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CURRENT PRACTICES IN THE DESIGN AND EVALUATION OF STEEL SABO FACILITIES IN JAPAN

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ABSTRACT
In Japan, many types of steel Sabo (erosion and sediment control) facilities have been developed since about 1970. In all, more than 1,500 steel Sabo facilities have been constructed to date. The steel Sabo facilities, which are classified as either closed or open steel Sabo dams, are planned, designed and constructed in a systematic manner in accordance with highly specific, location-dependent design standards. Closed steel Sabo dams include shaped steel frames filled with sand and gravel and hollow walls constructed using steel sheet piles or sheet steel segments which are filled with sediment. Open steel Sabo dams typically employ a steel pipe frame-based structure, with appropriate openings provided on the upstream surface.
This paper will:
i) explain the types and the characteristics of steel Sabo facilities in relation to practical use;
ii) explain the contents of steel Sabo facilities design;
iii) present and evaluate some examples of steel Sabo facilities, including the effects achieved; and
v) outline future prospects and challenges of steel Sabo facilities in Japan.

Key words: steel Sabo dams, closed steel Sabo dams, open steel Sabo dams, debris flow

1. Types and features of steel Sabo facilities

Table 1 shows the method of selecting the steel Sabo facilities for each sediment discharge type. As shown in Table 1, the closed Sabo dam is classified into frame structure, double wall structure, cell structure, etc. In contrast, the open type is classified into steel pipe frame structure or cell structure. Applications of these Sabo dams are shown in Table 1.

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Table 1：Type and use of steel Sabo facilities in Sabo facilities

Type of steel Sabo facilities	Classification of steel Sabo facilities	Sabo dam							
		Measures for debris flow			Measures for flood wood		Measures for volcanic debris		
		Reduction of occurrence	Capture and control	Reduction of flow angularity	Reduction of occurrence	Capturing	Reduction of mudflow	Capture and control of mudflow	Control of mudflow angularity
Closed type	Frame structure	○			○		○		
	Double wall structure Cell structure	○	○	○	○		○	○	○
Open type	Steel pipe frame-based structure Cell structure		○			○		○	

1.1 Closed steel Sabo dam

As shown in Fig. 1 and Photo 1, the double wall structure has panel wall materials such as steel sheet pile or expansion metal at the upstream/downstream faces to fill the inside. The wall surface is connected with a flexible tie rod. This Sabo dam has the feature of a fill dam in which the filled soil is reinforced with densely positioned tie rods. In this way the entire dam has excellent flexibility. The greatest advantage of this dam is that sediment generated at the construction site can be used as the filling material.

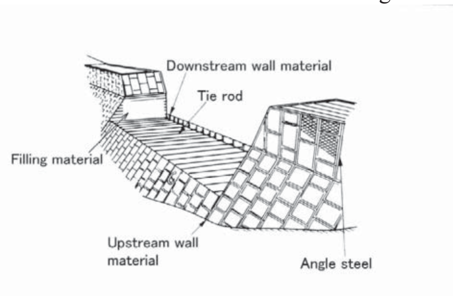


Fig. 1：Double wall

Photo 1 ：Double wall

As shown in Fig. 2 and Photo 2, the closed cell structure has continuous cells with filled sediment such as earth generated at the construction site in a steel body consisting of steel segments. The assembly methods of these steel bodies are sequential insertion of linear steel

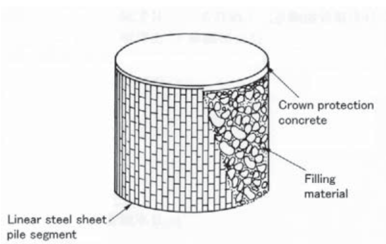


Fig. 2 ：Steel sheet pile dam

Photo 2 ：Steel sheet pile dam

sheet piles with claws and connection of bent steel panels with bolts. The former is called a steel sheet pile segment cell and the latter is called a steel segment cell.

1.2 Open steel Sabo dam

The open steel Sabo dam is a Sabo dam that has the opening at the spillway to multiply the maximum gravel diameter by a suitable factor. This Sabo dam has a vacant space to capture debris flow by discharging non-hazardous soil under normal circumstances or during small or intermediate-scale freshets. In the case of a debris flow, it functions to capture a group of frontal boulders. In recent years, the open Sabo dam has been increasingly used to maintain continuous flows, to ensure free movement of water-borne fauna, to reduce scouring of the riverbed, or to prevent recession of a coastline.

The open steel Sabo dam can be classified into a steel pipe frame-based structure and a cell structure. The former has steel slit Sabo dams A, B, L, I ,and CF, and grid steel Sabo dam by sectional shape. These steel pipe frame-based structures have columns embedded in the foundation concrete. Type L has a foundation with H-section steel instead of foundation concrete.

As an example of the former dam, the grid type is shown in Fig. 3 and Photo 3. As an example of the latter dam, type L is shown in Fig. 4 and Photo 4. These Sabo dams are featured by flanges at the ends of steel pipes prefabricated in plants that can be tightened at a construction site with high-strength bolts, reducing lead-time at the site.

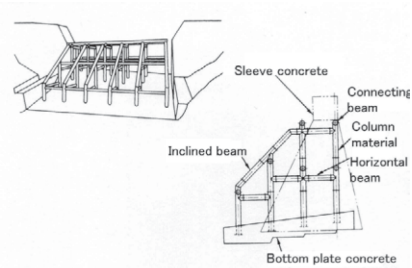


Fig. 3 ：Grid type steel Sabo dam

Photo 3 ：Grid type steel Sabo dam

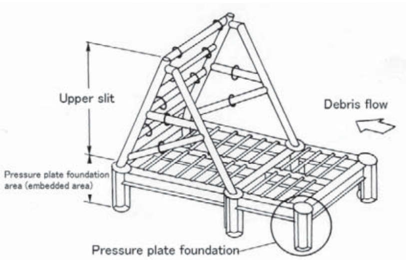


Fig. 4 ：Steel slit dam type L

Photo 4 ：Steel slit dam type L

In contrast, the cell structure has the cell steel bodies previously described with some intervals. The function of this Sabo dam is to stop boulders by hitting the cell for debris flow and to capture debris flow by collecting groups of gravel between cells.

2. Design of steel Sabo dam [1)]

2.1 General items for design

1) Definition of minimum thickness: The minimum thickness of the steel used for the closed steel Sabo dam is 6 mm. The minimum thickness of the steel used for the open steel Sabo dam is 8 mm. The minimum thickness of steel pipes used as major members is defined in the following equation so that safety may be ensured for local buckling of the member.

T≧ (D - 2・ ⊿ t) / 80 + ⊿ t

Where, t: Thickness of steel pipe (mm), ⊿ t: Corrosion allowance (mm), D: Outer diameter of steel pipe (mm)

2) Definition of corrosion allowance: Corrosion allowance is defined as the distance when adding allowance of wear and impact to rust allowance. It is specified as shown in Table 2 for the closed type and the open type.

Table 2 : Design corrosion allowance for each structure

Type	Description	Member	Corrosion allowance	Remark
Closed type	Form structure, double wall structure, etc.	Main members	1.5mm	The dam is covered with an abrasion-resistant material if impact or wear might occur.
Open type	Framework structure	Upstream most forward member Other main members Joint, etc.	5.0mm 3.0mm 1.5mm	

2.2 Design of closed Sabo dam

Fig. 5 shows a flow of the closed steel Sabo dam.

1) Design of spillway: In principle, the spillway should be designed so that the center is positioned at the center of the torrent bed. The width of the spillway should be as large as possible to prevent scouring at the downstream edge of the dam due to water flow. The spillway height is determined by adding the free board or higher to the water depth that can achieve the required water discharge.

2) Determination of sectional shape: The crown width of the spillway is determined by the torrent bed material or the sediment discharge type. In the filling dam, the minimum value of the crown width is specified to be 2 m.

3) Stability calculation for gravity structure: Combinations of loads used for stability calculation are shown in Table 3.

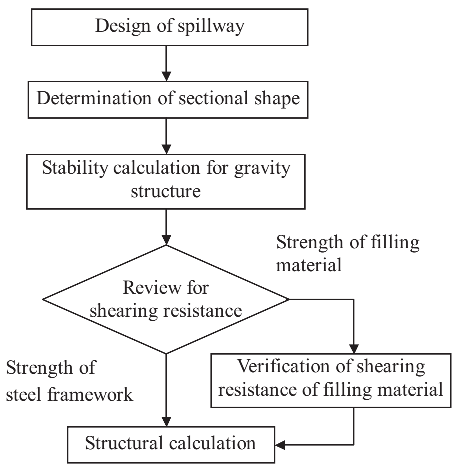


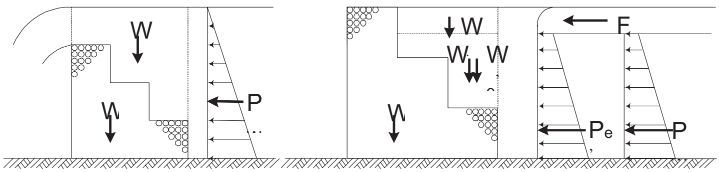
Fig. 5 : Design flow of closed dam

Conditions for stability are: (1) No overturn of wall body, (2) No sliding between the dam and the foundation ground or within the foundation ground, (3) The maximum load strength applied to the foundation ground is within the allowable bearing capacity of the ground.

Table 3 : Combination of closed dam design load

Case of load	Self-weight	Static water pressure	Sediment pressure	Fluid force of debris flow
Flood	○	○		
Debris flow	○	○	○	○

W: Self-weight
Ww: Water weight
Wd: Self-weight of debris flow
We’: Sediment weight
Pw: Water pressure
Pe’: Sediment pressure
F: Fluid force of debris flow



Flood   Debris flow

4) Review for shearing resistance: It must be ensured that a dam using filling materials such as frame-based structure, double wall structure, or cell structure maintains its form under a horizontal force. To estimate this resistance to shearing deformation, the major methods available are: (1) Dependence on the steel framework strength, (2) Dependence on shearing resistance of filling material. For Method (1), the frame-based structure may be analyzed as the steel framework structure. Method (2) estimates the resistance of soil material to shearing deformation. This estimation is performed according to the standard.

5) Structural calculation: For a frame-based structure that depends on steel framework strength, the member force in addition to the load used for the stability calculation as the truss or the rigid frame supported with the foundation ground and the earth pressure of the filling material are calculated to examine stress. In contrast, for the frame structure that depends on the shear strength of the filling material, strength of each member is calculated as simple beam or tension material against the earth pressure of the filling material transferred from the wall material to examine the stress.

For the double wall structure, the member force of the upstream/downstream wall material that prevents a discharge of filling material under the earth pressure of the filling material, and the member force of the waling and the tie rod that connects these wall materials are calculated to examine stress.

For the cell structure, the member strength of the cylindrical wall material against the earth pressure of the filling material is calculated to examine the stress.

2.3 Design of open Sabo dam

Fig. 6 shows the design flow of the open steel Sabo dam.

1) Design of spillway: The design method is the same as that of the closed Sabo dam.

2) Determination of opening[2]: Opening size b at the open type Sabo dam is determined based on Fig. 7 [3]. In the past, the value has often been determined to be $n=b/d_{max} = 2.0$ to stop boulders and to reduce the peak discharge of debris flow. To ensure capturing, the value is determined to be n = 1.5. To ensure more accurate capturing, the value may be determined to be

$n = 1.0$. Maximum gravel diameter d_{max} here is determined as the grain diameter equivalent to 95% of the cumulative value from the cumulative curve by measuring the gravel diameters carried in debris flow at a distance of 200 m upstream and downstream around the position of the Sabo dam. Opening size b may often be the genuine distance of the vertical material or the horizontal material.

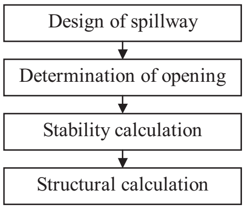


Fig. 6 : Design flow of open dam

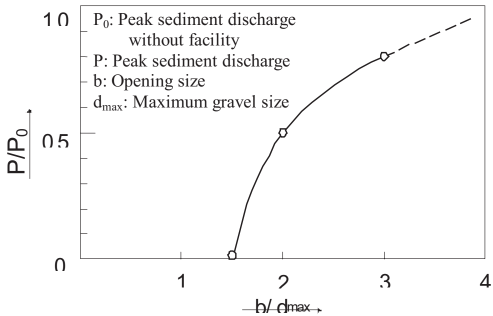


Fig. 7 : Opening size and reduction of peak sediment discharge

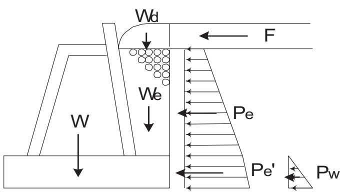
3) Stability calculation: Combination of loads used for stability calculation is shown in Table 4. The large difference from the combination of loads for the closed Sabo dam gives no consideration to water pressure at the open area.

Conditions for stability are: (1) Bonding point of the resultant force from the self-weight and the external force of the Sabo dam is within 1/3 of the distance from the center of the dam bottom. (2) Sliding must not occur between the dam bottom and the foundation ground or within the foundation ground. (3) The maximum load strength applied to the foundation ground must be within the allowable bearing capacity of the ground.

Table 4 : Combination of design load in stability calculation of open dam

Case of load	Self-weight	Static water pressure Note 1)	Sediment pressure	Fluid force of debris flow
Debris flow	○	○	○	○

Note 1) This is considered only when the bottom plate is thick and the same function as that of the open type can be expected.



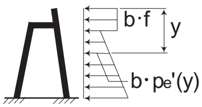
W: Self-weight
Wd: Self-weight of debris flow
We: Self-weight of sediment
Pe: Sediment pressure
Pe': Sediment pressure considering buoyancy
F: Fluid force of debris flow
Pw: Water pressure

4) Structural calculation: Combinations of structural calculation loads are shown in Table 5. Many steel pipe structures connecting panel points are used in the open Sabo dam. Therefore, the structural calculation considering temperature variations is necessary. For the structural

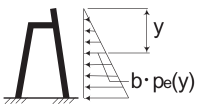
calculation method, the member force is calculated for a given design load. Stress of each member, joint, and bottom concrete is examined for this member force.
The following two calculation methods are used to study gravel collisions. One method is to review the strength of an individual steel pipe against gravel collisions. Gravel collision energy E_R should be smaller than the total value of absorption energy E_d due to dent deformation of steel pipes and absorption energy E_N due to plastic deformation as a steel pipe member. Another method is to examine if lateral movement δ of the entire structure due to gravel collision is 2% or less of the effective height.

Table 5：Combination of design load in structural calculation of open dam

Case of load	Self-weight	Fluid force of debris flow	Sediment pressure	Temperature variation ±30℃	Remark
Debris flow	○	○	○		Refer to figures below
Full soil	○		○		Refer to figures below
Temperature variation	○			○	– –



Debris flow



Full soil

b: Effective loading width (m)
f: Fluid force of debris flow (kN/m^2)
Pe: Sediment pressure at position y from crown (kN/m^2)
Pe': Sediment pressure considering buoyancy at position y from crown (kN/m^2)

3. Effect example and evaluation

3.1 Crosed type Sabo dam

Photo 5 shows the frame structure Sabo Dam as consolidation works (Mushikawa Sabo dam: Itoigawa Public Works Office, Niigata Prefecture). Photo 5 is the status 5 years after installation. Plants are recovering on the entire hillside, which was shattered before installation.
From the above, it can be seen that the closed steel dam is very useful for stabilizing the riverbed by reducing and capturing sediment discharge and for recovering vegetation.

Photo 5：Overall view of frame structure of Sabo dam

3.2 Open type Sabo dam

Capturing debris flow mixed with woody debris

Photo 6 shows the longitudinal section of the steel pipe Sabo dam[4] (Nakatani-gawa Sabo dam: Kaibara Public Works Office, Hyogo Prefecture) capturing debris flow mixed with woody debris. The longitudinal section can be classified into areas①to⑦from the characteristics of the deposit sediment. Photo 7 shows the test result for capturing debris flow with woody debris in the past. Although this test is different from local conditions of the Nakatani-gawa Sabo dam, it is believed that qualitative behavior is very similar. Fig.8 shows a computer graphic of the sedimental deposit process on the Nakatani-gawa Sabo dam based on Photos 6 and 7.

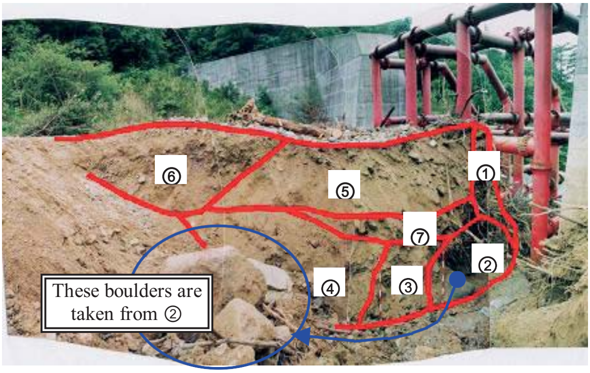


Photo 6： Longitudinal section of captured debris flow

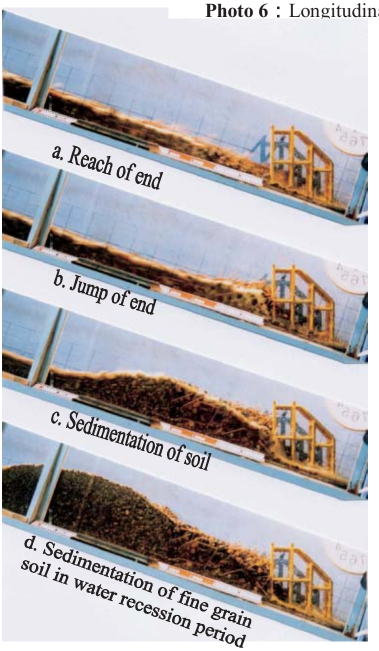


Photo 7： Test results

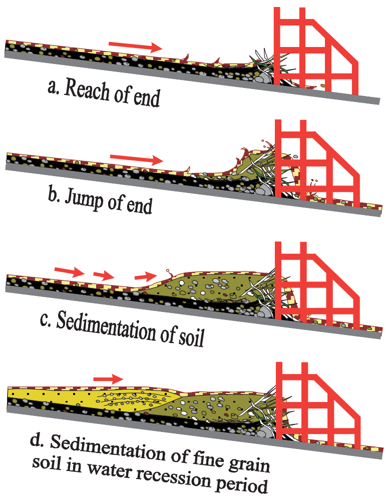


Fig.8： Image illustration of soil sedimentation status

Debris flow consists of woody debris at the front part, boulders, fine gravel, and sediment mixed with gravel in this order (Photo 7a and Fig. 8a). When the front part hits the opening of the dam, debris flow is ejected to a height that is 2 to 3 times the wave height and woody debris clogs the opening. At the same time, subsequent boulders, fine gravel, and sediment might be captured in the first layer equivalent to this wave height (Photo 7b and Fig. 8b). At this time, ① in Photo 6 indicates the area of ejected woody debris, ② indicates boulders, ③ indicates fine gravel, and ④ indicates sediment mixed with gravel. Then, the subsequent flow comes into the first layer of sedimentation, and sediment mixed with gravel is deposited at the rear resulting in ⑤ (Photo 7c and Fig. 8c). It seems that ⑥ is formed by deposits of fine grain soil (Photo 7d and Fig. 8d) in water recession period.

⑦ in Photo 6 is an area with many wood chips. It is assumed that these wood chips are the residues after removing woody debris on the surface of the first layer of the debris flow.

Photo 8：Status of captured debris flow (upstream)

Photo 9：Status of captured debris flow (downstream)

Photos 8 and 9 show similar examples for the steel pipe Sabo dam (Furuekawa Sabo dam: Aso Regional Development Bureau, Kumamoto prefecture) has captured debris flow mixed with woody debris. Photo 8 was taken upstream and Photo 9 was taken downstream. These photos show that the opening is clogged with woody debris. This is probably because woody debris flowed first, similar to the case of the Nakatani-gawa Sabo dam described above.

The above explains that the steel pipe Sabo dam functions to capture almost all of the debris flow with mixed woody debris.

Capturing of gravel type debris flow

Photo 10 shows the steel pipe Sabo dam (Ohtanasawa No. 2 Sabo dam: Fujikawa Sabo Works Office, Kanto Regional Development Bureau, Land Infrastructure and Transportation Ministry) upon completion (1987). Photo 11 shows the status of captured gravel type debris flow in 1994 at this dam. During the planning stage, the size of the opening was determined to be twice the maximum gravel diameter (d_{max} = 2.0 m). This dam was supposed to stop boulders and to reduce peak sediment discharge. From the follow-up survey result [5] after debris flow, the following items were found: i) The ratio between genuine column space b and maximum gravel diameter d_{max} was n = 2.2 and d_{max} was a little smaller, ii) Stopping boulders greatly reduced peak discharge, iii) Subsequent flow was passed. In contrast, the diameter of boulders deposited inside the grid dam were small from 1.2 to 1.5 m and no large variation was found depending on the location. It is believed that this sediment was deposited from the subsequent flow.

Corrosion depth ⊿ t of the steel material was surveyed. It was found that the greatest depth was ⊿ t = 0.2 mm and that the most common depth was⊿ t =0.1 mm or less.

From the above, the steel pipe Sabo dam with the ratio of n = 2.0 between opening size b and maximum gravel diameter d_{max} is effective in capturing boulders and reduction of peak sediment discharge. It also shows that progress of corrosion is not great in normal rivers.

Under the current standard, the opening size is determined to be n = 1.5 to capture debris flow without fail. There has been no example of a dam that had been subject to gravel type debris flow. In the future, the effects of the Sabo dam with n = 1.5 will be clarified.

Photo 10: Status immediately after completion

Photo 11: Status immediately after capturing debris flow

Photo 12 shows the cell structure Sabo dam with a staggered arrangement immediately after completion. Photo 13 shows sediment deposition when a gravel type debris flow hit the staggered cell structure Sabo dam in 1996. This dam was subject to three debris flows in four days. Photo 13 shows the sediment deposit after the third debris flow. After the follow-up survey [6), 7)], the ratio between maximum gravel diameter d_{max} of debris flow and interval b of cells was $n=b/d_{max} \fallingdotseq 2$.

From a videotape of the site and the survey of the sediment deposition, the following capturing system of debris flow was found.

Photo 12: Status immediately after completion

Photo 13: Status immediately after capturing debris flow

When the frontal part of the first debris flow reached the upstream cell, it was ejected and boulders were stopped. Frontal boulders reaching the cells were also captured by the opening between cells. Subsequent flow hit the downstream cells, riding over soil deposit between cells. Sediment concentration and gravel diameters of this subsequent flow were small. Not much sediment was captured and water flowed through cells. When the second debris flow occurred,

a similar phenomenon to the first was observed. When the third debris flow occurred, there was sediment deposited from two debris flows. The frontal part of debris flow has rode over the deposition.
It seemed that the cell structure dam showed performed reduce the speed of the debris flow by having boulders strike the cell and capture the debris flow by stopping boulders at the opening between cells.
Although this debris flow damaged part the cell steel bodies, it was expected that repairs could return its functions to the standard when newly installed.

4. Future prospects

Many steel Sabo dams have been planned according to the standard. There are still tasks to be studied in view of construction, function, strength, and economy.
As for construction, an unmanned construction where a debris flow hazard streams is required or construction for a short period is required. Photos 14 and 15 show an example of an unmanned construction [8] of the steel pipe Sabo dam used at Fugen-dake, Unzen. At this Sabo dam, all jobs including transportation, installation (Photo 14), concrete placement on the bottom panel and finishing the concrete surface with a trowel (Photo 15) are remote controlled. Unmanned construction can be performed only when the following conditions are satisfied: the local work site is large. Heavy machines or transportation vehicles can enter easily. The steel Sabo dam is not so large and it can be installed in blocks.
In the future, development of a method or a structure is desired that allows unmanned construction on a steep slope of a mountain.

Photo 14: Transportation of Sabo dam

Photo 15: Finish of concrete surface with trowel

As for function, it is not clear if the open dam showed its full performance. For example, if gravel equivalent to the maximum design gravel diameter flow or if the debris flow is equivalent to the planned flow is not known, despite detailed surveys. In this way, it is difficult to verify the functions of the Sabo dam. In the standard, the opening size is determined according to maximum gravel diameter d_{max} only. If the maximum gravel diameter is the same, the capturing function varies greatly depending on differences of grain distribution, and the capturing function may be questionable. In the future, it is necessary to clarify these unclear points with function test, simulation, and follow-up survey. After clarifying these points, it is expected that the results for reliability will be incorporated into the overall Sabo plan of the open Sabo dam.
As for the durability of the steel Sabo dam, there is no specific evaluation method or repair method for damage to facilities. Specifically, i) In overall steel Sabo facilities, there is no evaluation method for corrosion or wear to steel. ii) In the closed Sabo dam, there is no

evaluation method for bulges in walls caused by filling material, overall deformation of the facilities and damage to facilities members or joints. iii) In the open Sabo dam, there is no definite evaluation method for overall facilities deformation of steel pipes. These methods are currently under review and various repair methods or measures are being developed. When these evaluation methods or measures for repair are established in the future, it will be easy to use steel Sabo facilities.

The problem in economic terms is that the construction cost of the steel Sabo dam is generally higher than that of the concrete Sabo dam. The reason for this is that the steel Sabo dam has limited proven results compared to the concrete Sabo dam. Therefore, first priority is given to safety. The design load is determined to be larger and the steel section has a large allowance. In the future, follow-up survey or verification test of existing facilities will be performed. From these results, it is important to alleviate design conditions while maintaining safety and to reduce the amount of steel materials per dam.

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