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Eco-friendly Hydraulic Design of In-stream Flood Mitigation Dams

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Synopsis

Recently, huge floods have been experienced more than the past at the urban area. In order to survive the urban areas against the floods, it could be necessary to deep attention to Flood Mitigation Dams (FMDs). This paper deals with design and classification of FMDs worldwide and compares several case studies in Japan and Austria. Finally, a new concept is presented for one of the most important energy dissipating structures downstream of FMDs, named In-ground stilling basin (SB). As a result, several unique points which are the outcome of field investigations are presented to improve performances of FMDs.

Keywords: Flood mitigation dam, Stilling basin, Bottom outlet, Eco-friendly design.

1. Introduction

1.1 FMDs Definition

Urbanization creates the sharp growth in the value of property and the number of infrastructures at the flood plain areas. Recently, huge floods experienced even more of past at the urban area. There are a wide range of hydraulic engineering solutions have been constructed for centuries to provide flood protections. These traditional approaches predominately utilize hard engineering solution to protect from overflows and ensure quick outflow of flood volumes. Rivers are channelized, diverted, straightened and corseted in levees, with little or no thought for river dynamics and biodiversity preservation. Recently, this is widely criticized (E.U. Commission, 2004). Firstly, accelerating the flow often results in turbid water discharge and significant erosions in downstream reach. Secondly, multipurpose dam interrupt the continuity of natural sediment patterns and change the flow regimes at the downstream reaches of reservoirs, hence causing erosion or deposits. And finally, the consequences on ecosystems are often disastrous. How to both protect citizens from floods and biodiversity from flood-management schemes is very important issue (Geilen et al., 2004). In Japan, numbers of new multipurpose dam construction projects are very limited.

FMD could be a good solution in dam engineering for sustainable management of reservoirs, downstream river environment, and sediment transport. The definition of FMD is gateless outlet dam designed only for the purpose of flood control whose bottom outlets are installed at the original bed level of river. FMD is expected to be environmentally friendly, since almost all incoming sediment during flood periods can pass through its bottom outlets that designed at the original river bed level and there will be fewer impacts to downstream river environment.

Lempérière, (2006) has pointed out that ‘Future dams may generally be multipurpose, but dams devoted only to flood mitigation which are completely dry except for a few weeks per century may be very acceptable environmentally; their design may be quite different from multipurpose dams and their cost much lower for the same storage'. There are still several unknown factors in FMDs design issues such as: sediment trap rates, patterns and flow regimes in the upstream of the dam, number of bottom outlets, and SB dimensions (height, length, width), depending on flood hydrograph and water level. The features of FMDs are drawn in Fig. 1 based on different points of view such as hydraulic design, reservoir sediment management, ecosystem and clogging of bottom outlets (Kantoush and Sumi, 2010).

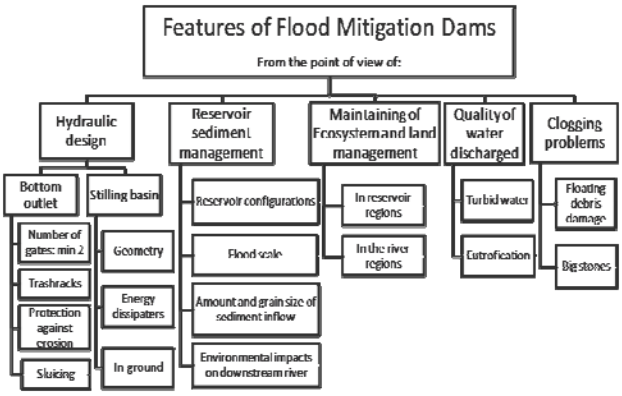

Fig. 1 Features of designing and operating of flood mitigation dams (Kantoush and Sumi, 2010)

1.2 Current FMDs Classification

Dams designed only for the purpose of flood control have different definitions and classifications. In USA they are called "Dry Dam", in Europe "Flood Retention Basin", in Japan "In stream Flood Control Dam", in other countries "Flood Mitigation Dam". Several definitions for the same hydraulic structure are given in different countries and languages whose frequently leads to legal disputes and misunderstandings between planners, engineers, politicians and people. Additionally, the absence of a universal definition and classification scheme for FMD leads to confusion about the status of individual structures and their functions. A classification scheme for FMD is therefore timely and urgently required to assist communication. Scholz and Sadowski (2009) proposed a conceptual classification model based on 141 sustainable flood retention basins (SFRB) including 75 diverse wetland systems in the River Rhine Valley, Baden, Germany. Six SFRB types were defined based on the expert judgment of engineers, scientists and environmentalists. The German flood retention basin guidelines (ATV-DVWK 2001) distinguish between passive and automated, and small, medium and large sized flood retention basins. In Germany the complete design and therefore the design flood discharges (DFQ) and flood water levels (FWL) are depending on the classification of the basins in the four classes very small, small, medium and large basins. The classification according to (DIN 19700-12/2004) takes into account the height of the dams and the reservoir volume. Eighty flood retention basins contribute significantly towards minimizing flood hazard especially in small watersheds in the land of Styria in the republic of Austria. Basins have been classified as small, medium and large according to capacities range from 5,000 m3 to 1,650,000 m^3, the dam heights are between 2.0 m and 24.5. The classification for flood retention basins according to mentioned code is given in (Fischer and Haselsteiner, 2008). Flood retention basins may also be either online or offline with respect to the local stream. Finally, the type of outlet is occasionally used as a classification criterion. Sumi (2008) has classified FMD based on outlet arrangement: 1) installing regulating gates in bottom outlets or not and 2) securing continuity of the river through these outlets or not. Fig. 2 shows the relationship between gross storage capacity and dam height of FMDs in Japan, Switzerland (Orden dam) and USA.

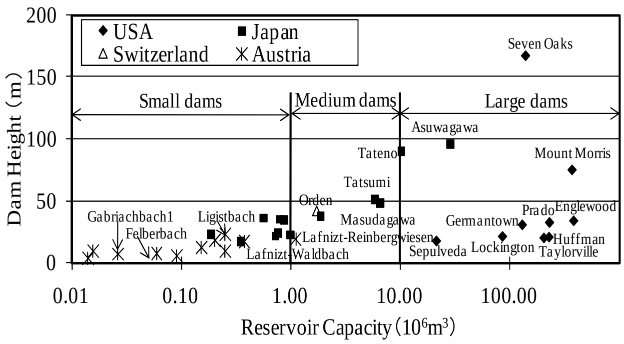

Fig. 2 Gross storage capacity and dam height of FMD (Sumi, 2008)

Because of geographical conditions, there is large difference between dams. Reservoir capacities to dam height of dams in USA are very large since they constructed in mild river slope and wide valley. Recently, relatively large dams for flood mitigation for urban areas have been planned and constructed. Masudagawa dam is one of them.

1.3 Objectives and Targets of this research

This paper deals with three main objectives, firstly the paper summarized field investigations for several flood mitigation structures in Styrian province (Austria) and comparison between Austrian and Japanese experiences, from several points of view such as dam structural and hydraulic design, reservoir sediment management, maintaining of ecosystem and land management in reservoir area, clogging problems of bottom outlets. Secondly Masudagawa FMD well introduced as a considerable case study in Japan to highlight its design strengths and drawbacks. Finally a new concept for SB downstream of FMD presented, named In-ground Stilling Basin (In-ground SB), then, by considering the new concept of SB and applying the Katakam and Rama's approach the new updated design for SB downstream of Masudagawa FMD proposed.

2. Field Investigation in Austria

2.1 Key parameters

Table 1 summarizes and characterizes all relevant key classification variables for FMDs in Japan and Austria, these key points mainly involved: rainfall;

Table 1 Classification and comparison of Flood Mitigation Dams in Austria and Japan

Item	Austria	Japan
Names of field investigation flood mitigation basin and dams	12 dams (Bärndorfbach, Dobelbach, Felberbach, Gabriachbach1 & 2, Labuchbach, Lafnizt-Reinbergwiesen, Lafnizt-Waldbach, Ligistbach, Sauhalt-bach, Stullneggbach, Gamlizbach)	8 dams (Sotomasuzwe, Rentaki, Kawachi, Matsuo, Sagatani, Ootouge, Sasakura, Takaono)
Dam Height (min-max)	5.8-23.2 m	17-37.7 m
Dam Length (min-max)	84-241 m	63.6-169 m
Gross Capacity (min-max)	14,000-1,100,000 m^3	186,000-6,500,000 m^3
Catchment area	0.8-162 km^2	5.5- 16.8 km^2
Dam arrangement in river basin	Distributed set of dams	Concentrated dam
Mean Annual Rainfall	865 mm/yr	1700 mm/yr
Utilization of reservoir area	Playground, habitat	Playground
Fish passages	Well design (Stepped ladder with natural sun light)	Under development
Screen system design	Bar pitches are designed by guideline	Under development
Design Flood frequency	Return period is 30-50 years	Return period is 80-100 years
Outlet Arrangement	Only one with bypass outlet for emergency	Usually two bottom outlet
Gate Operation	With gate (Automatic and Fixed opening)	Usually gateless
Stilling basin design	In-ground stilling basin and hydraulic jump	Hydraulic jump with end sill
Construction material	Earth fill with concrete outlet sections	Mainly concrete for gravity dams
Landscape planning	Well match with nature	Under development
River and basin bed gradient	Mild slope	Steep slope
Sediment load	Medium sediment yield	High sediment yield
Reservoir sedimentation	Less deposition	Less deposition

dam height, dam length; dam arrangement-concentrated or distributed; construction material, fish passage; screen system; basin and channel connectivity; design flood frequency; outlet arrangement; gate operation; catchment size; stilling basin design; and landscape planning and aesthetic. In the republic of Austria, Styrian government has actively constructed FMD from 1960s. More than 100 dams are located at small tributaries nearby city of GRAZ and mountain regions. In 1992, an interesting guideline for planning, designing and operation of FMD which explains engineering, economical and ecological aspects is published. The examined Styrian basins capacities range from 14,000 m3 to 1,100,000 m^3, the dam heights are between 5.8 m and 23.2 m, and they were all earth fill dam combined with concrete outlets.

While the Japanese Flood mitigation dam heights are between 17m to 37.7 m from concrete, the reservoir volume is ranging between 186,000-6,500,000 m^3. During our visit, we have discussed several unique points in Styrian case studies which will be very much valuable to improve performances of FMDs.

2.2 Unique points of Styrian flood mitigation dams

2.2.1 Bottom outlet design

Based on the guideline, bottom outlets are all gated. They are classified into (a) fixed small gate opening, (b) closed gate with small gate opening section, and (c) circular small diameter with automatic gate as shown in Fig. 3. All gates are designed large enough for maintenance.

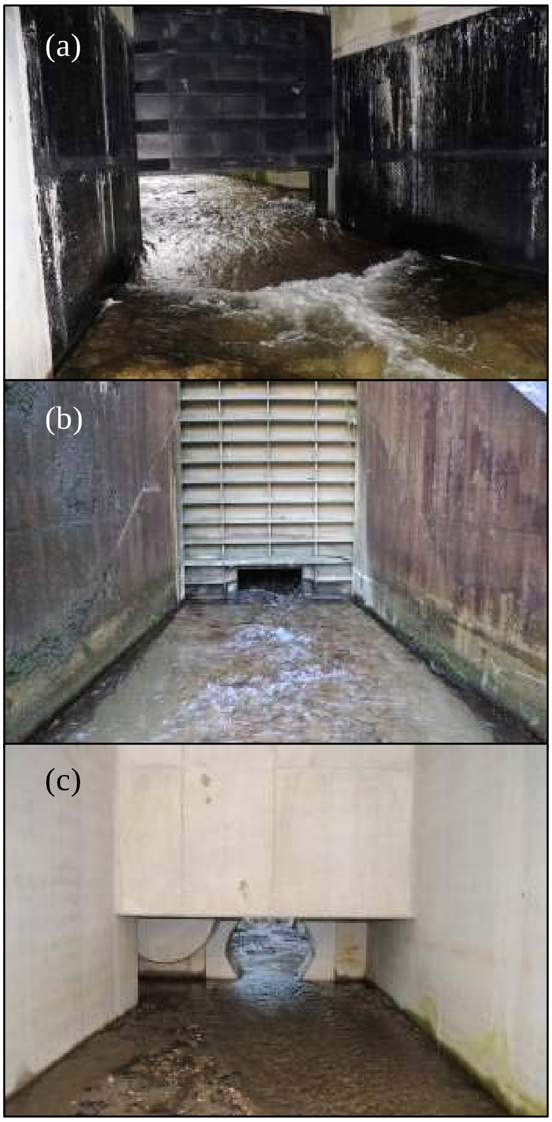

Fig. 3 Bottom outlet design: (a) Lafinizt-Waldbach, (b) Ligistbach and (c) Labuchbach

2.2.2 Safeguard for clogging of bottom outlet

Preventing from clogging by floating woods or big stones, all bottom outlets are covered by screens. These bar pitches are ranging from 15 to 50 cm based on design discharge of bottom outlets as Fig. 4. These screens are installed at not only inlet level but also on top of the bottom outlets to maintain enough discharge for safeguard Fig. 5. Periodical cleaning or screen design modification is requested because unexpected water storage is occurred by sediment and tree leaves trapping.

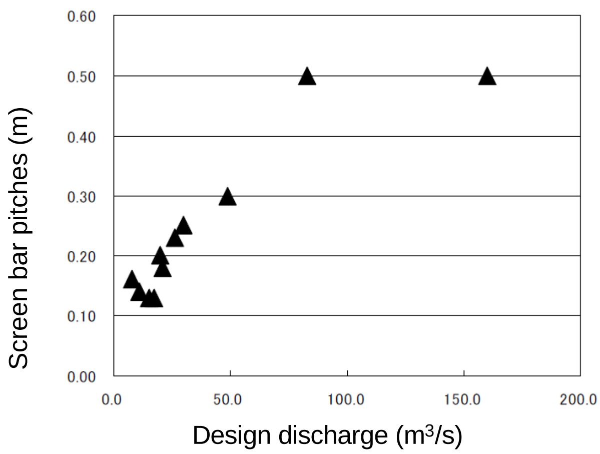

Fig. 4 Screen bar pitches based on design discharge of bottom outlets

Fig. 5 screens installed at the inlet of bottom outlet

Fig. 6 Natural fish passages in bottom outlet approach channel equipped by stones and sunlight

2.2.3 Fish passage

Bottom outlets are also designed for fish passage. Big stones or stepped pools are used to create natural stream in the channel by reducing velocity. Natural sunlight is also introducing to the channel by mesh opening at both upstream and downstream sides Fig. 6.

2.2.4 Reservoir area design

Total landscape design in reservoir area is well discussed with local communities and experts. Biotopes are designed in reservoir area for river restoration Fig. 7. In a reservoir, swimming pool is created for recreational use.

Fig. 7 Reservoir area and biotopes on the right side

2.3 Future Challenges for FMD in Worldwide

Recent flood events in Austria and Japan have shown the need for improved flood mitigation (retention) dams along the rivers. Therefore, several further research works is needed to update planning, designing and operating of flood retention dams. The FMD individualized and characterized for three future challenges parts have to be studied, reservoir area and the inlet, outlets and gate operation, and stilling basin with downstream reach of the dam.

2.3.1 In upstream reservoir and the dam inlet

During the flood discharge retardation, the characteristics of sediment (sand and gravel) outflow rate are changeable and unknown compared with the normal stage. The degree of change varies according to flood control plans, inflow sediment properties, and scale of the flood, so dams must be studied individually. Moreover, the development of a prediction and an optimum management measure of sedimentation in flood mitigation dams should be investigated.

2.3.2 Outlets and gate operation

As measures to mitigate changes of sediment transport properties, the geometry of the outlet works and stilling basins should be further studied in order to smooth the fish and sediment passages at the end of the flood period. The most effective approach is to accept variability of the reservoir water level less frequently within a range that satisfies flood control plans. By expanding the cross-section of outlet works installed on the elevation of riverbeds, it is possible to raise the reservoir level less frequently. But, in Japan, the peak cut rate of flood at dam site is generally large, so in order to achieve a flood control plan, it is necessary to make the outlet works section small when the reservoir water level is raised. The measure that is considered at this time is to install large outlet works for sediment discharge and separate small outlet works for flood control, and switch over from the former to the latter during flood control. To rationalize equipment and simplify its operation during a flood, at normal times, a large cross-section ensures the movement of sediment, stream, and aquatic life. But for flood periods, discharge equipment that permits the operation of gates to reduce the flow section, thereby controlling the flood discharge, should be developed. In that sense, automatic gate in Styrian examples are one of possible solutions for small discharge.

2.3.3 Stilling basin and downstream reaches

To improve current design method of outlets and stilling basins effective dissipation of energy, optimal design of stilling basin leading to optimal geometry is required. The main question is what are the optimal SB configuration and upstream conditions to maximize the energy dissipation, fish passage and minimize the cost? An optimal stilling basin geometry with acceptable flood risk therefore requires a holistic approach, addressing the flow parameters, design flood, upstream water level in the reservoir, dissipation energy, rivers, ecology and flood inundation as well as the human and socio-economic issues of planning, development and design.

3. In-ground SB concept

Despite of extensive studies on hydraulic jump in SB (Hager et al., 1986; Ohtsu and Yasuda, 19991; Sumi and Nakanishi, 1991; Moosa et al., 2003), a few research investigated the hydraulic jump within In-ground SB.The classical SB consists of prismatic, rectangular and nearly horizontal basin which is designed by implementing classical hydraulic jump approach. This kind of SB needs a relatively high downstream tail-water depth to ensure transition from supercritical to subcritical flow and reduce the erosion at the downstream river bed. By combining sudden enlargement and abrupt drop, the non-prismatic type of SB is created similar to a pool downstream of FMD as shown in Fig. 8. This type of SB can simplify sediment and fish transports where the SB bed is covered by large rocks and boulders naturally or artificially.

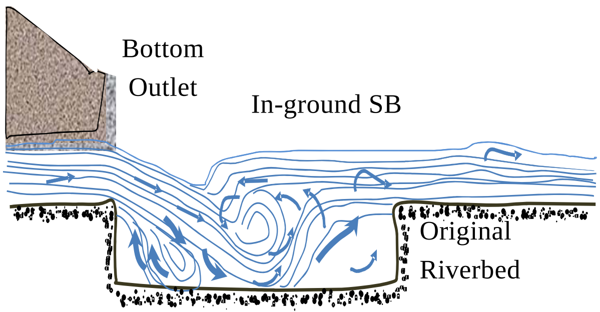

Fig. 8 The schematic view of In-ground SB downstream of FMD

3.1 Definition of Main Parameters

When drops is combined with an enlargement, the typical hydraulic phenomena of each measure overlap, reciprocally influencing each other, and produce hydraulic jumps whose overall characteristics are very complicated (Ferreri, 2002). An experimental research has started at Disaster Prevention Research Institute (DPRI) of Kyoto University, aiming to study on the flow pattern of hydraulic jump in the In-ground SB. Fig. 9 shows the schematic side and plan views of the constructed model and the main hydraulic parameters involved in this study. Energy loss (H_L)

in the In-ground SB in clear water phase may depends on parameters such as: outlet velocity at the bottom outlet (U_0), width of outlet (b), height of outlet (h_0), step depth (s), width of SB (B), length of SB (L), sequent depth (h_2), end-sill height (D), water density (ρ_w) and gravity acceleration (g):

$$H_L = f(U_0, b, h_0, s, \mathrm{B}, L, h_2, D, \rho_w, g) \quad (1)$$

Thus, the relative energy loss (HL/H1+s) may be written as a function of the following dimensionless parameters:

$$\frac{H_L}{H_1+s} = f(F_1, y, \gamma, \beta, S, \alpha, \delta) \quad (2)$$

where H1 and F1 are respectively total energy and Froude number at the face of bottom outlet to the SB, y is the ratio of sequent depth to the height of outlet (h_2/h_0), γ is the ratio of outlet width to the outlet height (b/h_0), β is the expansion ratio (B/b), S is the drop number or in other word ratio of step depth to the bottom outlet height (s/h_0), α is the aspect ratio of SB (B/L), and δ is the relative end-sill height (D/B). Moreover, the sequent depth (h_2) can be defined as in Eq. (3) where h_c is the critical water depth over the end-sill (Fr =1).

$$h_2 = s + D + h_c \quad (3)$$

3.2 Katakam and Rama's approach

The most similar research to our In-ground SB concept was carried out by Katakam and Rama (1988). Equation 4 was proposed by them to calculate the ratio of sequent depth to the height of outlet:

$$y = \frac{2F_1^2\left(y-\frac{1}{\beta}\right)}{\beta\left\{y^2-\left[(S+1)^2-\left(\frac{\beta-1}{\beta}\right)\right]\right\}} \quad (4)$$

Furthermore, Equation 5 was proposed to calculate the relative energy loss in the In-ground SB. The output of this equation could be one of the reliable criteria to found the optimal design of SB.

$$\frac{H_L}{H_1+s} = 1 - \left[\left(y + \frac{F_1^2}{2y^2\beta^2}\right)\Big/\left(1 + S + \frac{F_1^2}{2}\right)\right] \quad (5)$$

3.3 Masudagawa FMD and SB

Masudagawa FMD was completed in 2007, Japan. This dam is designed with probable flow rate of 100 years return period (Q_{peak} of flood = 640 m3/sec) at the Masuda River. Two gateless bottom outlet ($h_0$3.4×b4.4×2) and overflow spillways are installed. For energy dissipation, a conventional hydraulic jump type SB with an end-sill (D =3 m)

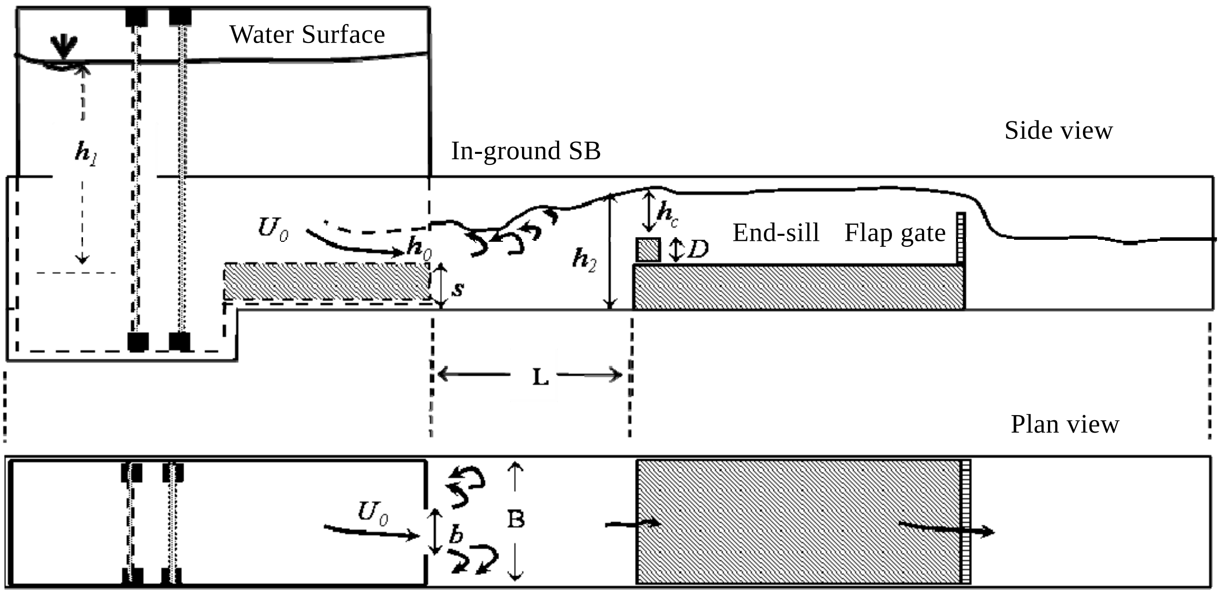

Fig. 9 the schematic side and plan views of the constructed model was designed where two slits are installed for self-sediment flushing from the SB as shown in Fig. 10. Design of Masudagawa SB is very close to the presented In-ground SB concept; because the bed level of SB in Masudagawa FMD is located 4 m lower than the level of its bottom outlet where a pool below this FMD is formed. But, there are three main differences between Masudagawa SB design and In-ground SB concept: first, the bottom outlet of Masudagawa FMD is connected to SB by a ramp (not abrupt drop).

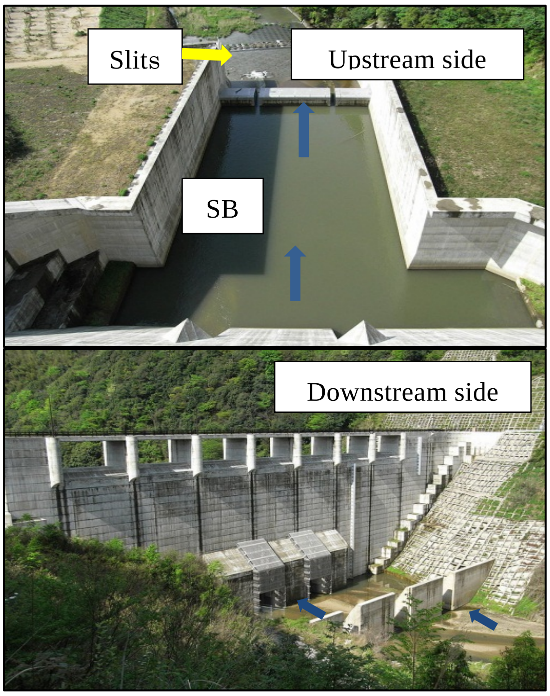

Fig. 10 Bottom outlet and SB of Masudagawa FMD.

Second, there is an end-sill at the downstream end of Masudagawa SB while in the In-ground SB concept intends to eliminate this end-sill. Third, the original river bed elevation at the downstream area of In-ground SB concept would level with its bottom outlet, in contrast to Masudagawa SB design. This is noteworthy to mention that, the width of SB was designed according to the width of the downstream river channel (B=30 m). Detail design of Masudagawa FMD is shown in Fig. 11.

3.4 Results and Discussion

In this section, the new design (re-design) for Masudagawa SB is presented by implementing the Katakam and Rama's approach. The re-design of SB was conducted by considering flood peak of 100 years return period (Q_{peak} of flood=640 m3/sec) passed through one bottom outlet and not two bottom outlet as the original one. Several scenarios are investigated in this study including different geometries of SB and various outlet dimensions for four flood discharge return periods 35, 50, 75 and 100 years. To re-design of SB, Equation 4 was used to calculate the ratio of sequent depth (h_2) to the bottom outlet height (h_0). Then, by substituting the sequent depth (h_2) in Equation 3, the end-sill height (D) was obtained.

The relative energy loss predicted by Equation 5 and the end-sill height (D) are two key criteria for assessing the design.

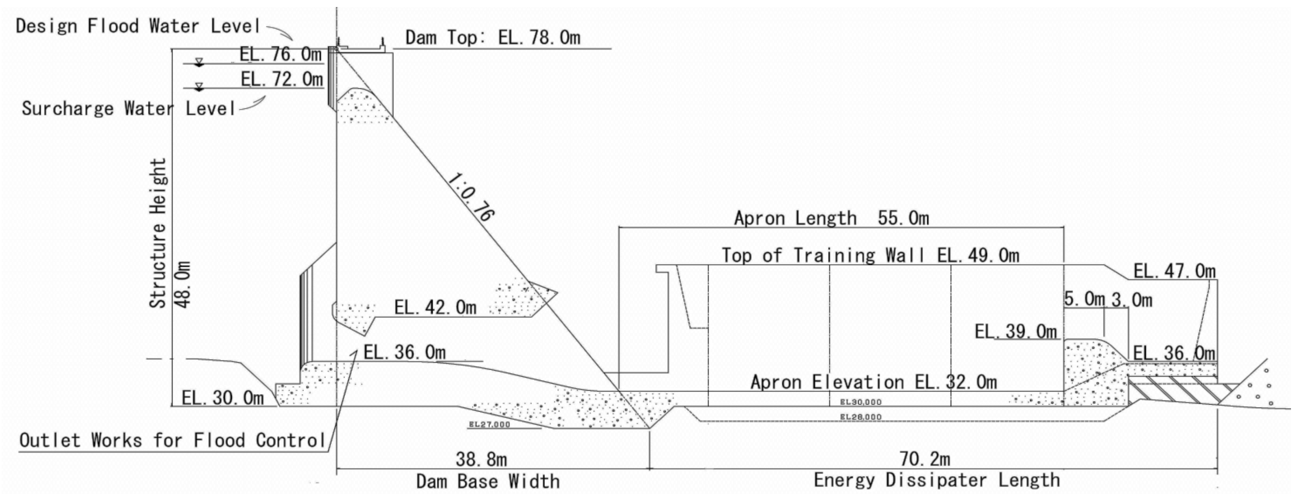

Fig. 11 Detail design of Masudagawa FMD

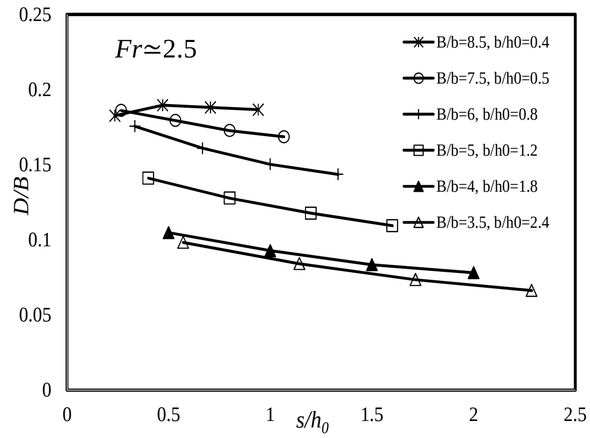

Fig. 12 Variation of drop number (s/h_0) versus the relative end-sill height (D/B) for different geometry of SB and different bottom outlet dimensions

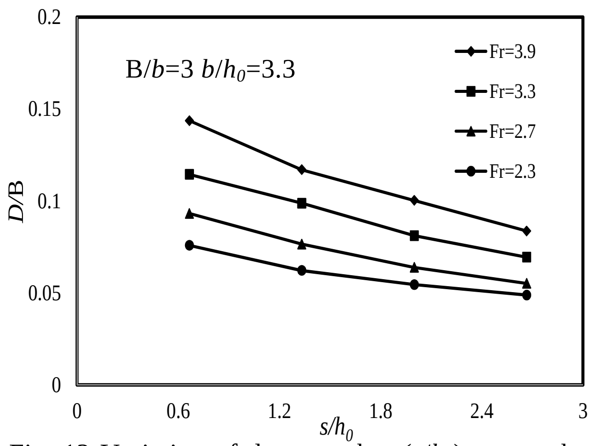

Fig. 13 Variation of drop number (s/h_0) versus the relative energy loss for different geometry of SB and different bottom outlet dimensions.

Fig. 12 shows the variation of drop number (s/h_0) versus the relative end-sill height (D/B), for different geometry of SB. As illustrated in Fig. 12, for a given geometry of SB and specific dimension of bottom outlet, by increasing the drop number (s/h_0) the relative end-sill height (D/B) decreased. In other words, increasing the step depth (s) allows reducing the end-sill height and consequently facilitates the fish migration.

By contrast, the greater drop number (s/h_0) would slightly reduce dissipation of energy in the SB which it could be neglected. The values of relative energy loss (REL) in In-ground SB concept were almost same for all scenarios which its average was equal to 55%. For a given drop number (s/h_0) in Fig. 12, the lowest relative end-sill height (D/B) occurred when the width of bottom outlet (b) is greater than the height of bottom outlet (h_0), horizontal rectangular shape, $b/h_0>1$.

In other side, when the width of bottom outlet (b) is smaller than height (h_0), the relative energy loss was increased, vertical rectangular shape, $b/h_0<1$. Therefore, it is necessary to find the optimal step depth (s) in order to satisfy both conditions of smaller end-sill height (D) and more dissipation of energy (REL) within SB. One practical solution could be equipping SB apron with rocks and boulders to create greater dissipation of energy, while simultaneously increasing the drop number (s/h_0) and increasing the bottom outlet width (b) to reduce the end-sill height (D). Table 2 shows the comparison between Masudagawa SB design with its re-design conducted according to Katakam and Rama's approach. As can be seen in Table 2, the relative energy loss in In-ground SB is 2.5 times larger than the original SB of Masudagawa FMD, and the end-sill height (D) is slightly decreased. Hence, the In-ground SB concept could have more advantages than other types of SB.

Fig. 13 shows the variation of drop number (s/h_0) versus the relative end-sill height (D/B), for different flood return period (in other words different Froude number) when the geometry of In-ground SB and dimensions of bottom outlet are constant. As can be seen in this figure, for a given drop number (s/h_0), the longer end-sill height is needed for greater Froude number.

Table 2 Comparison between Masudagawa SB design and re-design proposed in this study

Cases	SB width (B)	Bottom outlet dimensions	Step depth (s)	End-sill height (D)	Relative energy loss (REL)
Masudagawa FMD	30 m	[$h_0$3.4×b4.4 m]×2	Ramp 4 m	3 m	18%
Re-design In-ground SB	30 m	[$h_0$3.5×b8.5 m]×1	Abrupt 6 m	2.2 m	46%

Evidently, the flood discharge design, or put differently, flood return period has a key role in design criteria how shorter flood return period could ensure the smaller end-sill height (*D*).

As mentioned above, the Katakam and Rama's approach maybe is the only research that considered the In-ground SB concept. However, the proposed equations cannot directly be used for design purpose, mainly because no attempt was made to predict the jump length. One of the other drawbacks of Katakam and Rama's approach is using the narrow range of database to develop their empirical equations. Especially the effect of geometry of SB (step depth, width of SB) on flow pattern field was not well considered.

3.5 Conclusions and future challenges

The new concept of SB has been proposed in this paper, which it was analogous to a pool below the FMD and is named In-ground SB. This type of SB involved sudden expansion and abrupt drop simultaneously. Katakam and Rama's approach is used to re-design of Masudagawa SB. Increasing the drop number ($s/h0$) and installing the wider bottom outlet (horizontal rectangular shape, $b/h_0>1$), positively reduce the end-sill height (*D*). Re-design of Masaudagawa FMD according to the In-ground SB concept led to 2.5 times more energy dissipation and 25% reduction of the end-sill height (*D*). Similarly, flood return period could be one of the main design criteria so that short term flood return period may reduce the end-sill height (*D*).

Taking into account the eco-friendly features of In-ground SB and unknown factors in this concept, further study is needed to propose new design guidelines for SBs. Current experimental research at DPRI aiming to evaluate several new ideas as following: a) Identifying the effect of wide range of bottom outlet and SB dimensions on flow pattern within In-ground SB. b) Installing some separate piers (cylindrical baffles) instead of end-sill to eliminate the obstacle against fish and sediment passage. c) Considering additional outlets above the main bottom outlet to create waterfall into the SB to break the hydraulic jump and dissipate energy of flow. d) Increasing the roughness of SB apron and SB training walls.

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河川環境に適合した洪水調節専用流水型ダムの水理設計

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要　旨

近年，都市域においてゲリラ豪雨の発生が顕著である。このような洪水対策として，常用洪水吐を河床部標高に有し，洪水時に一時的に貯留するだけの洪水調節専用ダム（以下，流水型ダム）の検討事例が増加している。流水型ダムの最大の特徴は，洪水吐きを通じて流砂および生態系の連続性，特に魚類の遡上・降下の連続性を図ることにより，河川環境に対するインパクトを極力小さくすることができることである。本稿では，このような流水型ダムの設計上の課題，世界における分類，さらに日本と同様な規模の施設を数多く有するオーストリアの事例について比較検討を行った。これら施設の現地調査により，今後の設計を改善するための示唆に富む知見が得られた。最後に，河川環境に対する適合性を高めるために，ダム直下を潜り跳水式とした新しい減勢工形式について，その考え方と水理設計上の課題について検討を行った。

キーワード：流水型ダム，洪水調節専用ダム，減勢工，洪水吐，環境適合設計