Evolution of Hybrid-Structure Sabo Dams in Japan
— Toward their optimal structures —

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INTRODUCTION

Hybrid structures as check dam (hereinafter referred to as Sabo dam) have existed in a broad sense since over a century ago, when dams were constructed using soil, stone, and timber. To form a dam body with a steep downstream slope of approximately 1:0.2 using soil materials, and to prevent erosion by flowing sediment water, it was necessary to adopt a hybrid structure that appropriately combined these materials.

Since the advent of concrete and steel, these materials and their fabricated components have been used in place of stone and timber as upstream and downstream facing materials for dams composed primarily of soil, as well as for the connecting components between facing materials or as tie rods.

The hybrid structures that have evolved through this historical background, have recently reached what we consider ideal developmental forms for both closed and open dam structures, as shown in Fig.1. For closed dams, this is the double-wall (DW) structure filled with soil-cement; for open dams, it is the horizontal-beam buttress type and the vertical-column inverted T-shaped type.

The purpose of this paper is to present the chronological evolution of hybrid-structure Sabo dams in Japan to date and to systematically derive the latest optimal hybrid-structures based on this history, thereby providing useful information for engineers in other countries.

SCOPE OF HYBRID STRUCTURES

Hybrid structures may refer to aspects such as construction methods, materials, or design, however when applied specifically to Sabo dams, limiting the discussion to materials alone is considered sufficient in practice. For Sabo dams, the materials involved are primarily soil, concrete and steel. These materials are combined appropriately to form a hybrid structure. Currently, wood is not used due to durability concerns.

As a combination of these three materials, as shown in Fig. 2, closed sabo dams consist of soil as the core material combined with steel or concrete as the facing material. Soil provides the dam body weight, while steel or concrete reinforces the soil and forms the dam shape. For open type dams, steel and concrete are combined to ensure a open cross section. Both materials mutually reinforce each other as components or as the structural body, forming a hybrid structure.



Fig. 1 Advanced forms of hybrid structures

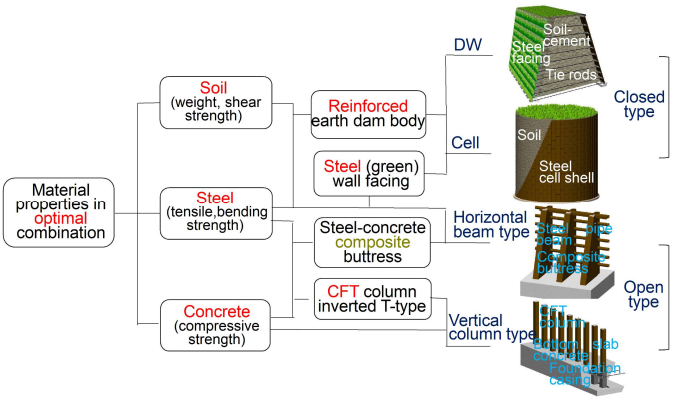


Fig. 2 Structural materials of hybrid structures

SOIL RELATED HYBRID STRUCTURES (CLOSED TYPE DAM)

1. Past hybrid structures

Hybrid structures, serving as closed type dams composed of soil, concrete, and steel materials, have been constructed for approximately 40 years.

Soil-concrete hybrid structures: This structure involves filling the hollow sections of hollow gravity concrete dams with in-situ generated soil (see Fig. 3). The hybrid soil-concrete structure reduces the amount of concrete required for the dam body and effectively utilizes soil as dam material. Compared to concrete-only dams, this wider base width reduces the maximum subgrade reaction intensity, allowing application even on grounds with insufficient bearing capacity. The infill soil serves as a substitute for the heavy shoring required during construction of the upstream and downstream walls of the hollow section. Although this type was quickly overshadowed by the rapid rise of soil-fill DW dams and forgotten after fewer than ten installations, it remains a rational hybrid structure, and there are voices calling for its revival.

Soil-steel hybrid structures ① DW: The DW is a structure constructed by connecting the upstream and downstream steel sheet pile dam-body facings usually with multi-stage tie rods and filling the interior with soil (see Fig. 4). The prototype for this structure is the double sheet pile temporary cofferdam or double sheet pile mooring wharf, used for underwater or waterfront structures for about 90 years. This DW moved onto land about 40 years ago and is currently used as Sabo dams.

Compared to underwater DW, land-based DW can fundamentally improves the strength of dam body where soil is the primary component. The factors contributing to this include the ability to spread and compact the infill soil in thin layers, resulting in higher shear strength, and the formation of a reinforced soil body where densely arranged multi-stage tie rods confine and reinforce the infill soil laterally. The establishment of the DW as a dam construction method required little time, as it logically utilized in-situ generated soil as the primary dam material. In addition, frame structures primarily using stone as infill material had been in use slightly earlier than DW structures, however their use ceased following failures caused by debris flow loads.

Soil-steel hybrid structures ② Cell: The cell is a hybrid structure similar to DW in material composition (see Fig. 5). Unlike DW, cells lack tie rods. Instead, they retain the infill soil by forming the dam body facing into an arc shape and applying hoop tension. Straight steel sheet piles, specially designed for cells to resist tension, are used for the facings. Since circular cells are individually

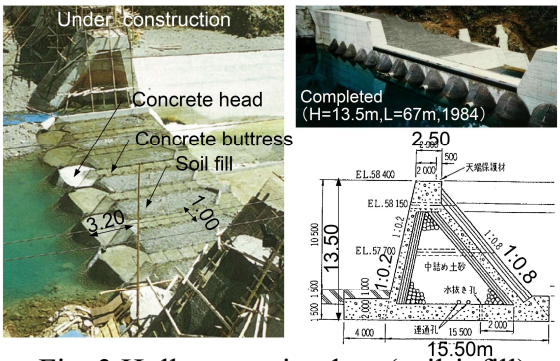


Fig. 3 Hollow gravity dam (soil-infill)

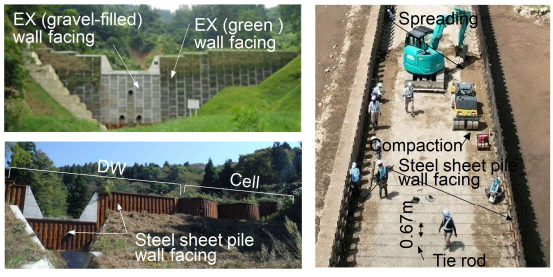


Fig. 4 Soil-steel hybrid structure ①：DW

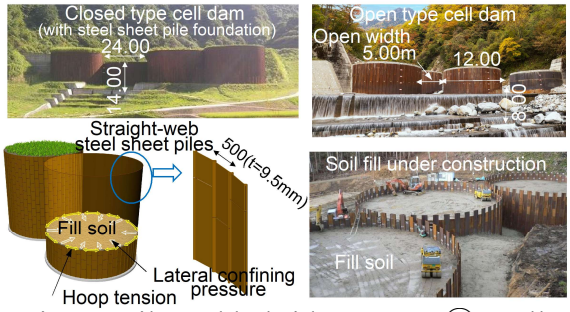


Fig. 5 Soil-steel hybrid structure ②：Cell

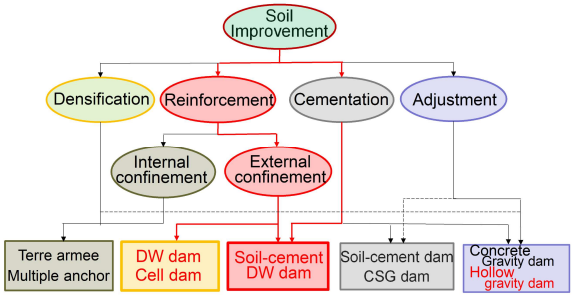


Fig. 6 Positioning of DW and cell structures from the perspective of soil improvement

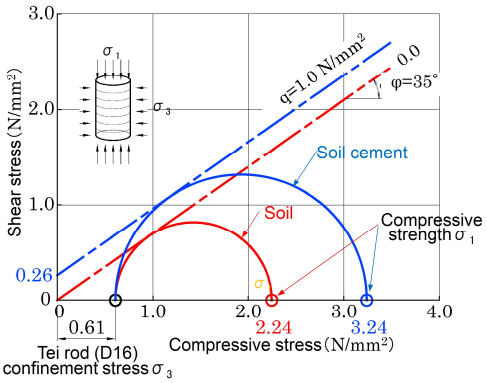


Fig. 7 Effect of multiple tie rods on increasing dam body strength in DW structures

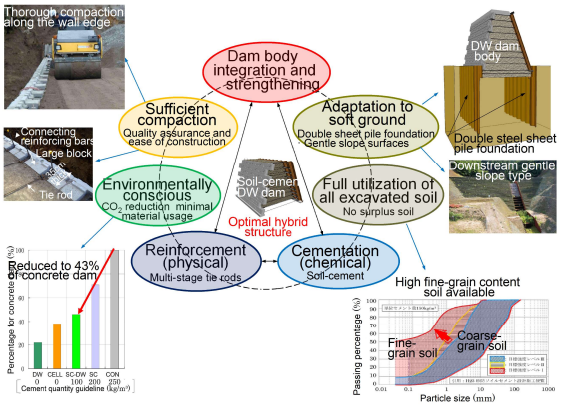


Fig. 8 Rational hybrid structure: soil-cement DW

independent dam body, using driven steel sheet pile foundation allows dam body to be constructed without excavation (excavation-free) even on slopes with landslide terrain.

2. Soil reinforcement in hybrid structures

Hybrid structures primarily composed of soil, such as DW and cell, can be positioned as shown in Fig. 6 from the perspective of soil improvement. Soil improvement is generally classified into densification, reinforcement, cementation, and particle size adjustment. DW and cell correspond to soil reinforcement within this classification. More specifically, they can be considered dam body where the infill soil is reinforced by external confinement provided by the facing and tie rods. Representing this reinforcement effect from external confinement using a Mohr circle yields the result shown in Fig. 7. The mechanism is that the lateral confinement stress from the tie rods increases the compressive strength of the infill soil, thereby also increasing the dam body strength.

3. Advanced form of hybrid closed type dam

An advanced form of DW is soil-cement DW, where the infill soil is treated with soil-cement at compressive strength relatively low (0.5–1.5 N/mm²). This has become the mainstream approach. Soil-cement infill provides a fundamental solution against both washout by flowing water during construction and potential failure due to seepage. As shown in Fig. 7, mechanically, this means increasing cohesion (shear strength). Increased cohesion, combined with reinforcement by the tie rods, significantly enhances the dam body strength. Also soil cement infill means that the dam body does not undergo shear deformation (inclination) that primarily determines the cross-sectional dimensions.

The soil-cement DW, as shown in Fig. 8, can be considered the rational hybrid structures utilizing soil. This is because, based on the DW structure, it offers multifaceted advantages, starting with the ability to enhance strength through the integration of the dam body—a key challenge for only soil-cement dams.

STEEL-CONCRETE HYBRID STRUCTURES (OPEN TYPE DAM)

1. Past hybrid structures

Hybrid buttress structures compositing steel and concrete were constructed approximately 25 years ago as open type dams (see Fig. 9). In the buttresses, the role of steel is to provide structural reinforcement and enhance its wear resistance for concrete. Since multi-row arrangements of buttresses alone were no longer recognized officially as effective debris flow control dams, the beams were arranged in a cross shape, with horizontal beams stacked vertical beams on the upstream side.

2. Mutual reinforcement of steel and concrete in hybrid structures

As discussed above regarding the buttress, this section presents experimental results from model beams demonstrating the bending characteristics of the CFT (Concrete Filled steel Tube) used in the vertical column inverted T-type structure. Fig. 10 shows the results of static loading tests conducted on approximately quarter-scale model beams with a span of 1 m and simply supported at both ends. Focusing on the half-span section of the simply supported beam, it can be considered as a 0.5 m high vertical column (cantilever beam) with the support reaction force as the load.

According to that diagram, the maximum load capacity and absorbed energy of CFT, due to the composite effect of the steel pipe confinement, is approximately 2.5 times that of hollow steel pipes for both circular and rectangular sections. However, tensile cracks occur in the outer steel pipe at a deflection angle of about 10°, causing a sudden reduction in strength. Therefore, the design specifies maximum deflection angle limits of 2° for permanent structures and 5° for temporary structures.

3. Advanced forms of open type hybrid structures

Regarding open type hybrid structures, the horizontal-beam type buttress and vertical-beam type inverted T-type have evolved into the current mainstream forms.

Horizontal-beam buttress type open dam: This type consists of steel pipe (hollow) horizontal beams arranged at clear spacing corresponding to the boulder diameter, supported by composite buttresses. This structure is well-suited as a capture structure for debris flows subject to severe external forces, including large boulders. This is because, as shown in Fig. 11,12, the flow of forces within the structure due to debris flow loads can be safely and smoothly transmitted to the ground, such as from the lateral beams with their buffering effect to the large-section composite buttresses.



Fig. 9 Steel-concrete hybrid buttress type dam

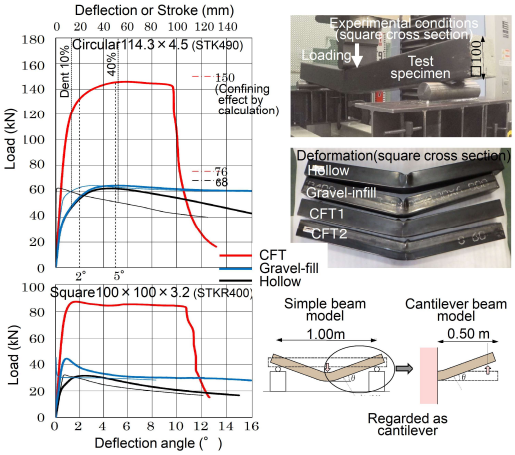


Fig. 10 Relationship between deflection angle and load, and deformation of beam models



Fig. 11 Example of horizontal beam buttress type structure

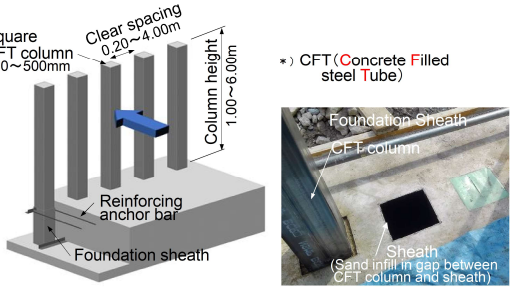


Fig. 14 Overview of vertical column inverted T-type structure

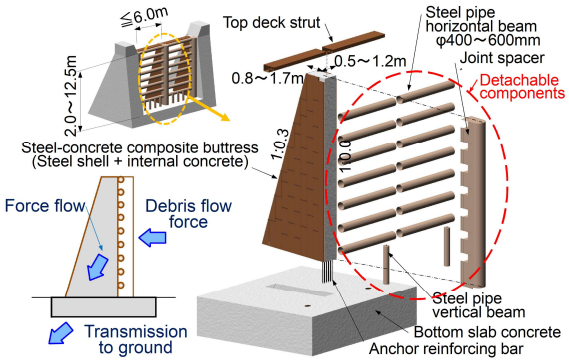


Fig. 12 Force flow and exploded view of horizontal beam buttress type

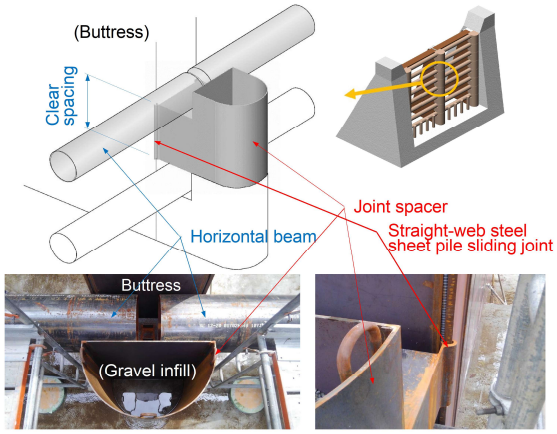


Fig. 13 Simple beam support structure of horizontal beam (detachable)



Fig. 15 Example of vertical column inverted T-type structure

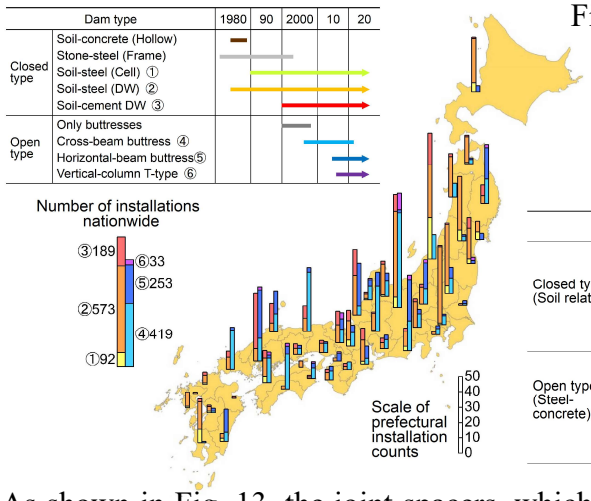


Fig. 16 Historical evolution and prefectural installation number of various hybrid structures

Tab.1 Advantages and disadvantages of various hybrid structures

Dam type		Advantages	Disadvantages
Closed type (Soil related)	Soil-steel① (DW)	Minimal material delivery Shortened build period, Cost reduction	Caution required regarding infill soil washed out during construction
	Soil-steel② (Cell)	Applicable to landslide-prone areas Shortened build period	Superstructure cost is somewhat high
	Soil-cement DW	Strengthening through dual reinforcement Full utilization of in-situ generated soil	Caution required regarding hexavalent chromium generation
Open type (Steel-concrete)	Cross-beam buttress	Strengthening through composite structure Easy management with detachable beams	Vertical and horizontal beam arrangement is somewhat complex
	Horizontal-beam buttress	Simplification using only horizontal beams Shortened build period, Cost reduction	EX(Expanded metal) auxiliary components required for cobble capture
	Vertical-column T-type	Tough CFT columns, Shortened build period, Cost reduction	EX auxiliary components required for cobble capture

As shown in Fig. 13, the joint spacers, which form this simple beam support, serve to connect and integrate the horizontal beams and the buttress, while also enabling the horizontal beams to be detachable.

Vertical-column inverted T-type open structures : This type is an inverted T-shaped structure, where square CFT columns are arranged longitudinally at necessary clear spacing according to the application. Installation of the CFT columns simply involves inserting them into steel casings embedded in the concrete base slab. During debris removal, the CFT columns feature a detachable function (see Fig. 14), allowing only the necessary number to be removed.

Currently they are not installed as officially evaluated Sabo dams. However, they have accumulated considerable experience such as driftwood capture works, emergency protections for ensuring safety during dam construction (see Fig. 15). With an increasing number of cases documenting the capture of debris flows, the conditions necessary for the official evaluation of the Sabo dam are considered to be in place.

NUMBER OF VARIOUS HYBRID STRUCTURES INSTALLED AND THEIR ADVANTAGES AND DISADVANTAGES

As discussed above, various hybrid structures have formed part of the structural framework for Sabo dams in Japan. For reference, Figure 16 shows the historical evolution of various hybrid structures and the number installed by prefecture. However, this is limited to structure types currently installed. Furthermore, Table 1 shows the advantages and disadvantages identified for each type.

CONCLUSIONS

The closed type soil-cement DW dam is a hybrid structure incorporating a composite reinforcement concept — both physical and chemical — to maximize the practical use of in-situ generated soil. This structure possesses mechanical rationality, thereby generating diverse characteristics. Overall, this type is considered the optimal Sabo dam for utilizing in-situ soil.

Simple dam types like the horizontal-beam buttress type and vertical-column inverted T-type of open structures, as the saying “simple is the best” generally goes, are rational as support structures for beams and columns in dam structures. This is because, as readily inferred from examples of structural failure, simple structures without joints demonstrate resilience against highly uncertain external forces like debris flows. These open type structures are considered to represent the ideal forms for future Sabo dams.

Such developments inevitably emerged through the technological systematization resulting from the historical evolution of hybrid-structure Sabo dams in Japan.

Keywords: Hybrid-structure, Soil-cement DW, Cell dam, Horizontal-beam buttress type, Vertical-beam inverted T-type