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PERFORMANCE-BASED DESIGN OF STEEL PROTECTIVE STRUCTURES AGAINST DEBRIS FLOW

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Abstract. *There have been recent damaged examples of steel protective structures against debris flow. This was caused due to large rocks carried in the debris flow resulted from torrential rainfall of abnormal weather. Therefore, it is imperative to prepare for the worst case scenario in the event of any natural disaster. This paper proposes a performance-based design for steel protective structures (hereafter, called as steel open dams) against debris flow load. First, the relationship between load level and limit state is illustrated for a steel open dam. Then, a steel open dam should be designed so that the external stability conditions (overturn, sliding and ground bearing capacity) may be satisfied against both normal scale design load (level 1) and extremely large load (level 2). Third, it should be also verified for the internal structural safety against load level 2 by dynamic analysis. Finally, a numerical example of the performance-based design is illustrated for a steel open dam against load level 2 by using a software of ANSYS AUTODYN.*

1 INTRODUCTION

Since 1980, many steel protective structures (steel open dams) have been constructed based on the Design Manual [1,2,3] as defensive measures in order to prevent and mitigate the debris flow hazards and sediment-related disasters in Japan. However, recently, steel open dams have partially collapsed due to rocks in the debris flow, as shown in Figures 1 and 2 . These disasters may have resulted from torrential downpour as a result of unusual weather conditions [4]. The site survey after disaster was performed in order to investigate the size of rocks as shown in Figures 3 and 4, at Nashizawa basin, Nagano Prefecture,Japan on July 2014 [4,5] . To this end, it has been needed to investigate the structural safety of a steel open dam against large scale debris flow. Many studies have devoted to the impulsive behaviors of steel and concrete Sabo dams against debris flow loads [6-10].

This paper proposes a performance-based design method of a steel open dam from the view point of structural safety. The basic performance requirements of strucures are required to be treated in an explicit manner to ensure transperency and accountability of decision making about public structures in terms of structural design, as these have recently become increasingly in demand from the view point of inernational and national standards [11-14].

First, the basic concept of performance-based design for a steel open dam is explained about the relationship between load levels and limit states. Then, a steel open dam is designed so that the external stability conditions (overturn, sliding and ground bearing capacity) may be satisfied against

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both normal design load (level 1) and extremely large load (level 2). Third, the internal structural safety is also examined by dynamic analysis. Finally, a numerical example of performance-based design is demonstrated by setting the load level 2 and performing the impact analysis for a steel open dam using a software of ANSYS AUTODYN [15,16].

Figure 1: Steel open dam trapped rocks in debris flow

Figure 2: Steel open dam was partially collpased by large rocks

Figure 3: Rocks found at downstream

Figure 4: The largest rock with average diameter of 6.7m

2. BASIC CONCEPT OF PERFORMANCE-BASED DESIGN FOR STEEL OPEN DAM

2.1 Objective of steel open dam

A steel open dam is composed of steel pipe components, which usually allow water, soil and small pieces of gravel to flow downstream through gaps in the steel structure. However, it functions to block rocks and wooden debris during debris flow. In Japan, the design guidelines for Sabo dams were revised in 2007 [17] such that a steel open dam should be basically constructed in the debris flow section as a countermeasure against debris flow and woody debris, because the woody debris can be easily captured by a steel open dam.

2.2 Basic requirement for steel open dam

When designing a steel open dam, the design working life should be specified, and the following basic performance requirement should be ensured for the specific period.

(1) Safety of human life in and around the steel open dam is ensured against foreseeable debris flow (Safety).

(2) The functions of the steel open dam are adequately ensured against foreseeable debris flow acting on the steel open dam (Serviceability).

(3) If required, continued use of the steel open dam is feasible against foreseeable debris flow by restoration using technologies available within reasonable ranges of cost and time (Restorability).

2.3 Performance requirement for steel open dam

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

(1) Capturing function is defined that a steel open dam can easily capture rocks, gravels and woody debris and sediment in the debris flow.

(2) Safety performance is defined that a steel open dam have to keep external stability (overturn, sliding, ground bearing capacity) and internal structural safety (strength and deformation).

This paper deals with only safety performance, but not capturing function.

2.4 Definition of limit states

The limit state conditions are defined as follows.

(1) Serviceability limit state (SLS)

Serviceable limit state (SLS) corresponds to the limit of damage not affecting the capturing function of a steel open dam. That is, Actual Behavior $\leq$ Allowable Behavior.

The local and global deformations must be kept less than the allowable ones, respectively.

Serviceability limit states don't tend to put people's lives at risk nor do they risk property damage.

(2) Restorability Limit State (RLS)

Restorability limit state (RLS) corresponds to moderate damage. Restorability limit state 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, failure or excessive deformation of the component or the structure under debris flow hazards.

Figure 5 shows the basic concept of limit states. If the response value is less than the SLS, then the dam is neglected as it is. If the response value is larger than the SLS and less than the RLS, then the dam will be repaired a little. If the response value is larger than the RLS and less than the ULS, then the dam should be greatly restored. If the response value is larger than the ULS, then the dam or a component of it should be exchanged or reinforced.

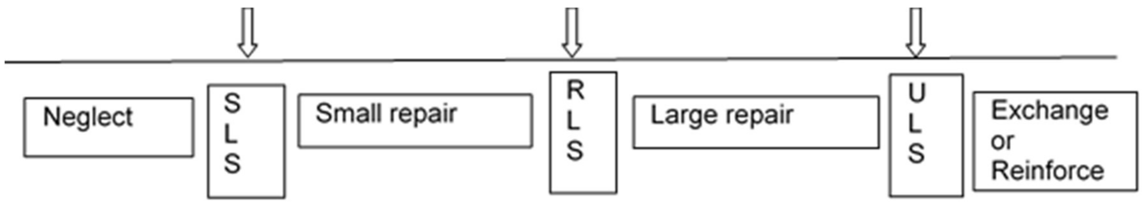


Figure 5: Basic concept of limit states

2.5 Definition of loads

The loads on a steel open dam are considered as self-weight load, hydrostatic pressure, filled soil pressure, debris flow fluid force, earthquake load, rock impact load, woody debris, rock impact load, uplift pressure. Herein, the loads onto the dams are classified as load levels 1 and 2 as follows.

(1) Load level 1 corresponds to the current design load and return period of about 100 years.

(2) Load level 2 corresponds to the large scaled loads occurred by the deep-seated landslide and return period of 200-500 years.

The load level 2 will be determined by either or combination of the following approaches.

A. The load level 2 is found by examining the relationship between annual exceedance probability of rain and large scale sediment movement (volume, flow rate, flow velocity, huge rock diameter) or deep-seated landslide.

B. The load level 2 is determined by carrying out the field survey of the past large scale debris flow disasters (fluid force, impact force, direction and acting position, etc.) necessary for the design of dam facilities.

C. The load level 2 is found by developing the load estimate method for a large scale debris flow. It can be estimated by debris flow analysis by using DEM or DEM-MPS simulation methods [18,19]. These methods will be developed by adopting the data of (a) annual exceedance probability of rain, (b) previous large scale of sediment movement (volume, velocity and water depth, etc.) in the future.

D. The load level 2 can be expediently found as the maximum fluid load by using the extreme stability condition for the exsisting steel open dam.

2.6 Performance criteria

The performance criteria for a steel open dam against the load level 1are adopted as it is [1-3]. The new performance criteria against load level 2 are proposed as follows.

2.6.1 External stability against load level 2

Stability analysis for a steel open dam against load level 2 is simplified into a two-dimensional rigid body analysis of a cross section of the structure.

(1) Overturn 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 safety ratio between the subgrade reaction capacity and the acting subgrade reaction onto the dam base should be larger than 1.0.

2.6.2 Internal structural safety against load level 2

The dynamic analysis against load level 2 is conducted and is verified as follows.

(1) Local deformation of a pipe member should be less than the limit local deformation.

(2) Horizontal displacement of a steel open dam should be less than the limit horizontal displacement.

2.7 Performance matrix

The performance matrices for a steel open dam against debris flow loads 1 and 2 are expressed as the two step design methods.

Table1 : Performance matrix against debris flow load

Scale of debris flow	Serviceability limit state	Restorability limit state	Ultimate limit state
Load level 1	◆	○	△
Load level 2		◆	○

The symbol in Table1 denotes the following steel dams.

△ is an emergency steel open dam, ○ is a current steel open dam, ◆ is an important steel open dam to protect an important facilities.

Therefore, the contents of Table 1 can be explained as follows.

(a) In case of an emergency steel open dam, the design aims at the ultimate limit state (ULS) against load level 1.

(b) In case of a current steel open dam, the design aims at the restorability limit state (RLS) against load level 1, and at the ultimate limit state (ULS) against load level 2.

(c) In case of an important steel open dam, the design aims at the serviceability limit state (SLS) against load level 1 and at the restorability limit state (RLS) against load level 2.

2.8 Performance verification

The performance verification for a steel open dam should be conducted as follows.

(1) Rock impact : A steel open dam against rock impact should be verified from the viewpoint of the internal structural safety.

(2) Debris flow fluid force: A steel dam should be verified by both external stability and internal structural safety against debris flow fluid force.

(3) After damage: A remaining structure after debris flow disaster should be confirmed for the external stability. Because, the structure may be damaged and may be required to be safe against reservoir deposit pressure.

Therefore, the performance verification of a steel open dam will be conducted agaisnt both load levels 1 and 2 as follows.

Table 2 Performance verification of a steel open dam

Scale of debris flow	External stability verification	Internal safety verification
Load level 1 (return period of 100 years)	Stability verification against fluid force and filled soil pressure	Stress verification against fluid force, filled soil pressure and rock impact
Load level 2 (return period of 200-500 years, large scale deep-seated landslide)	Stability verification against fluid force and filled soil pressure	Strain and deformation verification against fluid force, filled soil pressure and rock impact

2.9 Flow chart of Performance-based design

Therefore, the performace-based design of a steel open dam is basically performed as the two step design and the flow chart is as shown in Figure 6.

2.9.1 The 1st step design

(1) The load level 1 is first found by the field suvey; for instance, flow volume, slope of river bed , river width, rock diameter. Then, debris flow fluid force, filled soil pressure, hydrostatic pressure, flow velocity and design rock size are determined.

(2) The basic shape of a steel open dam is assumed by engineering judgement or experience; the height, the width and pipe member size of a steel open dam, base concrete thickness,etc..

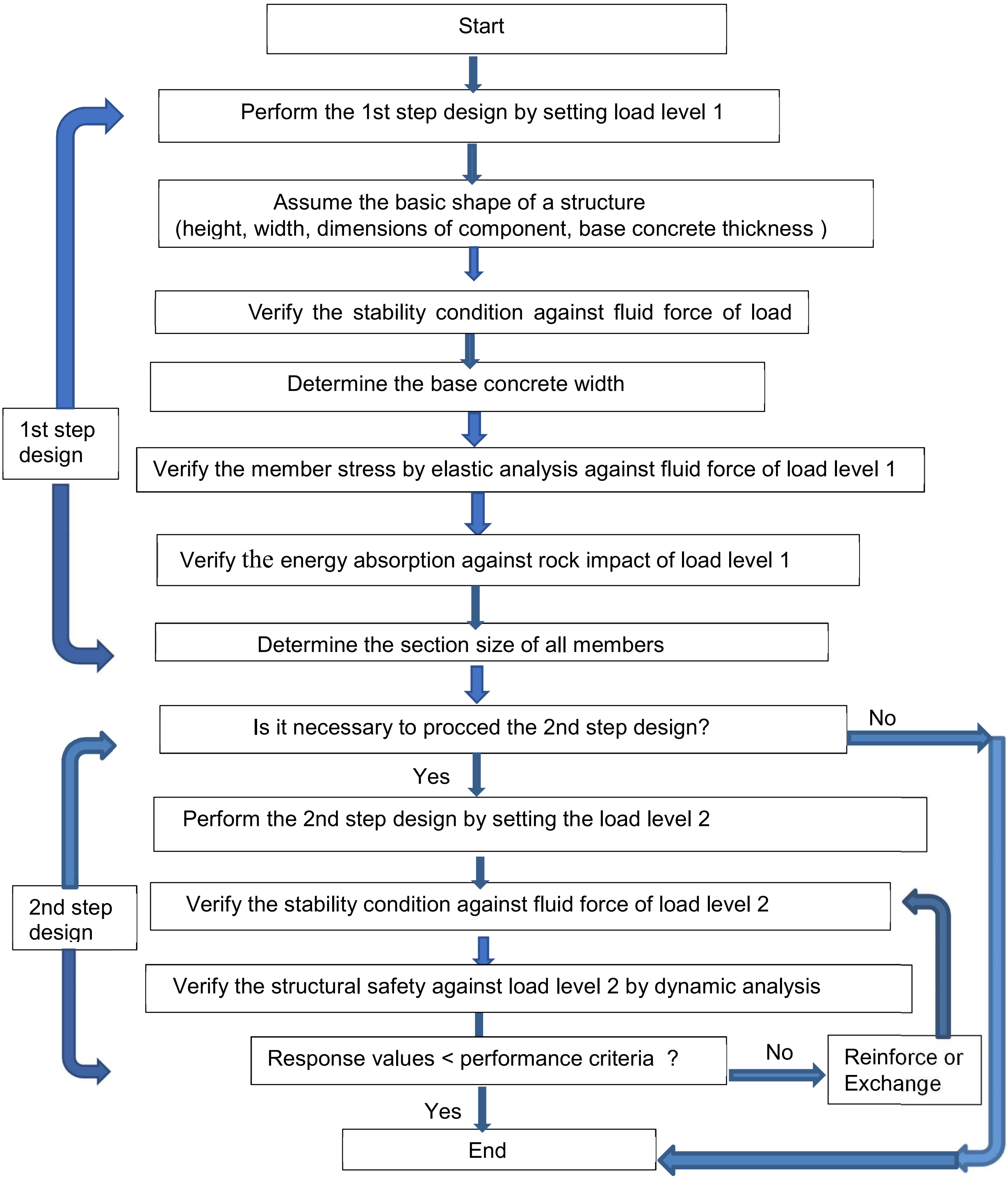


Figure 6 Flow chart of performance-based design of a steel open dam

(3) The external stability verification is conducted against load level 1. Then, the base concrete width is determined.
(4) The stress verification is proceeded by elastic analysis of a steel open dam.
(5) The energy absorption verification is performed by the local and global deformation analyses.

2.9.2 The 2nd step design

If the one of the following three conditions is satisfied,then the 2nd step design is proceeded.

A. The topography such as sharp slope and going straight of debris flow.
B. The possibility of large scale sediment movement (large volume, flow rate, flow velocity and large rocks with the diameter of more than 3m).
C. The dangerous possibility of deep-seated landslide.

Therefore, the 2nd step design is conducted after the above three conditions were examined.

(1) If it is necessary to verify the safety against the load level 2, then, the next step should be performed. Otherwise, the design will be ended at the 1st step design.
(2) The external stability verification is executed against the fluid force of load level 2.
(3) The internal structural safety verification is proceeded by the dynamic analysis against the fluid force and rock impact of load level 2.
(4) If the response values are less than the performance criteria, then the 2nd step design is ended. Otherwise, a component or a structure should be repaired or reinforced or exchanged, and then, the above steps (2), (3) are repeated until the performance criteria are satisfied.

3. NUMERICAL EXAMPLE

First, the 1st step design is conducted to determine the dam shape and the size of components by satisfying the stability conditions and the structural safety against the fluid force and rock impact of load level 1. If the one of three conditions of A-C in 2.9.2 is found, then the 2nd step design should be proceeded. Herein, the load level 2 should be determined by either or combination of the methods of A-D in 2.5. Finally, the 2nd step design is executed to verify the performance criteria against load level 2 by the dynamic analysis.

3.1 Steel open dam model

The steel open dam model with the height of 8m and the width of 5.2m is shown in Figures 7,9 and 10 which is connected by the joints between the pipe diameter of 508mm with the pipe diameter of 318mm. The properties of steel pipe are the density of 7.85t/m^3, Young's modulus of 206GPa, Poisson's ratio of 0.3, yield stress of 315Mpa and tensile strength of 593Mpa with the stress -strain curve neglecting the strain rate effect as shown in Figure 8. The foots of pipes were fixed into the base concrete footing.

The loads for stability analysis of a steel open dam are indicated as shown in Figure 7. That is, the horizontal loads are fluid force and sediment pressure and the vertical loads are steel weight, concrete footing weight, debris flow weight and sediment weight.

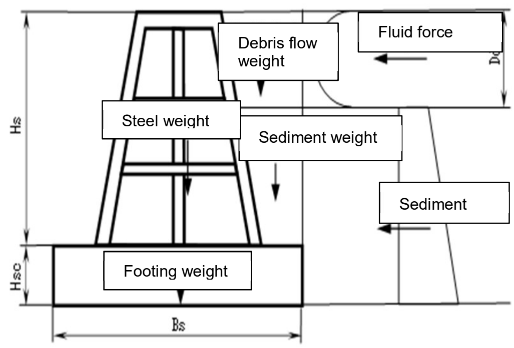


Figure 7: Steel open dam model and loads for stability analysis

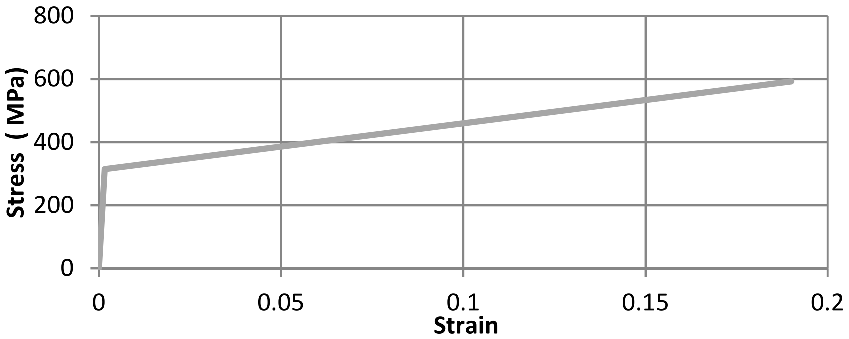


Figure 8: Stress- strain curve of STK490 of pipe component

3.2 Debris flow model and limit values for stability analysis

Table 3 shows the properties of debris flow of load level 1 and the limit values for stability analysis agaisnt load levels 1 and 2.

Table 3: Properties of debris flow and limit values

Drainrage 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
Friction coefficient of dam base	f = 0.7
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 (level 1)	σ_{ca}= 4500 kN/m^2
Ultimate concrete compressive strength (level 2)	σ_{ca}'= 6750 kN/m^2
Allowable concrete tensile strength	σ_{ta}'= -337.5 kN/m^2
Steel open dam height	H_s = 8.0m
Base concrete thickness	H_{cs} = 2.0m

3.3 Stability analysis against load levels 1 and 2

The stability conditions (i.e., sliding, overturn, ground bearing capacity and internal stress) against load levels 1 and 2 are as shown in Table 4.

Table 4: Stability conditions against load levels 1 and 2

Stability condition	Against load level 1	Against load level 2
Sliding	$F_s \geq 4.0$	$F_s \geq 1.0$
Overturn	$\lvert e \rvert \leq \frac{B}{6}, \ \frac{B_s}{6}$	$F_r \geq 1.0$
Ground bearing capacity	$Q_{1,2} \leq Q_a$	$Q_{1,2} \leq Q_a'$
Internal stress	$\sigma_{1,2} \leq \sigma_{ca}$	$\sigma_1 \leq \sigma_{ca}', \sigma_2 \geq \sigma_{ta}'$

where, F_s: safety factor of sliding, e: eccentricity distance, F_r: safety factor of overturn, $Q_{1,2}$: subgrade reaction of down-stream and upper- stream, Q_a: allowable subgrade reaction, Q_a': limit subgrade reaction, $\sigma_{1,2}$: internal stress of concrete of down-stream and upper- stream, σ_{ca} : allowable compressive stress, σ_{ca}' limit compressive stress, σ_{ta}' : limit tensile stress.

3.4 Computational results of stability analysis

(1) Results against load level 1

The shape of base concrete foundation was determined as the width B_s=8.4m by satifying the stability condions against load level 1 as shown in Table 5.

Table 5 Results of stability analysis

	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 < 450	σ_1= 425.1 <6750 σ_2= -211.8 > -337.5

(2) Stress verification against load level 1

The 1st step design was performed by elastic analysis and it was confirmed that the acting stress was verified within the allowable stess.

(3) Judgement for 2nd step design

In this example, the 2nd step design was needed to verify the structural safety from the viewpoint of possibility of large scale sediment movement (B in 2.9.2).

(4) Determination of load level 2

The load level 2 was determined as follows.

(a) The extreme fluid force and the maximum velocity was expediently found by satisfying the extreme stability conditions load level 2, as shown in Table 4 by increasing the flow volume for the steel open dam.

(b) The maximum rock size of load level 2 is found by the field survey in the recent biggest debris flow disaster [20].

Therefore, the fluid force(583.5kN/m) and the flow velocity (8.45m/s) of load level 2 were found as shown in Table 5. These values are compared with those of the biggest disaster in Nashizawa 2014[20]. Then, the maximum rock diameter D_{max} =3.0m was found by the field suvey of Nashizawa disaster.

Table 5: Results of load level 2

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

Consquently, the fluid force of F=583.5 kN/m, the flow velocity of U=8.45m/s and the rock diameter of D_{max}=3.0 m were adopted as the load level 2 in this example.

3.5 Steel open dam model for structural safety verification against load level 2

Figure 9 shows the bird's-eye view of the steel open dam which is composed of components with the pipes of 508mm x 16mm and 318mmx10.3mm. Figure 10 (a) and (b) illustrate the front and side of the steel open dam with the hieght of 8m and the width of 5.2m, which is fixed into the base concrete footing. This steel open dam is verified by a dynamic 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).

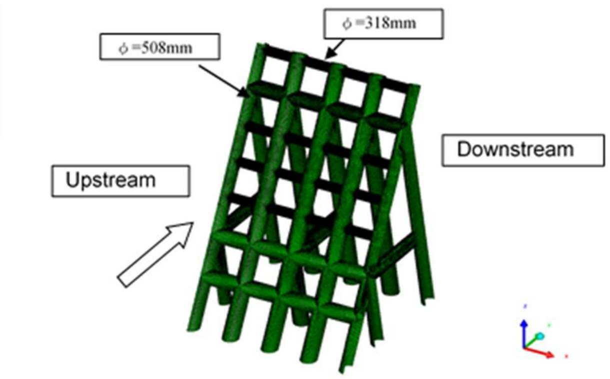


Figure 9: Bird's-eye view of steel open dam

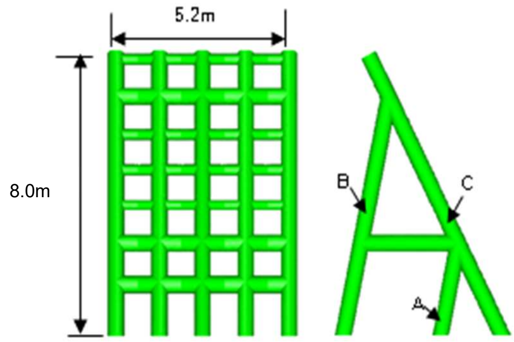


Figure 10: Steel open dam model
(a) front and (b) side

Figure 11 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. Figure 12 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.

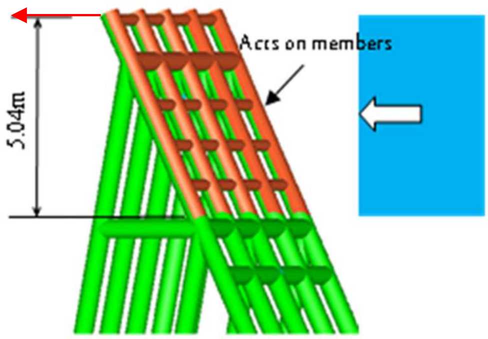
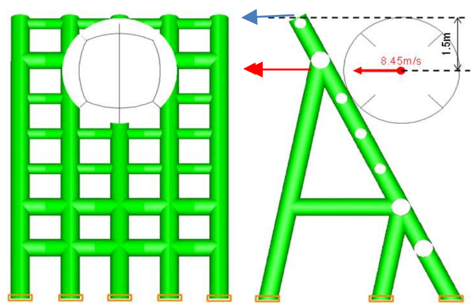


Figure 11: Fluid force for FEM analysis (3-D)



(a) front (b)side

Figure 12: Rock impact for FEM analysis (3-D)

3.6 Peformance criteria of steel open dam

Before the dynamic FEM analysis, the preformance criteria is needed to judge the internal structural safety as follows.

(1) The local formation of a steel pipe component is assumed as follows.

Table 3 Residual local deformation(δ)

	Neglect	SLS	Small repair	RLS	Large repair	ULS	Exchange
Local deformation/ Steel pipe diameter (δ/D)	δ/D<0.1	0.1	0.1<δ/D<0.4	0.4	0.4<δ/D<0.7	0.7	0.7<δ/D

(2) The global deformation of a whole structure is also assumend as follows.

Table 4 Residual horizontal displacement(⊿)

	Neglect	SLS	Small repair	RLS	Large repair	ULS	Exchange or reinforce
Horizontal displacement / dam height (⊿/H)	⊿/H<0.02	0.02	0.02< ⊿/H<0.05	0.05	0.05< ⊿/H<1.0	0.1	1.0<⊿/H

3.7 Computational results of dynamic FEM anallysis against load level 2

(1) Horizontal displacement – time relations against fluid force and rock impact

Figure 13 shows the horizontal displacement (crown of dam) – time relation against the fluid force. The resuidual displacement was 55mm. Figure 14 illustrates the horizontal displacemets (crown of dam and impact point) – time relations against the rock impact. The residual displacemant was 70mm at the imapct point.

(2) Impact load- time relation against rock impact

Figure 15 shows the impact load – time relation, and the maximum average impact load was 5MN. However, it was recognized that the vibration was occurred at the moment of rock impact, as shown in Figure 15.

(3) Local deformation profile against rock impact

Figure 16 illustrates the local deformation profile of pipe component at the impact point, and the residual local deformation / pipe diameter (δ/D) was 0.75 as shown in Figure 17.

(4) Impact load – deformation relations against rock impact

Figure 17 represents the impact load – (local deformation/pipe diameter) relation obtained by eliminating the time axis, and, as such, the area surrounded by curves means the local absorbed energy. Figure 18 demonstrates the impact load – horizontal displacement relation at impact point, and, as such, the area surrounded by curves means the global (whole structural) absorbed energy.

3.8 Safety verification

(1) Safety verification for global deformation
- (a) Against fluid force; $\Delta_{max}/H=55/8000=0.007<0.02$ (less than serviceability limit)
- (b) Against rock impact; $\Delta_{max}/H=70/6500=0.01<0.02$ (less than serviceability limit)

Therefore, the structure as a whole was not damaged, and was neglected as it is.

(2) Safety verification for local deformation

Against rock impact; $\delta_{max}/D=0.75>0.7$ (larger than ultimate limit)

Therefore, the component at the impact point should be exchanged or reinforced.

(3) Energy absorption
- (a) External energy; $E_R=\frac{1}{2}mv^2$ =36.7t x(8.45m/sec)^2/2=1310kJ
- (b) Internal energy; U_L= 945kJ (area surrounded by curves in Figure 16)
  U_G= 299kJ (area surrounded by curves in Figure 17)

It was found that the total internal absorbed energy was 1244 kJ which corresponds to 95% of the external energy 1310kJ, and it was also recognized that the rock impact energy was 72% absorbed by the local deformation of the pipe component at the impact point. The remaining energy may be dissipated by the vibration of the structure as shown in Figure 15.

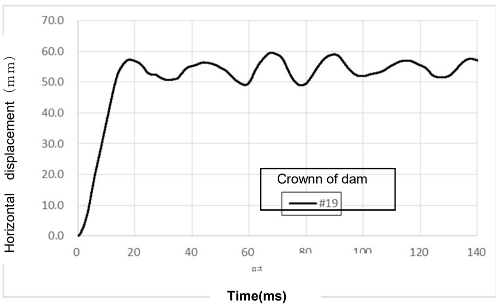


Figure 13: Horizontal displacement – time relation against fluid force

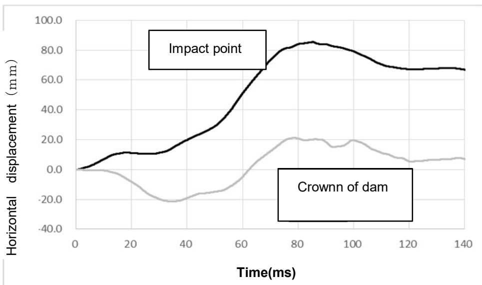


Figure 14: Horizontal displacement – time relation against rock impact

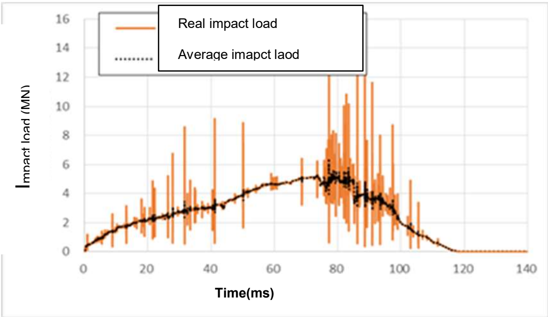


Figure 15: Impact load – time relation against rock impact

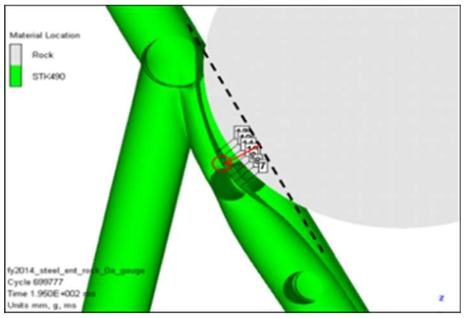


Figure 16: Local deformation profile at imapct point against rock impact

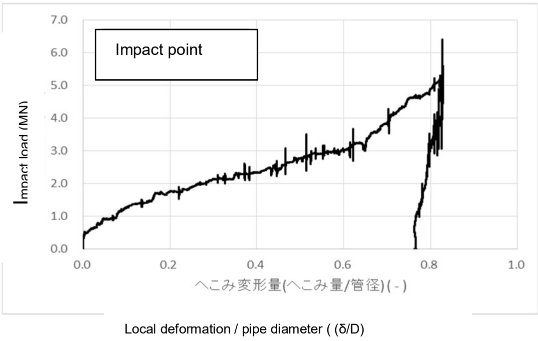


Figure 17: Impact load – local deformation relation against rock impact

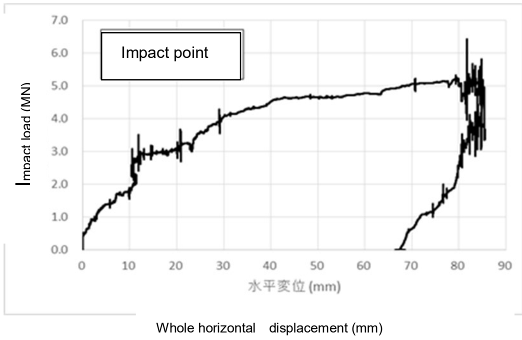


Figure 18: Impact load – horizontal displacement relation against rock impact

4. CONCLUSIONS

The following conclusions were obtained from this study.

(1) The performance-based design of steel open dam was proposed by adding to the 2nd step design (load level 2).

(2) However, the 2nd step design is performed by judgement if one of three conditions of 2.9.2 is satisfied or not.

(3) The load level 2 will be determined by either or combination of A-D in 2.5, but in this numerical example, the load level 2 was decided by the combinations of the extreme limit stability conditions and the field suvey of Nashizawa debris flow disaster,2014.

(4) From the results of computation against the fluid force of load level 2, the steel open dam was not so damaged.

(5) From the computational results against rock impact of load level 2, the damage of the steel open dam was only local deformation, which was greater than the ultimate limit displacement at the impact point.

(6) However, the steel open dam was not so damaged in the whole structure, because the horizontal displacement was less than the serviceability limit state.

REFERENCES

〔1〕 Steel Sabo Structure Committee, Sabo & Landslide Technical Center: *Design Manual of Steel Sabo Structures* (2009), (in Japanese).

〔2〕 Sabo Planning Division, Sabo Department, National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure and Transport: *Manual of Technical Standard for establishing Sabo master plan for debris flow and driftwood*, Technical note, No.904, April (2016), (in Japanese).

〔3〕 Sabo Planning Division, Sabo Department, National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure and Transport: *Manual of Technical Standards for designing Sabo facilities against debris flow and driftwood,* Technical Note, No.905, April (2016), (in Japanese).

〔**4**〕 Central Regional Bureau, Ministry of Land, Infrastructure and Transport: *Survey Report of Nashizawa Debris Flow, Nagiso, Nagano Prefecture*, July (2014). (in Japanese)

〔**5**〕 S.Katsuki, T.Horiguchi and R.Tateishi, *Nashizawa Disaster Report,* Private Survey Report,July (2014), (in Japanese).

〔**6**〕 N**.** Ishikawa, J. Shima and M. Beppu, *Impulsive Behavior of Check Dam under Debris Flow*, Proc.of the 6th Asia-Pacific Conference on Shock & Impact Loads on Structures, pp.1-8. Perth, Australia, December (2005).

〔**7**〕 N. Ishikawa, R. Inoue, M. Beppu, Y. Hasegawa and T. Mizuyama, *Impulsive loading test of debris flow model*, Proc.of the 8th International Conference on Shock & Impact Loads on Structures, Adelaide, Australia, December (2009).

〔**8**〕 N. Ishikawa*, R. Matsuzawa, T. Shibata, T. Kaneko, M. Beppu and T. Mizuyama, *The Effects of Low Velocity Impact on Concrete Dams,* Proc. of 3rd International Conference on Protective Structures (ICPS3), Newcastle, Australia, February (2015).

〔**9**〕 N.Ishikawa, H.Shibuya, S. Katsuki and T. Mizuyama, *Protective steel structures against Wooden Debris Hazards*, Proc.of 6th International Conference on Protection of Structures Against Hazards*,* Tianjin, China, October (2014).

〔**10**〕 J.Shima, I. Takeda, R. Matsuzawa, M. Beppu,N. Ishikawa and T. Mizuyama, *Failure Mechanism of Concrete Sabo Dam by Rock Impact,* Proc.of 11th International Conference on Shock & Impact Loads on Structures, Ottawa, May (2015).

〔**11**〕 International Organization for Standardization:ISO2394, *General Principles on Reliability for Structures*, Oct. (1997).

〔**12**〕 Ministry of Land, Infrastructure and Transport: *Basis of Structural Design for Buildings and Public Work*s, Oct.(2002), (in Japanese).

〔**13**〕 Japan Society of Civil Engineers: *Comprehensive Design Codes, Principles, guidelines and terminologies for structural design code drafting founded on the performance based design concept ver.1*, code PLATFORM ver.1, March (2003), (in Japanese).

〔**14**〕 Japan Society of Civil Engineers: *Performance-Based Design Guideline for Civil Engineering Structures subjected to Impact Loading,* Structural Engineering Series 22 (Edited by Y. Sonoda), Jan.(2013), (in Japanese).

〔**15**〕 M.Itoh, M. Beppu, and R.Matsuzawa, *Numerical Simulations of RC Slabs Subject to Impact Loadings by Using the Improved Caprous Constitutive Model,* 10th International Conference on Shock & Impact Loads on Structures, Singapore, November (2013).

〔**16**〕 http://www.engineering-eye.com/AUTODYN/.

〔**17**〕 Sabo Planning Division, Sabo Department, National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure and Transport: *Manual of Technical Standards for designing Sabo facilities against debris flow and driftwood,* Technical Note, No.364, Nov. (2007), (in Japanese).

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

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

〔**20**〕 Central Regional Bureau, Ministry of Land, Infrastructure and Transport: *Report of Examination Committee on Sabo Dams in Nashizawa Basin,* Nov.(2014), (in Japanese).