaged by large scale debris flow load (hereafter, load level 2). This was caused due to large rocks carried in the debris flow resulted from torrential rainfall of abnormal weather. This paper presents safety verification methods of concrete and steel open dams against load level 2. First, the estimation methods of load level 2 are explained. The fluid force and rock impact of load level 2 are assumed by performing the extreme stability analysis and by the field survey of the past debris flow disaster. Second, the safety verification methods for concrete and steel open dams are proposed against the load level 2 from the viewpoint of performance-based design. Finally, numerical examples of concrete and steel open dams are illustrated against load level 2 by performing the FEM impact analysis using the software of ANSYS AUTODYN.

Key words: Safety verification, Sabo dam, load level 2, performance-based design, FEM impact analysis

1. INTRODUCTION

In Japan, many concrete and steel open-type Sabo dams (hereafter, steel open dam) have been constructed as defensive measures in order to prevent and mitigate the debris flow hazards and sediment-related disasters.

However, concrete and steel open dams were recently collapsed by the large scale debris flow (hereafter, load level 2), as shown in **Figs. 1** and **2**. These disasters may have resulted from torrential downpour as a result of abnormal weather conditions. The site survey after disaster was conducted in order to examine the cause of collapse at Nagiso, Nagano Prefecture, Japan in July 2014 [Chubu Regional Burea,2014]. Taking the opportunity, it has been needed to investigate the structural safety of concrete and steel open dams against load level 2.

This paper proposes a safety verification method of Sabo dams from a view point of performance-based design [JSCE, 2017].

First, the performance-based design for Sabo dams is proposed about the relationship between load level and limit state. Second, a Sabo dam is designed so that the external stability conditions (overturn, sliding and ground bearing capacity) may be satisfied against both normal design load (load level 1) and extremely large scale load (load level 2). Third, the internal structural safety methods for concrete and steel open dams are proposed by setting the load

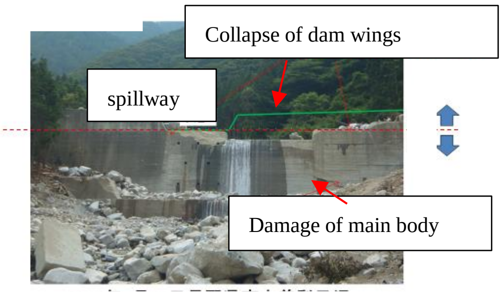


Fig.1 Collapse of concrete dam body and wing

Fig. 2 Damage of steel open dam by large rocks

level 2. Finally, the numerical examples of safety verification for concrete and steel open dams against load level 2 are demonstrated by performing the FEM impact analysis using the software of ANSYS AUTODYN.

2. PERFORMANCE-BASED DESIGN OF SABO DAM

2.1 Objective of Sabo dam

A Sabo dam is constructed to control sediment and to capture the debris flow and woody debris.
Especially, woody debris can be easily captured by a steel open dam.

2.2 Requirement performance

As for the requirement performance for a Sabo dam, capturing function and safety performance are required as follows.

(1) Capturing function is defined that a Sabo dam can capture large rocks and woody debris and sediment in the debris flow [Ishikawa,N. et al., 2014].
(2) Safety performance is defined that a Sabo dam have to keep external stability (overturn, slide, bearing capacity) and internal structural safety (evaluation of strength and deformation).

In this paper, only safety performance is dealt with.

2.3 Load acts on dams

The loads on a Sabo dam are considered as self-weight load, hydrostatic pressure, deposited sediment pressure, debris flow fluid force, earthquake load, rock impact load, woody debris load, uplift pressure.

Herein, the loads onto the dams are classified as load levels 1 and 2 as follows.

(1) Load level 1 means the current design load considering the return period of 100-years of rainfall.
(2) Load level 2 means the large scale debris flow load considering the return period of 200-years of rainfall. The aim of load level 2 is to design and construct the resilient dams .

2.4 Necessity of load level 2

If the one of the following conditions is expected to be happend, then the load level 2 should be considered from the viewpoint of the safety performance of a Sabo dam.

(1) The possibility of large scale sediment movement (large volume, flow rate, flow velocity and large rocks with the diameter of more than 3m).
(2) The dangerous possibility of deep-seated landslide.
(3) The important protective structures are existed in the downstream, e.g., school, hospital and nuclear power plant facilities, etc..

2.5 Determination methods of load level 2

(1) By examining the possibility of the deep-seated landslide.
(2) By investigating the relationship between annual exceedance probability of rainfall and large scale sediment movement (volume, flow rate, flow velocity, huge boulder diameter).
(3) By examining the field survey report of the past large scale debris flow disasters i.e., fluid force, impact force, direction and acting position, etc..
(4) By developing the load estimate methods such as DEM [Horiguchi, et al., 2016] or DEM-MPS [Beppu, et al., 2016] simulations.
(5) By using the extreme stability analysis or an elastic-plastic analysis for the exsisting Sabo dams expediently.

2.6 Limit states of Sabo dam

(1) Serviceability limit state (SLS)
Serviceable limit state (SLS) corresponds to the limit of damage not affecting the capturing function of a Sabo dam. The local and global deformations must be kept less than the allowable ones, respectively. SLS doesn't tend to put people's lives at risk nor do they risk property damage.

(2) Repairable Limit State (RLS)
Repairable limit state (RLS) corresponds to moderate damage. RLS is defined as the maximum damage level which allows planned maintenance and repair methods to be used.

(3) Ultimate limit state (ULS)
Ultimate limit state (ULS) corresponds to very severe damage, for instance, collapse or excessive deformation of the component or the structure under debris flow hazards.

2.7 Safety verification of Sabo dam

The current safety verification should be satisfied against the load level 1. However, the new safety verification is proposed against load level 2 as shown in **Table 1**.

2.7.1 External stability against load level 2

(1) Over turn condition
The safety ratio between resistant moment and overturn moment should be larger than 1.0.

(2) Sliding condition
The safety ratio between the shearing force capacity and the acting shearing force at the dam base should be larger than 1.0.

(3) Bearing capacity condition
The base bearing reaction should be less than the base bearing capacity.

(4) Internal stress condition:
The internal stress of concrete should be less than the extreme internal stress of base concrete.

Table 1 External stability condition

Stability condition	Load level 1	Load level 2
Sliding	$F_S \geqq 1.2$	$F_S \geqq 1.0$
Over turn	$e \leqq B/6$ $e \leqq B_S/6$	$F_r \geqq 1.0$
Bearing capacity	$Q_1, Q_2 \leqq Q_a$	$Q_1, Q_2 \leqq Q_{a'}$
Internal stress of concrete	$\sigma_1, \sigma_2 \leqq \sigma_{ca}$	$\sigma_1 \leqq \sigma_{ca}'$ $\sigma_2 \geqq \sigma_{ta}'$

where, F_S : safety factor for sliding, e : eccentric distance, F_r : safety factor for over turn, B : base width of concrete dam, B_S : base width of steel open dam, Q_1 : bearing reaction at lower stream, Q_2 : bearing reaction at upper stream, Q_a : allowable bearing capacity, $Q_{a'}$: extreme bearing capacity, σ_1 : internal stress at lower stream, σ_2 : internal stress at upper stream, σ_{ca} : allowable compressive stress, σ_{ca}' : extreme compressive stress, σ_{ta}' : extreme tensile stress.

2.7.2 Internal structural safety

(1) Damage level

The damage level is defined as an index of performance criteria by combining with the limit states, as shown in **Fig.3**.

Damage level 1: This level is less than the SLS and as it is.

Damage level 2: This level is from SLS to RLS and needs the small repair.

Damage level 3: This level is from RLS to ULS and needs the large repair .

Damage level 4: This level is larger than ULS and needs the exchange.

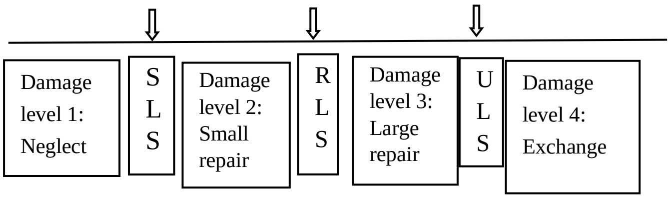
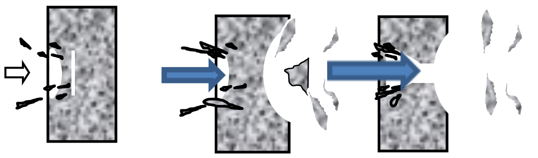


Fig.3 Relationship between damage level and limit state

(2) Local failure

Local failure of a concrete dam is expressed as **Fig.4.**



(a)SLS(penetration/spalling) (b) RLS(scabbing) (c) ULS(perforation)

Fig.4 Local failure of concrete dam

Local deformation of a steel open dam is classified and the limit state of local deformation is assumed as shown in **Table 2** referring to **Fig.5** 〔JSCE,2017〕.

Table 2 Local deformation of steel open dam

Limit state	**SLS**	**RLS**	**ULS**
Local deformation / Steel pipe diameter (δ/D)	0.1	0.4	0.7

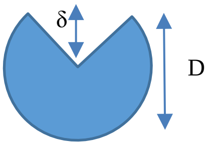
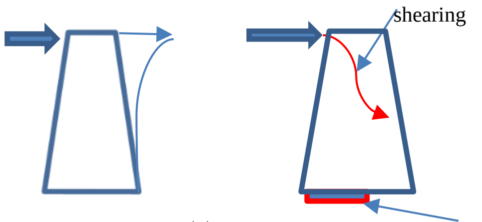


Fig. 5 Local deformation of steel pipe

(3) Global failure

Global failures of concrete and steel open dams are illustrated as shown in **Figs.6,7** and assumed as shown in **Table 3**, respectively 〔JSCE,2017〕.



(a) SLS(bending failure) (b) RLS(shearing) (c) ULS(tensile failure)

Fig.6 Global failure of concrete dam

Table 3 Global deformation of steel open dam

Limit state	**SLS**	**RLS**	**ULS**
Horizontal displacement /dam height (⊿/H)	0.02	0.05	0.1

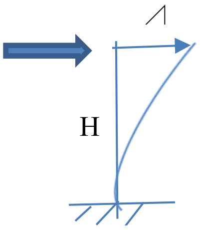


Fig.7 Horizontal displacement of steel open dam

2.8 Performance matrix

Therefore, the performance matrix for a Sabo dam against load levels 1 and 2 is expressed as two step design method as shown in **Table 4**.

Table 4 Performance matrix against debris flow

Scale of debris flow	SLS	RLS	ULS
Load level 1	◆	○	Δ
Load level 2		◆	○

The symbol in **Table 4** means the following Sabo dams.

△ is an emergency Sabo dam,

○ is a current usual Sabo dam,

◆ is an important Sabo dam constructed at the upper stream of an important protective facility.

Accordingly, the contents of **Table 4** can be explained as follows.

(a) In case of an emergency Sabo dam, the design aims at the Ultimate Limit State (ULS) against load level 1.

(b) In case of an existing usual Sabo dam, the design aims at the Repairable Limit State (RLS) against load level 1, and Ultimate Limit State (ULS) against load level 2.

(c) In case of an important Sabo dam, the design aims at the Serviceable Limit State (SLS) against load level 1 and Repairable Limit State (RLS) against load level 2.

2.9 Safty verification of Sabo dams against load level 2

The safety verification of a Sabo dam should be conducted against load level 2 as follows:

(1) Rock impact :

A Sabo dam against rock impact should be verified by internal safety based on an impact analysis.

(2) Debris flow fluid force:

A Sabo dam should be checked by both external stability and internal safety against debris flow fluid force.

(3) After damage:

A remaining dam after debris flow disaster should be confirmed by the external stability. Because, the dam may be damaged and may be required to be safe against deposited sediment pressure.

Therefore, the safety verification of a Sabo dam should be conducted as shown in **Table 5.**

Table 5 Safety verification of Sabo dam

Scale of debris flow	External stability	Internal safety
Load level 1 (return period of 100 years)	Stability check against fluid force Stability check against filled soil	Stress check against rock impact Stress check against fluid force Stress check against filled soil
Load level 2 (return period of 200 years)	Stability check against fluid force Stability check against filled soil after damage	Strain and deformation check against rock impact Strain check against fluid force Strain check against filled soil after damage

3. NUMERICAL EXAMPLE

First, the concrete and steel open dam shapes are determined by satisfying the stability conditions (i.e., overturn, sliding and bearing capacity) against the design debris flow load (load level 1). Second, the load level 2 is determined by either or combination of the methods mentioned in **2.5 (3),(5)**.

Finally, the safety verifications of concrete and steel open dams are confirmed by performing the impact FEM analysis against load level 2.

3.1 Dam and debris flow models

The dam and debris flow load models are assumed as shown in **Fig.8(a),(b**) and **Table 6,** respectively. The concrete dam has the height of H_c=10m, the slope of downstream of n=0.2, the thickness of spillway of B_w=3m, as shown in **Fig.8(a)**. The steel open dam has the height of H_s=8m, the width of B=5.2m, the footing concrete thickness of H_{sc}=2m, as shown in **Fig.8(b) [**Shima, J., et al.2017]**.**

3.2 Properties of Concrete

The properties of concrete are assumed as shown in **Table 7**.

Table 6 Properties of debris flow

Drainrange area	A=0.32 km^2
Bed slope	I=1/6
Peak discharge of debris flow	Q_{sp}=73.50 m^3/s
Width of stream	B_{da}=15.0 m
Water depth	D_d=1.12 m
Flow velocity	U = 4.37 m/s
Table 7 Properties of concrete	
Allowable bearing capacity (level 1)	Q_a = 1200 kN/m^2
Ultimate bearing capacity (level 2)	Q_a' = 3600 kN/m^2
Shearing strength	τ_c =600 kN/m^2
Design concrete strength	σ_{ck}= 18000 kN/m^2
Allowable concrete compressive strength	σ_{ca}= 4500 kN/m^2
Ultimate concrete compressive strength	σ_{ca}= 6750 kN/m^2
Allowable concrete tensile strength	σ_{ta}= -337.5 kN/m^2
Friction coefficient of dam base	f = 0.7

3.4 Computational results of stability analysis

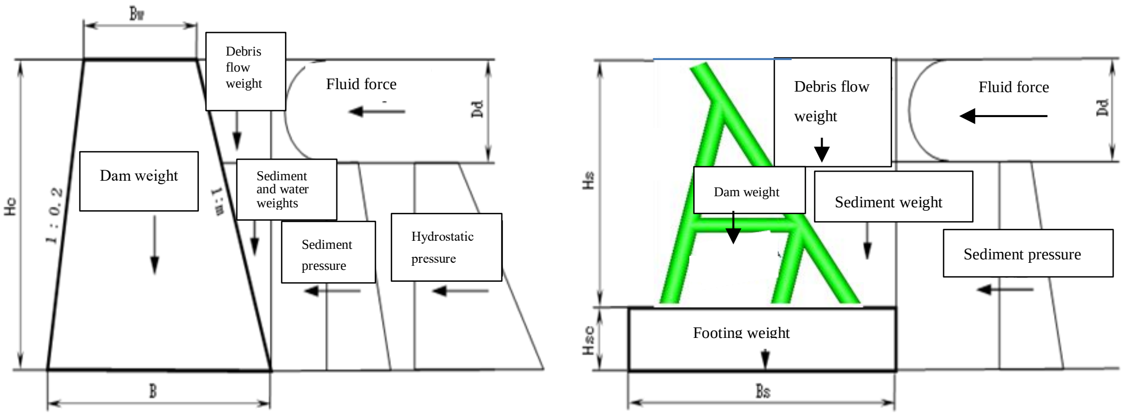
(1) Results against load level 1

The computational results of stabilty analysis against load level 1 are shown in **Tables 8 and 9**. The shape of concrete dam was determined as the slope of upstream of m=0.3 and the width of base of B=8.00m. The shape of footing of steel open dam was determined as the width of B_s=8.40m.

(2) Results against load level 2

Computational results of load level 2 were found by increasing the flow volume until the extreme limit stability condions were satisfied as shown in **Tables 8 and 9.**

The maximum fluid forces were found as F=723.0kN/m in case of the concrete dam, as F=583.5kN/m in case of steel open dam.



(a) Concrete dam model (b) Steel open dam model

Fig.8 Dam and debris flow models

Table 8 Results of stability analysis for concrete dam

	Load level 1	Load level 2
Sliding	8.09> 4.0	4.97>1.0
Over turn eccentric distance e (m)	$\|e\|$ =1.28< 1.33	F_r=1.07 $\geq$1.0
Ground bearing capacity (kN/m^2)	Q_1=374.24 < 1200 Q_2=7.64< 1200	Q_1=707.78 < 3600 -------------------
Internal stress (kN/m^2)	σ_1= 374.24 <4500 σ_2= 7.64< 4500	σ_1= 707.78 <6750 σ_2= -335.02 > -337.5

Table 9 Results of stability analysis for steel open dam

	Load level 1	Load level 2
Sliding	21.52> 4.0	7.47>1.0
Over turn eccentric distance e (m)	$\|e\|$ =0.09 < 1.40	F_r=1.0 $\geq$1.0
Ground bearing capacity (kN/m^2)	Q_1=112.2 < 1200 Q_2=98.67 < 1200	Q_1=425.1 < 3600 -------------------
Internal stress (kN/m^2)	σ_1= 112.2 <4500 σ_2= 98.67 < 4500	σ_1= 425.1 <6750 σ_2= -211.8 > -337.5

Table 10 Results of Load level 2 by stability analysis and Nagiso disaster

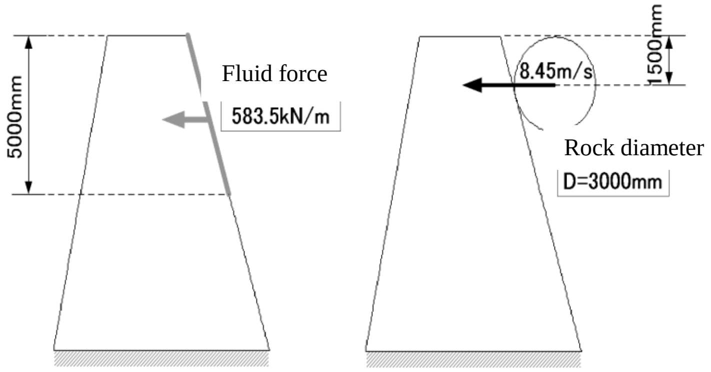
	Load level 1	Load level 2 for concrete dam	Load level 2 for steel open dam	Load level 2 by Nagiso disaster
Peak discharge of debris flow Q_{sp} (m^3/s)	73.50	754.0	638.0	730
Water depth D_d(m)	1.12	5.68	5.04	2.27
Flow velocity U (m/s)	4.37	8.86	8.45	8.28
Unit volume weight of debris flow γ_d (kN/m^3)	15.90	15.90	15.90	16.42
Fluid force F(kN/m)	34.7	723.0	583.5	260.8
Rock diameter D_{max}(m)	1.1		--------------	3.0

(3) Determination of load level 2

In this study, F=583.50kN/m in case of steel open dam was assumed as the fluid force of load level 2, since this value was smaller than the one in case of concrete dam. Futhermore, the maximum rock diameter D_{max} =3.0m was found by the field suvey of Nagiso disaster,2014. Therefore, the fluid force F=583.5 kN/m, the flow velocity U=8.45m/s, and the rock diameter D_{max}=3.0 m were adopted as the load level 2.

3.5 Safety verification of concrete dam against load level 2

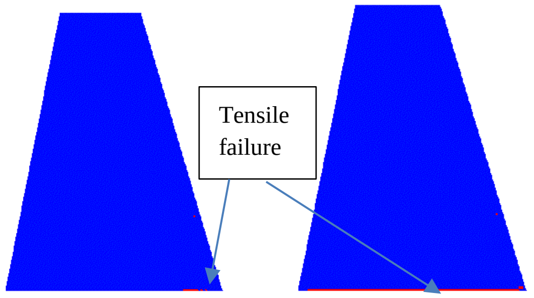
Fig.9(a) and (b) shows the fluid force and rock impact of load level 2 acting on the concrete dam with height of 10m, respecyively. The concrete dam base is assumed to be fixed in the ground.



(a) Fluid force (b) Rock impact

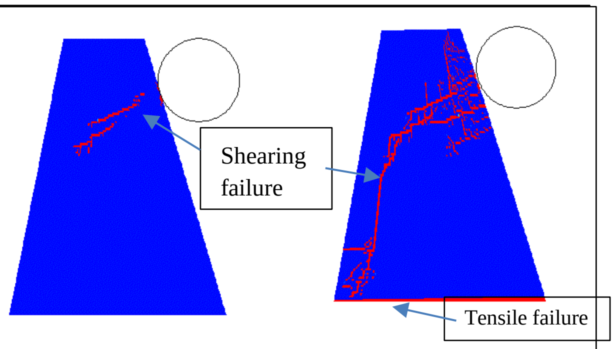
Fig. 9 Concrete dam model and load level 2

Fig.10 illustrates the tensile failure at the base of concrete dam against fluid force of load level 2 which means the turnover of the dam. On the otherhand, **Fig.11** shows the shearing failure + tensile failure of concrete dam against rock impact which means the complete collapse of the concrete dam [Matsuzawa, et al.2017].



(a) Initiation of crack (b) Final failure

Fig. 10 Failure mode by fluid force of load level 2 acting on concrete dam



(a) Initiation of crack (b) Final failure

Fig. 11 Failure mode by rock impact of load level 2 acting on concrete dam

3.6 Safety verification of steel open dam against load level 2

3.6.1 Analytical model

Fig. 12 shows the bird's-eye view of the steel open dam which is composed of pipe components with diameters of 508mm and 318mm. **Fig.13** (a) and (b) illustrate the front and side of the steel open dam with the

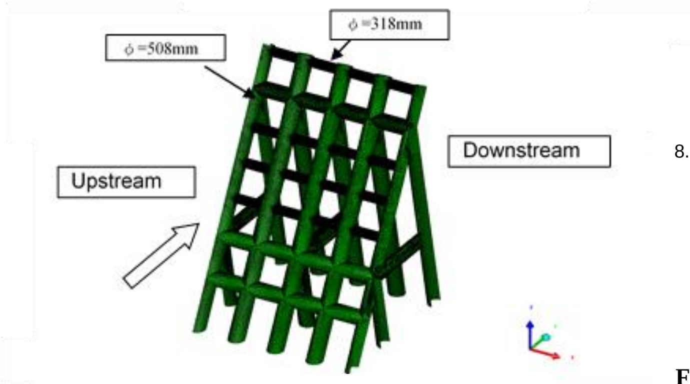
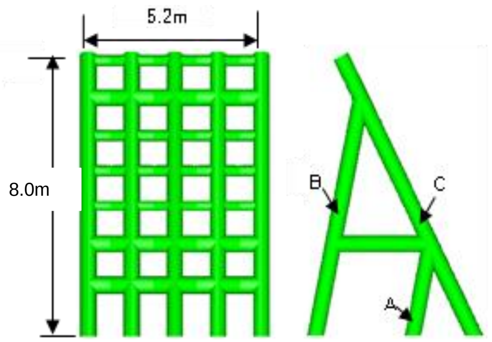


Fig. 12 Bird's-eye view of steel open dam



(a) front (b) side

Fig.13 Steel open dam analytical model hieght of 8m and the width of 5.2m. The steel open dam is fixed into the base foundation and is verified by an impact FEM analysis against load level 2 (fluid force of F=583.5kN/m, flow velocity of U=8.45m/s and rock diameter of D_{max} =3.0m).

3.6.2 Load level 2 acting on steel open dam

Fig. 14 shows the steel open dam subjected to the fluid force (F=583.5 kN/m) of load level 2, which acts on the range from the top to the depth of 5.04m.

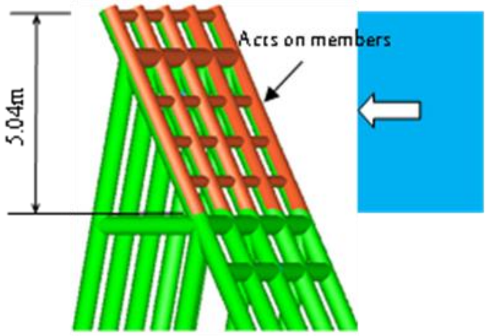
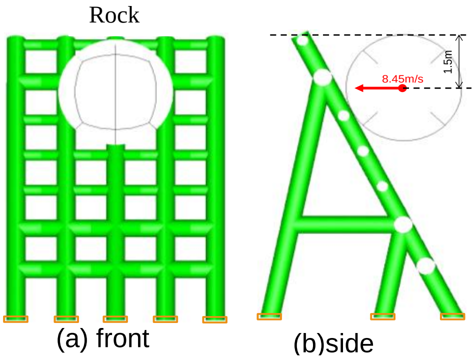


Fig.14 Fluid force for FEM analysis (3-D)

Fig. 15 illustrates the steel open dam subjected to the rock imapct with the diameter of D_{max} =3.0m and the velocity of U=8.45m/s which acts on the position of 1.5m from the top.



(a) Front (b) side

Fig.15 Rock impact for FEM analysis (3-D)

3.6.3 Computational results

(1) Horizontal dispalacement – time relations

Fig.16 shows the horizontal displacement at crown of dam – time relation against the fluid force. The maximum resuidual displacement was 55mm. This value was larger than the one of 20mm at the crown of dam and smaller than the one of 85mm at the imapct point by the rock impact as shown in **Fig. 17.**

(2) Impact load- time relation

Fig.18 shows the impact load – time relation, and the maximum average impact load was 5.2MN. It is found that the real impact load is vibrating during the contact period between rock and steel open dam. This vibration will dissipate the kinetic energy due to rock impact.

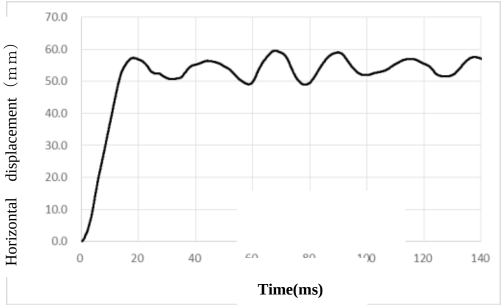


Fig.16 Horizontal displacement – time relation against fluid force

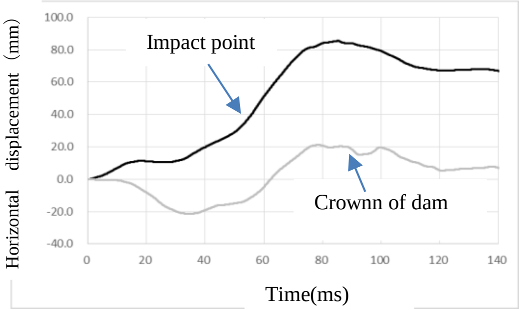


Fig. 17 Horizontal displacement – time relation against rock impact

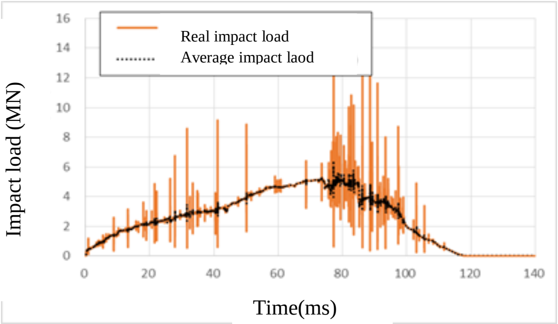


Fig.18 Impact load-time relation against rock impact

(3)Local deformation profile

Fig.19 illustrates the local deformation profile of pipe component at the impact point, and the residual local deformation / pipe diameter (δ/D) was found as 0.75 as shown in **Fig.20.** This value exceeds 0.7 of ULS in **Table 2**.

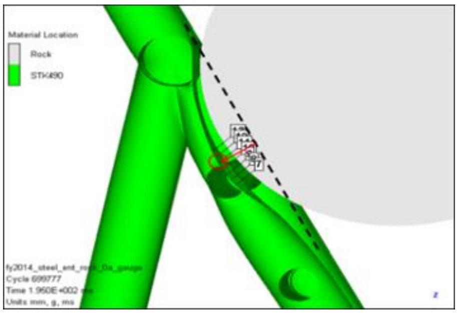


Fig. 19 Local deformation profile at imapct point against rock impact

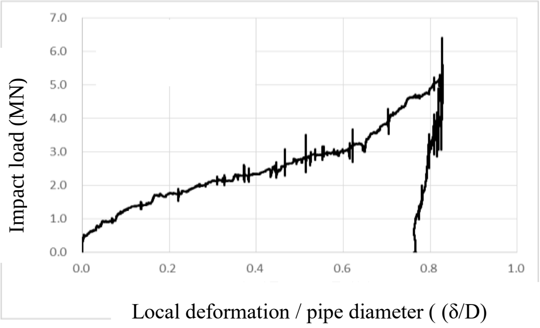


Fig.20 Impact load – local defromation/pipe diamter relation against rock impact

(4) Absorbed Energy

Fig.20 shows the impact load-(local deformation /pipe diameter) relation obtained and the area surrounded by the curves means the local absorbed energy.

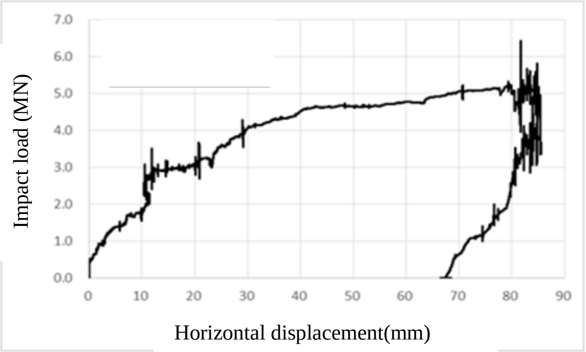


Fig.21 Impact load - horizontal displacement relation against rock impact

Fig.21 demonstrates the imapct load – horizontal dispacement relation at impact point, and the area surrounded by curves is defined as the global absorbed energy.

3.6.4 Safety verification of steel open dam

(1) Safety verification of global deformation

(a) Against fluid force;

$\Delta_{max}/H=55/8000=0.007<0.02$

It is less than serviceability limit, then it can be neglected.

(b) Against rock impact;

$\Delta_{max}/H=70/6500=0.01<0.02$

It is less than serviceability limit, then it can be neglected.

(2) Safety verification of local deformation

Against rock impact; $\delta_{max}/D=0.75>0.7$

It is larger than ultimate limit, then, the pipe component at impact point should be exchanged.

(3)Energy verification

(a) External energy

$$E_R=\frac{1}{2}mv^2=36.7\text{tx}(8.45\text{m/sec})^2/2=1310\text{kJ}$$

(b)Internal energy

The local and global absorbed enegies are obtained by computing the areas surrounded by curves in **Figs.20** and **21,** respectively, as follows.

U_L= 1016kJ, U_G= 285kJ

Therefore, the total internal energy is 1301 kJ which corresponds to 99.3% of the external energy E=1310 kJ. The difference of 0.7% may be dissipated by the vibration during impact period. It was also found that about 78% of rock impact energy was absorbed by the local deformation of pipe component.

4. CONCLUSIONS

(1) The safety verification of dams against load level 2 was proposed from the viewpoint of performance-based design.

(2) The load level 2 was decided by the the extreme limit stability analysis and the past large scaled debris flow disaster.

(3) The concrete dam against load level 2 was over turned by the fluid force and completely collapsed by rock impact.

(4) The steel open dam against load level 2 was not so damaged by the debris flow fluid force. However, the pipe component at impact point was severely damaged by rock impact load, and it should be exchanged.

REFERENCES

Beppu,M., Matsuzawa,R., Shima,J., Ishikawa,N. and Mizuyama (2016): A Study on the Debris Flow Load Evaluation and Load Carrying Capacity of Sabo Dam by DEM-MPS Method, The 2016 Conference Proc. of Erosion Control Engineering, R5-24, B222-2023.

Chubu Regional Bureau, Ministry of Land, Infrastructure and Transport (2014) : Survey Report of Nashizawa Debris Flow, Nagiso, Nagano Prefecture, Japan, July (2014).

Horiguchi,T., Tsuji, Y., Katsuki, S., Shima,J., Ishikawa,N. and Mizuyama,T. (2016): A Study on the Estimation of Debris Flow Loads acting on Steel Open Dam, The 2016 Conference Proc. of Erosion Control Engineering, R5-14, B202-203.

Ishikawa,N., Shima,J.,Matsubara,T., Tatesawa,H., Horiguchi,T. and Mizuyama,T.(2014): Trapping Mechanism of Debris Flow by Steel Open Dams, INTERPRAEVENT2014, Natural Disaster Mitigation to Establish Society with the Resilience, Nara, Japan.

Japan Society of Civil Engineers (2017): Safety Evaluation for Civil Engineering Structures under Impact and Blast loadings -Preparing for Rare Events- Structural Engineering Series 27 (Edited by K. Fujikake).

Matsuzawa,R., Shima, J., Takeda, I., Ishikawa,N. and Mizuyama,T. (2017): Current Design Problems and Impact Analysis of Concrete Sabo Dam against Rock Impact, Journal of the Japan Society of Erosion Control Engineering, Vol.69,No.5, pp.59-65.

Shima,J.,Matsuzawa.R.,Takeda,I.,Yamaguchi,M.,Ishikawa,N., and Mizuyama,Y.(2017): Current design problems and impact analysis of steel open type Sabo dam under rock impact, Journal of the Japan Society of Erosion Control Engineering, Vol.70,No.1, pp.54-59.