May 9-12
Kyoto-Japan
2017

2nd International Workshop on
Sediment Bypass Tunnels

Case analysis of sediment bypass tunnels（Switzerland, Taiwan, Japan）

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Abstract

This research collected and analyzed the specifications of 15 sediment bypass tunnels in order to assist in the systematizing of planning and design methods for sediment bypass tunnels. First we classified the sediment bypass tunnels by the purpose of the dam and the main purpose of the sediment bypass tunnel, and then we analyzed each for design discharge, tunnel structure, and target grain size of sedimentation. We found that the approach to setting of the design discharge changed according to the classification of the sediment bypass tunnels and that the efficiency of the design discharge may be impacted by regional characteristics. Based on the analysis results for factors such as tunnel structure and target grain size of sedimentation, we have listed points to consider in the planning and design of sediment bypass tunnels in the future.

Keywords: sediment bypass tunnel, design discharge, target grain size of sedimentation

1 Introduction

A sediment bypass tunnel is an effective engineering structure offering permanent results as a measure for reservoir sedimentation. However, cases of execution worldwide are few, and the planning and design used in each case differ by the situation with any particular dam. In order to plan and design more efficient and economical sediment bypass tunnels, systemization of the tunnel planning and design procedure is essential. Considering these background factors, this research presents in Table 1 the specifications of sediment bypass tunnels in Switzerland, Taiwan and Japan, where collection of data was possible, and by applying analysis to the contents of this table we have defined points to consider in the planning and design of sediment bypass tunnels.

2 Classification of sediment bypass tunnels

Of the 15 dams listed in Table 1, two dams in Japan lacked of sufficient information (Nunobiki Gohonmatsu and Tachigahata at Karasuhara Reservoir). For the remaining 13 dams, we focused on the “purpose of the dam” and the “main purpose of the sediment bypass tunnel”, which can be considered to have a large impact on setting of the design discharge, in order to make a classification of sediment bypass tunnels.

Table 1: Specifications for actual sediment bypass tunnels

Country /Region	Name of Dam	Dam Specifications							Bypass Tunnel Specifications																	Note
							Flood Control Plan*3				Tunnel Specifications				Design Discharge						Intake Specifications					
		Completion Year (Dam structure)	Purpose /Shape *1	Dam Height (m)	Catchment Area (km^{2})	Dam Design Flood Flow*2 (m^{3}/s)	Planned Maximum Flow (m^{3}/s)	Planned Maximum Release Flow (m^{3}/s)	Completion Year (SBT)	Purpose	Cross Section Shape	Length (m)	Longitudinal Slope	Presence of Curved Section	Design Discharge (m^{3}/s)	Specific Discharge (m^{3}/s/km^{2})	Probability Scale*4 (flow probability	Tunnel Maximum Flow/Planned Maximum Release	Design Velocity (m/s)	Workdays In Year (/year)	Intake Position	Flow Control	Reservoir operation at time of sediment discharge	Outlet Section Energy dissipator	Target Grain Size of sedimentation (mm)	
Japan	Nunobiki Gohonmatsu	1900	W/G	33.3	10.7	—	—	—	1908	Sediment discharge/Water utilization bypass	Hood-type 2.9m×2.9m	258	1.3 (1/75)	No	39	3.64	—	—	—	—	Reservoir upstream end	Branch from diversion dam	Hold water level (inflow = outflow)	No	—	
	Tachigahata	1905	W/G	33.3	18.9	—	—	—	1905	Sediment discharge/Water utilization bypass	—	—	—	—	—	—	—	—	—	—	Reservoir upstream end	—	—	—	—	Karasuhara Reservoir
	Miwa	1959	F.N.P /G	69.1	311.1	1,200	1,200	500	2005	Sediment discharge	Horseshoe shape 2r=7.8m	4,308	1.0% (1/100)	Yes	300	0.96	1/4.3 year	60.0%	10.8	1 to 2 times	Reservoir midstream to upstream	Controls surplus flow with a spillway *5	Flood control	Yes	Wash load	
	Asahi	1978	P/A	86.1	39.2	1,200	1,200*	1,200*	1998	Sediment discharge	Hood-type 3.80m×3.80m	2,350	2.9% (1/35)	Yes	140	3.57	1/0.5 year	11.7%	11.4	16 times	Reservoir upstream end	Flow control by orifice structure	Hold water level (inflow = outflow)	No	dm: 50 d90: 300	
	Koshibu	1969	F.A.P /A	105.0	288.0	2,160	1,500	500	2016	Sediment discharge (Substitutes flood control function with sediment bypass structure)	Horseshoe shape 4r=7.95m	3,999	2.0% (1/50)	Yes	370	1.28	1/6.2 year	74.0% (Currently) 100.0% (Planned)	15.8	—	Reservoir upstream end	Executes flow control equal to planned flood control by combining overflow crest with orifice *5*6	Flood control	Yes	dm: 10 d90: 70	Started operation in 2016
	Matsukawa	1975	F.N.W /G	84.3	60.0	560	440	200	2016	Sediment discharge (Substitutes flood control function with sediment bypass structure)	Hood-type 5.20m×5.20m	1,417	4.0% (1/25)	Yes	200	3.33	1/25.1 year	100.0%	15.0	—	Reservoir upstream end	Executes flow control equal to planned flood control by spillway *5	Flood control	Yes	dm: 10 d90: 60	In operational test
Switzerland	Egschi	1949	P/G	45.0	109.0	464	464*	464*	1976	Sediment discharge	Circle D=2.80m	360	2.6% (1/38.5)	Yes	50	0.46	—	10.8%	10	10 days	Reservoir upstream end	Gate present (Full open/Full close)	Hold water level (inflow = outflow)	No	dm: 100 d90: 300	
	Palagnedra	1952	P/G	72.0	138.0	2,380	2,380*	2,380*	1977	Sediment discharge	Horseshoe shape 6.20m×6.13m	1,760	2.0% (1/50)	Yes	250	1.81	—	10.5%	13	2 to 5 days	Reservoir upstream end	Gate present (Full open/Full close)	Hold water level (inflow = outflow)	No	dm: 74 d90: 160	
	Pfaffensprung	1922	P/A	32.0	30.0	530	530*	530*	1922	Sediment discharge	Horseshoe shape 4.70m×4.85m	282	3.0% (1/33.3)	Yes	220	7.33	—	41.5%	14	Approx. 200 days	Reservoir upstream end	Gate present (Full open/Full close)	Hold water level (inflow = outflow)	No	dm: 250 d90: 2,700	
	Rempen	1924	P/G	32.0	82.7	257	257*	257*	1986	Sediment discharge	Horseshoe shape 3.45m×3.42m	450	4.0% (1/25)	Yes	80	0.97	—	31.1	12	1 to 5 days	Reservoir upstream end	Gate present (Full open/Full close)	Hold water level (inflow = outflow)	—	dm: 60 d90: 200	
	Runcahez	1961	P/G	33.0	50.0	343	343*	343*	1962	Sediment discharge	Hood-type 3.80m×4.50m	572	1.4% (1/71.4)	Yes	110	2.20	—	32.1	9	4 days	Reservoir upstream end	Gate present (Full open/Full close)	Hold water level (inflow = outflow)	No	dm: 230 d90: 500	
	Solis	1986	P/A	61.0	900.0	1,000	1,000*	1,000*	2012	Sediment discharge	Hood-type 4.40m×4.68m	968	1.9% (1/52.6)	Yes	170	0.19	1/5 year	17.0	11	1 to 10 days	Reservoir midstream	Gate present (Full open/Full close)	Lower water level (Promotes sediment movement)	—	dm: 60 d90: 150	
Taiwan	Shihmen	1964	F.W.A. P.R/R	133.0	763.4	13,800	14,500	14,149	2012	Sediment discharge	—	—	—	—	380	0.50	1 to 2/1 year	2.7%	—	—	Directly upstream of dam	Controls flow with Intake gate	Flood control	—	dm: 0.004 to 0.008 d90: 0.05	Modification of release pipe for existing power generation
									In planning	Strengthen release capability, sediment discharge	Hood-type 8.00m×9.00m	3,685	2.86% (1/34.9)	No	600	0.79	1 to 2/1 year	4.2%	10 to 20	—	Reservoir midstream	Controls flow with radial gate	Flood control	No	dm: 0.04 (Density flow)	
	Nanhua	1994	F.W /E	87.5	108.3	4,332	5,379	5,500	2018	Strengthen release capability, sediment discharge	Horseshoe shape 9.50m×9.50m	1,287	1.85% (1/54.1)	No	1,000	9.23	1/5 year	18.2%	24.5	—	Reservoir midstream	Controls flow with radial gate	Flood control	Yes	dm: 0.02 (Density flow)	Under construction
	Tsengwen	1973	F.W.A. P/E	133.0	481.0	9,470	12,430	12,966	2017	Strengthen release capability, sediment discharge	Horseshoe shape 9.50m×9.50m	1,235	5.32% (1/18.8)	No	995	2.07	1/2 to 3 years	7.7%	18 to 30	—	Directly upstream of dam	Controls flow with radial gate	Flood control	Yes	dm: 0.005 (Density flow)	Under construction

*1) Purpose〔F : Flood control、N : Normal function of the river water、A : Agriculture、W : Water supply、P : Power generation、R : Recreation〕
Shape 〔G : Concrete gravity dam、A : Concrete arch dam、E : Earth dam、R : Rock-fill dam〕
*2) The design flood flow for the Swiss dams is arranged by the total for the release capability of the spillway and bottom outlet.
*3) Water utilization dams are arranged with "Design flood flow = Planned maximum flow = Planned maximum release flow."
*4) The probability value for designed flow of dams in Japan is calculated using the "Hydrology Statistics Utility."
Furthermore, the probability distribution with highest suitability (SLSC becomes minimum) was used. (Miwa Dam: Gev. Asahi Dame: LogP3. Koshibu Dam: LN2PM. Matsukawa Dam: Exp.)
*5) Full open/Full close gate present
*6) Releases shortfall amount through the dam conduit with current operation.

We applied the following two classifications under “purpose of the dam”. The dams in Japan and Taiwan, which were all multipurpose dams except for one case (Asahi) were classified as type A, and the Swiss dams and Asahi, which were dams for water utilization (power generation), were classified as type B.

- Type A: multipurpose dams that perform both flood control and water utilization functions
- Type B: water utilization dams that perform only the water utilization function

We then classified the “main purpose of the sediment bypass tunnel” to the following two types. Dams in Japan and Switzerland were classified as Type I because the main purpose was sediment discharge. In comparison, many dams in Taiwan have insufficient release capability for large floods, which have occurred frequently in recent years, so the sediment bypass tunnels are planned and constructed with the main purpose being not only to discharge sediment but also to boost release capability, and these are classified as Type II.

- Type I: sediment discharge as a main purpose
- Type II: sediment discharge + boosting release capability as main purposes

Based on the above criteria, each of the 13 dams has then been classified as being in one of three groups, “A-I,” “A-II” or “B-I,” as shown in Table 2.

Table 2: Results of classifying actual sediment bypass tunnels

Country /Region	Name of Dam	Purpose of Dam (A: Multipurpose. B: Water utilization)	Main purpose of sediment bypass tunnel (I: Sediment discharge. II: Sediment discharge + water release)	Sediment Bypass Tunnel Classification
Japan	Miwa	A	Ⅰ	A-Ⅰ
	Asahi	B	Ⅰ	B-Ⅰ
	Koshibu	A	Ⅰ	A-Ⅰ
	Matsukawa	A	Ⅰ	A-Ⅰ
Switzerland	Egschi	B	Ⅰ	B-Ⅰ
	Palagnedra	B	Ⅰ	B-Ⅰ
	Pfaffensprung	B	Ⅰ	B-Ⅰ
	Rempen	B	Ⅰ	B-Ⅰ
	Runcahez	B	Ⅰ	B-Ⅰ
	Solis	B	Ⅰ	B-Ⅰ
Taiwan	Shihmen	A	Ⅱ	A-Ⅱ
	Nanhua	A	Ⅱ	A-Ⅱ
	Tsengwen	A	Ⅱ	A-Ⅱ

While the sample size at this time is small, trends by country or region can be seen according to the usage purpose of each dam and the sediment bypass tunnel, such that the dams in Japan were all in the A-I group, except for the Asahi dam, all of the dams in Taiwan belonged to the A-II group, and all of the dams in Switzerland were in the B-I group, showing that the sediment bypass tunnel classification was uniform according to each country or region.

In the next chapter, we use the classified three groups to analyze design discharge, tunnel structure and target granule diameter, and to organize the respective characteristics.

3 Analysis of characteristics based on sediment bypass tunnel classifications

3.1 Design discharge

First we analyzed design discharge as a way of understanding how much sediment discharge capability was inherent in the sediment bypass tunnel of each dam.

Figure 1 presents the relationship between the design discharge and the completion year for each sediment bypass tunnel. This confirms the historic growth of sediment bypass tunnels. In order to examine geographic trends, we also plotted the relationship of catchment area to design discharge (specific discharge) in Figure 2. We assessed the design discharge (specific discharge) using a probability scale for dam flow (Figure 3).

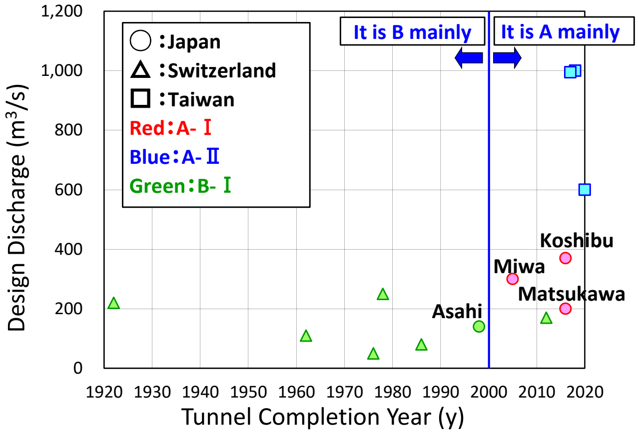

Figure 1: Relationship between sediment bypass tunnel completion year and design discharge

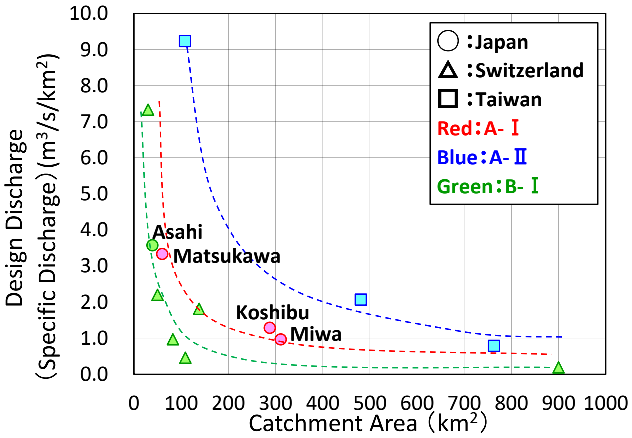

Figure 2: Relationship between catchment area and design discharge (specific discharge)

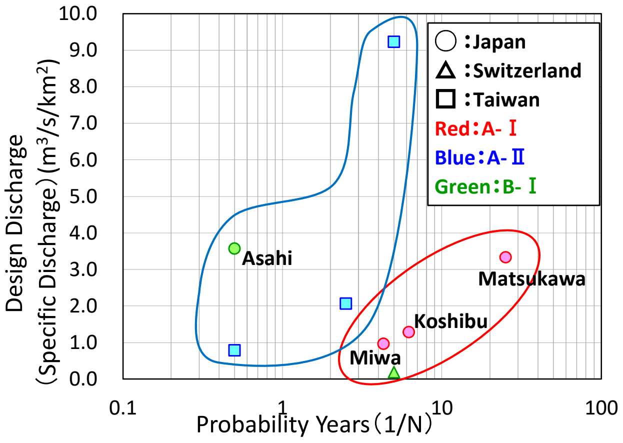

Figure 3: Relationship between probability years and design discharge (specific discharge)

The trends and characteristics derived from these figures are

- Many Type B dams have an old construction year, and Type A dams have been increasing since the year 2000.
- In conjunction with the shift from Type B to A, the design discharge has also become larger (= large scale sediment bypass tunnels have been built).
- Design discharge (specific discharge) for a given catchment area may differ according to the type of sediment bypass tunnel or may reflect local geographic characteristics, which is not clear due to the small sample size of this analysis. However, because the tunnels in A-II group (Taiwan dams) were aimed to increase release capacity as well as sediment transport, if local geographic characteristics can be assumed to be similar among the groups, the target flow of A-II group is expected to be about the sum of the target flow of A-I group (three dams in Japan) and release capacity.
- The probability occurrence of design discharge varied from 1/0.5 year to 1/25 years among the dams, which is partially associated with region. The relationship between probability occurrence and design discharge suggests an effect of the local geographic characteristic on the design discharge.

3.2 Tunnel structure

In order to understand the approximate scale and range of conditions that applied at construction of past structures, we focused on structural aspects of each tunnel and analyzed tunnel diameter, tunnel longitudinal slope, and intake structure. Figure 4 shows the relationship between design discharge and tunnel diameter. Figure 5 shows the relationship between tunnel longitudinal slope and designed velocity. In addition, Table 3 presents information on intake structure obtained from each sediment bypass tunnel.

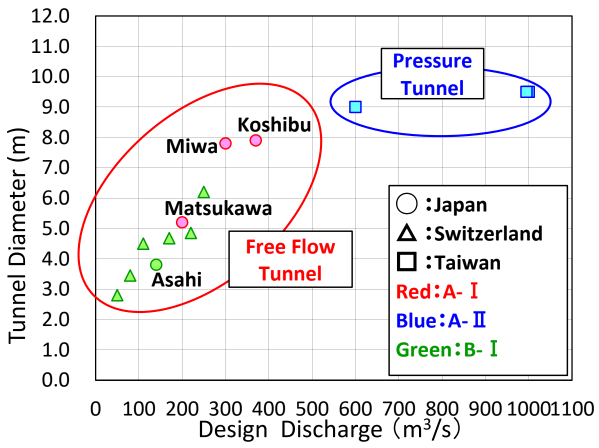

Figure 4: Relationship between design discharge and tunnel diameter

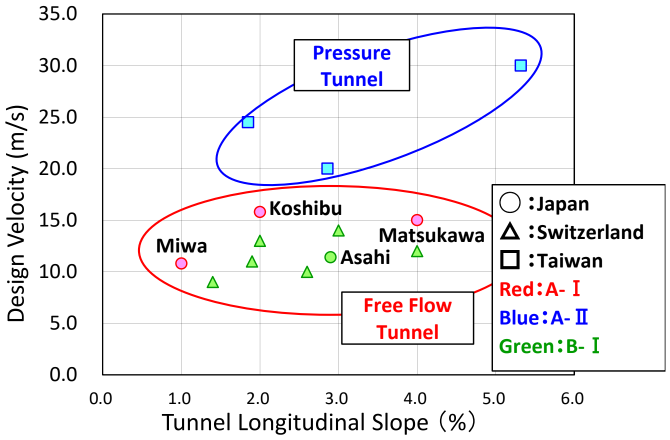

Figure 5: Relationship between tunnel longitudinal slope and designed velocity

The trends and characteristics derived from these figures are

- Tunnel longitudinal slope was within a range of approximately 1% to 5%. From the perspective of sediment discharge efficiency, hydraulic stability, and sediment abrasion countermeasure, longitudinal slope of this range is the standard.
- With Type A dams, a gate for flow control is established at the tunnel intake.
- The intake position is usually in the vicinity of the reservoir upstream end, but can be constructed near the dam structure for a group that performs sediment discharge with density current for the main purpose of increasing the release capability, such as with the A-II group. In such a case, a pressure tunnel is used and the designed velocity becomes exceptionally high. Thus, the approach for establishing the intake position will greatly differ between free versus pressure flow tunnel.

- As in the case of the Solis, it is possible to place the intake position near the dam structure as a measure to lower the reservoir water level at time of sediment discharge. This method allows shortening of the tunnel extension and raising of the sediment discharge efficiency, but needs rainfall forecasts in the operation, and should assess the risk of failures in the recovering of reservoir water level.
- When we checked the horizontal alignment of the tunnel using a plane drawing of each dam, we confirmed a curved section in all but the Nunobiki Gohonmatsu in Japan and the three dams in Taiwan. The curvature radius of the tunnel curved section in Palagnedra in Switzerland was the smallest.

Table 3: Intake structure in actual sediment bypass tunnels

Country /Region	Name of Dam	Sediment Bypass Tunnel Classification	Intake Structure			Note
			Intake Position	Flow Control	Reservoir operation at time of sediment discharge	
Japan	Miwa	A- I	Reservoir upstream end	Controls surplus flow with a spillway [Full open/Full close gate present]	Flood control	
	Asahi	B- I	Reservoir upstream end	Flow control by orifice structure	Hold water level (inflow = outflow)	
	Koshibu	A- I	Reservoir upstream end	Executes flow control equal to planned flood control by combining overflow crest with orifice [Full open/Full close gate present]	Flood control	(Releases shortfall amount through the dam conduit with current operation.)
	Matsukawa	A- I	Reservoir upstream end	Executes flow control equal to planned flood control by spillway [Full open/Full close gate present]	Flood control	
Switzerland	Egschi	B- I	Reservoir upstream end	Gate present (Full open/Full close)	Hold water level (inflow = outflow)	
	Palagnedra	B- I	Reservoir upstream end	Gate present (Full open/Full close)	Hold water level (inflow = outflow)	
	Pfaffensprung	B- I	Reservoir upstream end	Gate present (Full open/Full close)	Hold water level (inflow = outflow)	
	Rempen	B- I	Reservoir upstream end	Gate present (Full open/Full close)	Hold water level (inflow = outflow)	
	Runcahez	B- I	Reservoir upstream end	Gate present (Full open/Full close)	Hold water level (inflow = outflow)	
	Solis	B- I	Reservoir midstream	Gate present (Full open/Full close)	Lower water level (Promotes sediment movement)	
Taiwan	Shihmen	A- II	Reservoir midstream	Controls flow with radial gate	Flood control	
	Nanhua	A- II	Reservoir midstream	Controls flow with radial gate	Flood control	
	Tsengwen	A- II	Directly upstream of dam	Controls flow with radial gate	Flood control	

3.3 Target grain size of sedimentation

Lastly, we analyzed the target granule diameter of sediment bypass tunnel. Figure 6 shows the relationship between target grain size of sedimentation and the design velocity. Figure 7 shows the relationship between target grain size of sedimentation and the catchment area.

The trends and characteristics derived from these figures are

- The target grain size of sedimentation was finer for Type A than B dams. With Type A dams (especially the A-II group), to target the finest granule diameter a regulating function (gate function) must be installed. In comparison, when focusing only on sediment discharge, as with Type B dams, coarse granule diameter can be the target, but in this case abrasion countermeasures are necessary and longer tunnels are unsuitable. Abrasion countermeasures are implemented with dams that target coarse granule sediment (Table 4).

- The target granule diameter tended to be smaller for the dams with larger catchments, with the exception of Solis, which performs a water level lowering operation at time of sediment discharge. In Solis relatively coarse sediment may be efficiently discharge through the water level drawdown operation.

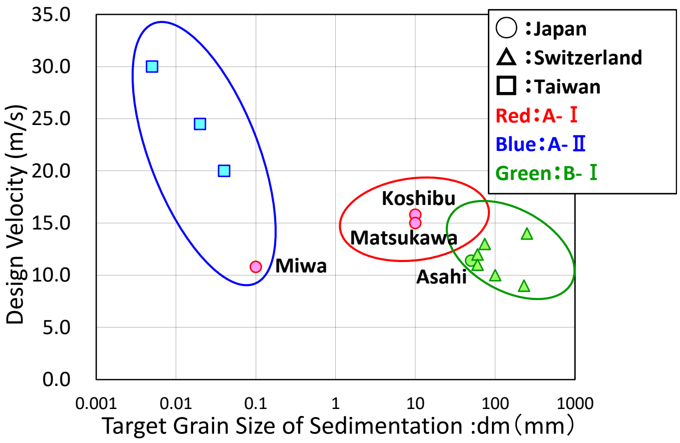

Figure 6: Relationship between target grain size of sedimentation (dm) and design velocity

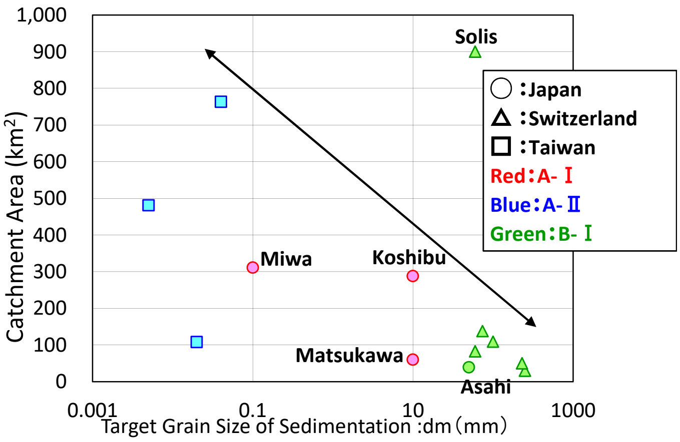

Figure 7: Relationship between target grain size of sedimentation (dm) and catchment area

Table 4: Examples of abrasion countermeasures for sediment bypass tunnels

Examples	
Palagnedra	Originally there was no lining, but a steel lining was later placed at the acceleration section of the entrance
Pfaffensprung	Reinforced with 0.5m thick granite blocks.
Rempen	Protected with basalt concrete.
Runcahez	Local experiment confirmed high abrasion resistance of polymer concrete and steel fiber concrete.

4 Conclusions

This research analyzed 13 dams with sediment bypass tunnel in Switzerland, Taiwan and Japan, in terms of planning and design of tunnel along with flow and sediment conditions of individual dams. We classified the sediment bypass tunnels into three groups according to the "purpose of the dam" and the "main purpose of the sediment bypass tunnel." Based on the classification, we additionally analyzed factors such as design discharge and target grain size of sedimentation. Our analyses provided some key points to consider in the planning and design of sediment bypass tunnels.

The results of case analysis are valuable and basic data for planning and design of efficient sediment bypass tunnels and for establishing planning and design systems as well.

Because examples of sediment bypass tunnels are still not many, continuous efforts are needed to collect information and enlarge the data set as much as possible, which is an important step in improving the accuracy and reliability of the analysis results.

Acknowledgement

The content of this paper includes the topics discussed in the Symposium on Management of Dam Sediments, and much advice was received from the committee members. Dr. Christian Auel and Dr. Fong-Zuo Lee kindly helped us collecting the additional data. We express our appreciation to gratitude here.

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