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RESERVOIR SEDIMENTATION MANAGEMENT WITH BYPASS TUNNELS IN JAPAN

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Abstract: This paper focuses on sediment bypass tunnels for reservoir sedimentation management. Worldwide, number of constructed sediment bypass tunnels is very small because of topographical, hydrological or economical conditions. Bypass tunnels, however, have many advantages such as they can be constructed even at existing dams and prevent a loss of stored reservoir water caused by the lowering of the reservoir water level. They are also considered to have a relatively small impact on environment downstream because inflow discharge can pass through tunnels very naturally during flood times.

In Japan, sediment bypass tunnels of the Nunobiki Dam completed in 1908, and of the Asahi Dam completed in 1995, have been successfully introduced to realize sustainable reservoir management. Sediment bypasses of the Miwa Dam, Koshibu Dam and Matsukawa Dam on the Tenryu River are expected to be next leading projects in Japan. In this paper, we discuss design criteria and lessons learned from existing facilities, and future challenges of planning projects. The focus is on tunnel geometries such as diameter, slope, bottom shape etc., and an abrasion-resistance design of the tunnel invert.

Keywords: Reservoir sedimentation, Sediment bypass, Diversion tunnel, Abrasion damage

1 INTRODUCTION

Reservoir sedimentation is surely proceeding at dams in the world. Current gross storage capacity in the world is 6,000 km_3 with 45,000 large dams (higher than 15m, ICOLD), and total storage loss and annual sedimentation rate are about 570km^3 (12%) and 31km^3-year (0.52%-year) respectively. If additional new development projects are not considered, total capacity will be decreased even to less than half by 2100.

In many countries, various countermeasures have been implemented to decrease sediment accumulation and loss of storage capacity. They are (1) Reduce sediment inflow by erosion control and upstream sediment trapping, (2) Route sediments by sediment sluicing, off stream reservoirs, sediment bypass, and venting of turbid density currents, and (3) Sediment removal by hydraulic flushing, hydraulic dredging or dry excavation. Sediment bypassing and flushing are considered to be as permanent remedial measures.

Worldwide, limited numbers of sediment bypass tunnels have been constructed because of topographical, hydrological or economical conditions. Bypass tunnels, however, have many advantages such as they can be constructed even at existing dams and prevent a loss of stored reservoir water caused by the lowering of the reservoir water level. They are also considered to have a relatively small impact on the environment downstream because inflow discharge can be passed through tunnels very naturally during flood time.

In Switzerland, five bypass tunnels have been constructed and proved an effective means to counter reservoir sedimentation (Visher *et al.*, 1997). It is found that problems may arise with tunnel abrasion, particularly if the sediment has a considerable quartzite component.

In Japan, sediment bypass tunnels at Nunobiki Dam, completed in 1908, and at Asahi Dam, completed in 1995, have been successfully introduced to realize sustainable reservoir management. Sediment bypasses at Miwa Dam have been almost completed, and ones at Matsukawa Dam and Koshibu Dam are under construction and planning. For the purpose of designing these bypass systems, hydraulic characteristics of tunnel and diversion weir have been studied (Ando *et al*., 1994, Kashiwai *et al*., 1997, Harada *et al*., 1997).

In this paper, we discuss design criteria and lessons learned from existing facilities, and future challenges of planning projects. We focus on tunnel geometries such as diameter, slope, bottom shape etc., and an abrasion-resistance design of the tunnel invert.

2 RESERVOIR SEDIMENTASTION AND ITS MANAGEMENT IN JAPAN

In Japan, approximately 2,730 dams over 15 m in height have been constructed for water resource development or flood control purposes, but the total reservoir storage capacity is only up to 23 billion m^3. The sediment yields of the Japanese rivers are relatively high due to the topographical, geological and hydrological conditions and this has consequently caused sedimentation problems to those reservoirs.

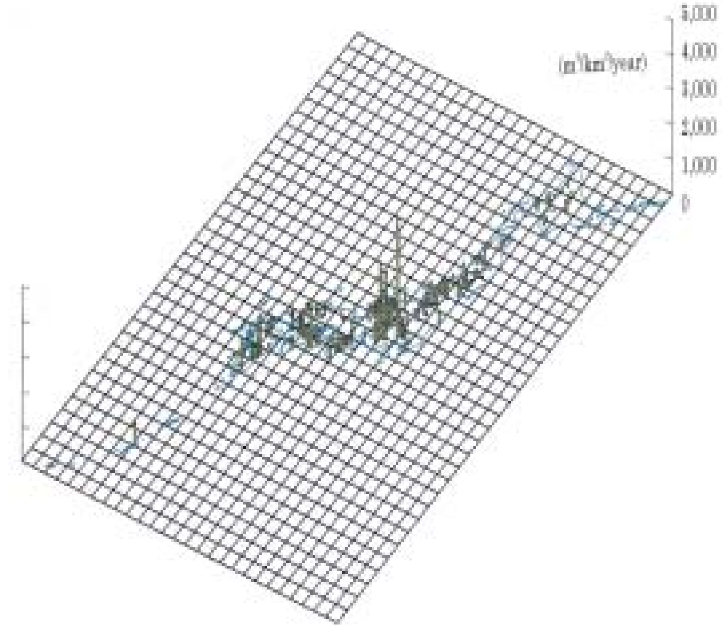

Fig. 1 Specific Sedimentation Volume in Japanese Reservoirs

Based on the annual research conducted for 877 reservoir which have gross storage capacities of over one million m^3, specific sediment yields in these catchment areas are ranging from several hundred to several thousand m^3·(km^{-2}·yr^{-1}), and the specific sedimentation volume becomes higher in central high mountainous regions along the Median Tectonic Line and the Itoigawa-Shizuoka Tectonic Line as shown in Fig. 1.

Fig. 2 shows the relationship between reservoir sedimentation rates, e.g. sedimentation volumes to gross storage capacities, and reservoir ages. Concerning the dams constructed before World War II (ended in 1945) and used for more than 50 years, sedimentation proceeded in the range from 60% to beyond 80 % in some hydroelectric reservoirs. For the dams constructed approximately between 1950 and 1960 and used for more than 30 years, sedimentation rates beyond 40 % were found in many cases. Following this period, meanwhile, large numbers of multi-purpose dams gradually came to be constructed. This type of dams does not have high sedimentation rates compared to the hydroelectric type, though, the rates of 20% to beyond 40 % were found in some dams. Since maintaining storage capacities for water supply and flood control is much more important, the influence of sedimentation in those multi-purpose reservoirs becomes large.

Annual storage capacity losses in those reservoirs are ranging approximately from 1.0% to 0.1 %. In other words, it is noted that the reservoir lives are approximately 100 to 1,000 years. Reservoir sedimentation problems are represented by such as the siltation of intake facilities, aggradations of upstream river bed, reservoir storage capacity loss and, sometimes, lack of sufficient sediment supply to downstream which may cause river bed degradation or coastal erosion.

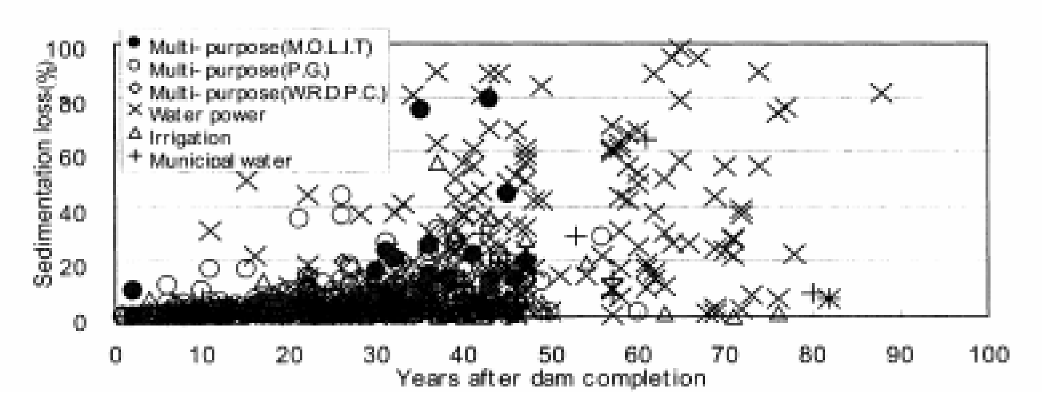

Fig. 2 Relationship Between Reservoir Sedimentation Rates and Years after Dam Completion

Sediment management in reservoirs is largely classified into the three approaches: (1) to reduce sediment inflow to reservoirs. (2) to route sediment inflow so as not to accumulate in reservoirs, and (3) to remove sediment accumulated in reservoirs. In Japan, check dams to reduce sediment yield from catchment area, sediment bypassing, draw down sediment flushing, excavating and dreging are selected for management measures.

3 SEDIMENT BYPASS TUNNELS IN JAPAN

In Japan, sediment bypass tunnels have been studied most exhaustively. Although this technique involves high cost caused by tunnel construction, there are many advantages such that it is applicable to existing dams; it does not involve drawdown of reservoir level and therefore no storage capacity loss; and it has relatively small impact on environment because sediment is discharged not so rapidly as sediment flushing which can be considered as the other countermeasure.

The subjects of designing sediment bypass tunnels are to secure the safety of sediment transport flow inside tunnels and to take countermeasures for abrasion damages on the channel bed surface. Among factors that significantly relate to these problems are grain size, tunnel's cross-sectional area, channel slope, and design velocity. Table1 shows examples of existing sediment bypass tunnels in Japan and Switzerland.

Table 1 Sediment Bypass Tunnels in Japan and Switzerland

No	Name of Dam	Country	Tunnel Completion	Tunnel Shape	Tunnel Cross Section (B×H(m))	Tunnel Length (m)	General Slope (%)	Design Discharge (m·s^{-1})	Design Velocity (m·s^{-1})	Operation Frequency
1	Nunobiki	Japan	1908	Hood	2.9×2.9	258	1.3	39	-	-
2	Asahi	Japan	1998	Hood	3.8×3.8	2,350	2.9	140	11.4	13 times·yr^{-1}
3	Miwa	Japan	2004	Horseshoe	$2r = 7.8$	4,300	1	300	10.8	-
4	Matsukawa	Japan	Under construction	Hood	5.2×5.2	1,417	4	200	15	-
5	Egshi	Switzerland	1976	Circular	$r = 2.8$	360	2.6	74	9	10d·yr^{-1}
6	Palagnedra	Switzerland	1974	Horseshoe	$2r = 6.2$	1,800	2	110	9	2d·yr^{-1}-5 d·yr^{-1}
7	Pfaffensprung	Switzerland	1922	Horseshoe	$A= 21.0\mathrm{m}^2$	280	3	220	10〜15	-200d·yr^{-1}
8	Rempen	Switzerland	1983	Horseshoe	3.5×3.3	450	4	80	〜14	1d·yr^{-1}-5d·yr^{-1}
9	Runcahez	Switzerland	1961	Horseshoe	3.8×4.5	572	1.4	110	9	4 d·yr^{-1}

3.1 Bypass Tunnel Examples In Japan

3.1.1 Example Nunobiki Dam

The municipal water supply reservoir Nunobiki Dam completed in 1900, the oldest gravity concrete dam in Japan, is located at Kobe city. The scheme is composed of a 33.3m high gravity concrete dam and 0.76 million m^3 gross storage volume reservoir with 9.8km^2 catchment area. The Rokko Mountains, its catchment area, is characterized by high sediment yield rate because of both surface geology of deep weathered granite and steep slopes. After completion of the project, reservoir sedimentation had extremely proceeded from the above reasons. In order to reduce inflow sediment to the reservoir, a sediment bypass system (comprised of a 3.0m high diversion weir and a 258m long bypass tunnel with a maximum discharging capacity of 39$m^3 \cdot s^{-1}$) is constructed in 1908, just 8 years after the dam completion. Fig. 3 shows the schematic diagram of the bypass system. The tunnel is designed to divert inflow discharge over 1.11 $m^3 \cdot s^{-1}$ and the effect of the system can be estimated as follows.

Daily sediment inflow in ca.100 yrs can be calculated by the following stream power equation (Ashida and Okumura 1977).

$$D = \alpha (A \cdot R \cdot I)^{\beta} \qquad (1)$$

where, D : sediment yield during a flood event(m^3), A : catchment area(km^2), R : daily rainfall(mm), I : average riverbed slope in 200 m upstream from the calculating point, α , β : constants. All catchment area and the one downstream diversion weir are A_1=9.83km^2 and A_2=0.47km^2 respectively. Daily rainfall R is estimated by the historical records at the Kobe Ocean Meteorological Station from 1897 and riverbed slope is defined as I=0.044 by the geographical survey.

Since constant β is usually fixed as 2.0 (Ashida and Okumura 1977), constant α is inversely estimated as 6.0 by real accumulated sediment volumes in the reservoir measured in 1938, 1967, 1978 and 1990.

By using A_1 and A_2, mean annual sediment inflow before and after a sediment bypass completion is estimated ca.30,000 $m^3 \cdot yr^{-1}$and ca.1,500 $m^3 \cdot yr^{-1}$ respectively.

From the view point of sedimentation management, reservoir life has extended from ca.30 years to ca.500 years.

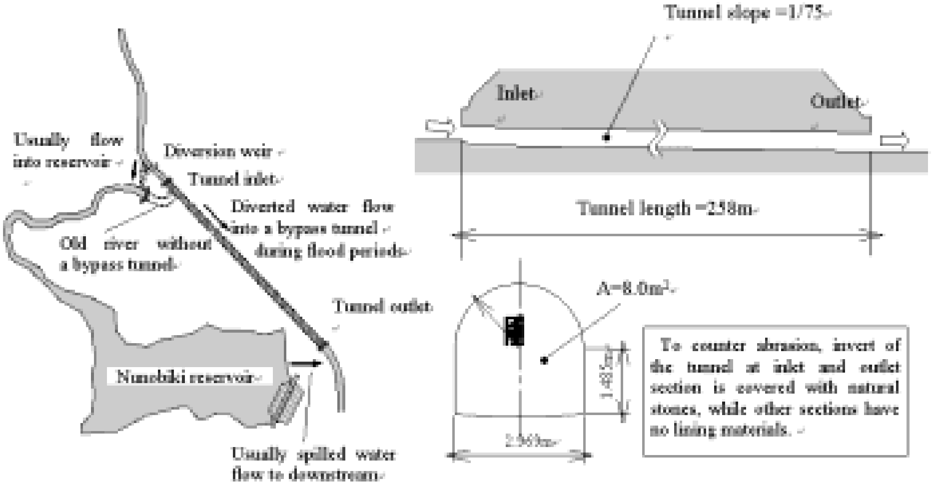

Fig. 3 Sediment Bypass Scheme at Nunobiki Dam

3.1.2 Example Asahi Dam

The lower regulating reservoir Asahi dam completed in 1978, located in the Shingu river system in Nara Prefecture, belongs to the Okuyoshino Power Plant (pure pumped-storage type, 1,206 MW) operated by the Kansai Electric Power Co. Inc. The lower regulating scheme is composed of a 86.1m high arch dam and 15.47million m^3 gross storage volume reservoir with 39.2km^2 catchment area.

Since completion of the dam, the prolonged turbidity problem has been getting noticeable due to the upstream condition changes by the collapse of mountain slopes and the devastation of forests caused by large-scale runoffs(Kataoka 2003). Moreover, because of the frequent typhoons in 1989 and 1990, the mean annual accumulated sediment volume from 1989 to 1995 also increased sharply to 85,000$m^3 \cdot yr^{-1}$ which is more than four times of that from 1978 and 1988.

Following the above view points, a sediment bypass system (comprised of a 13.5m high diversion weir and a 2,350m long bypass tunnel with a maximum discharging capacity of 140$m^3 \cdot s^{-1}$) was constructed in April 1998 to reduce the prolonged turbidity and reservoir sedimentation. Fig. 4 shows the schematic diagram of the bypass system.

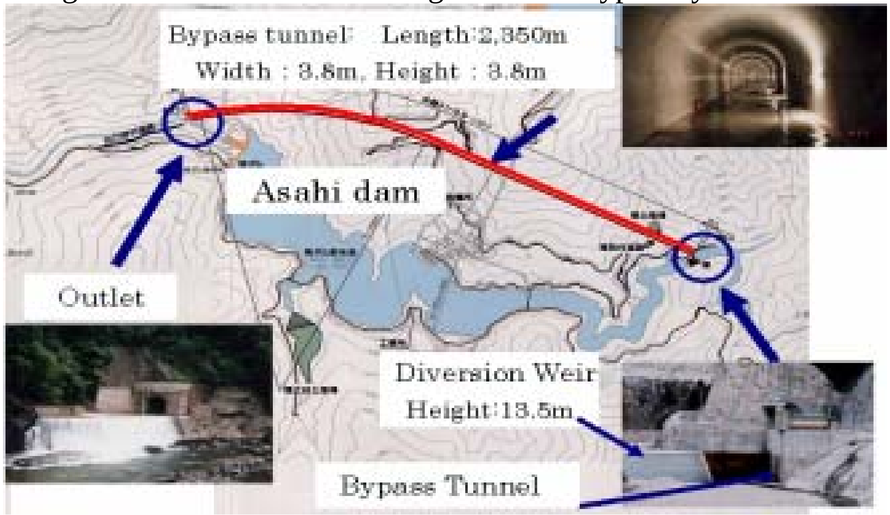

Fig. 4 Sediment Bypass Scheme at Asahi Dam

The bypass system was designed to flow both suspended load and bed load, and the design discharge, 140 $m^3 \cdot s^{-1}$, was determined considering a scale of one-year return period flood with a peak discharge of ca. 200 $m^3 \cdot s^{-1}$. The cross-section of the bypass tunnel was determined on the basis of uniform flow calculation, and it can release the maximum design discharge at a water depth of 80% of the tunnel height. Hood type cross section of the tunnel was selected from the viewpoint of economy and easy maintenance.

During the four years from 1998 to 2002, sediment bypassing was performed about 16 times a year and about 40 percentage of the annual run-off was diverted through the tunnel. It is found that bypass could have reduced both turbidity period and sediment inflow. It is estimated that 10% to 20% of the annual inflowing sediment is deposited in the reservoir, while the remaining 80% to 90% is bypassed downstream through the bypass system. Fig. 5 shows the effect on the reduction of reservoir sedimentation by the bypass tunnel.

From just after the tunnel operation, local abrasion damages was found on the tunnel invert. A total of 400m^3 of abrasion on all tunnel invert (area 9,000m^2) and an average abrasion depth of 45 mm, locally up to maximum 200mm, was found in 1998. From a study on the relationship between the mean abrasion depth and the estimated bypassed sediment from 1998 to 2001, it can be found that the abrasion quantity is almost proportional to the bypassed sediment volume.

Though these abrasion damages are within the range forecast at the design stage, locations where invert concrete of the tunnel with design strength of 36 N/mm^2 is seriously damaged are repaired during non-flood season.

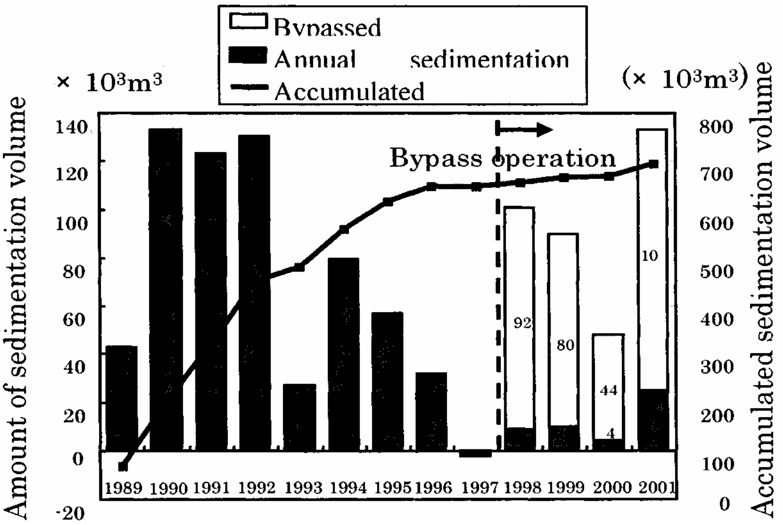

Fig. 5 Effect on the Reduction of Reservior Sedimentation by the Bypass Tunnel(Kataoka 2003)

3.1.3 Example Miwa dam

The multi-purpose reservoir Miwa Dam completed in 1959, located in the Tenryu river system in Nagano prefecture, is operated for the purpose of flood control, irrigation water supply and hydroelectric power generation by the Ministry of Land, Infrastructure and Transport. The scheme is composed of a 69m high gravity concrete dam and 29.95 million m^3 gross storage volume reservoir with 311 km^2 catchment area.

Since the dam was completed, extreme runoff events occurred in 1959, 1961, 1982 and 1983 causing serious disasters and sediment yield in the catchment river basin that resulted in quick increasing of reservoir sedimentation. Since 1966, gravel have been constantly removed by a maintenance plan and then approximately 5.32 million m^3 sediment have been dredged in 33 years up to 1998. If those gravel is not removed, the total sedimentation is approximately 19.47 million m^3, and estimated the mean annual sedimentation is 0.47 million $m^3 \cdot yr^{-1}$.

From the view point of the eternal reservoir sedimentation management, a sediment bypass system (comprised of a 20.5m high diversion weir and a 4,300m long bypass tunnel with a maximum discharging capacity of 300 $m^3 \cdot s^{-1}$) is completed in March 2004 to reduce sedimentation of the reservoir. Fig. 6 shows the schematic diagram of the bypass system.

Fig. 6 Sediment Bypass Scheme at Miwa Dam

This bypass system was designed to flow mainly wash load since about 3/4 of the sediment deposited in the reservoir is wash load smaller than 74 μm. According to the master plan of the redevelopment project, 685,000 m^3 of sediment including 525,000 m^3 of wash load, and 160,000 m^3 of bed load and suspended load will flow into the reservoir. The bypass tunnel will divert 399,000 m^3 of wash load and the remaining 126,000 m^3 will flow into the main reservoir. The bed load and the suspended load that flow in at an annual average of 160,000 m^3 are captured by the 15.0m sediment trap weir that has sedimentation capacity of 200,000m^3, then it is removed mechanically and transported for construction materials.

3.2 Bypass Tunnel Design Against Abrasion Damages

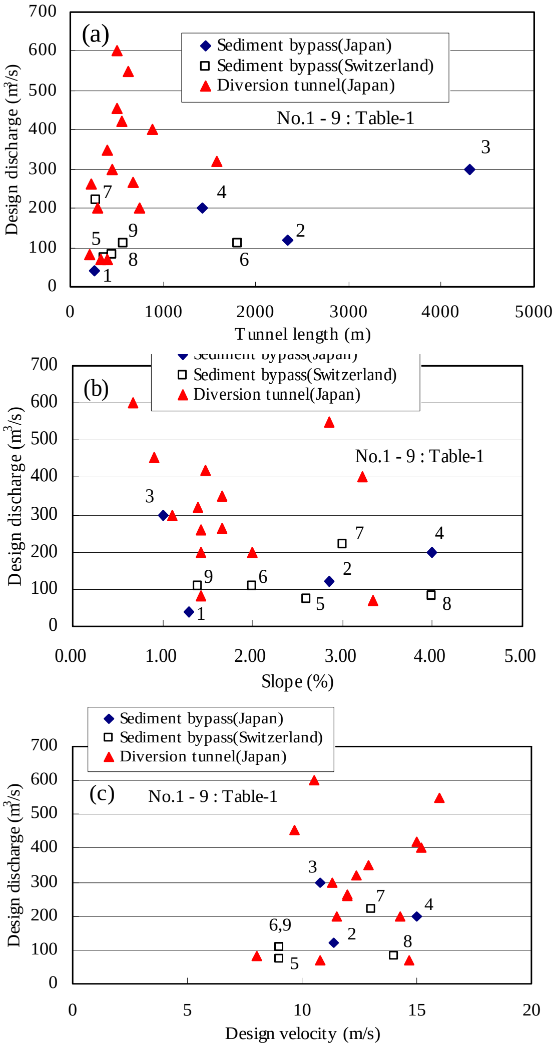

Fig. 7 Sediment bypass dimensions

Figs. 7 (a) -(c) shows relationship between tunnel length, bottom slope, design velocity and design discharge of bypass tunnels in Japan and Switzerland. Since up to now, sediment bypass examples are very limited, diversion tunnels in Japan are also plotted for comparison in the figure. Regarding tunnel length, some sediment bypasses are longer than 1,000 m since inlet of bypass tunnels should be located upstream reach of reservoirs, while almost diversion tunnels are shorter than 1,000 m. Design discharge is ranging up to 300 $m^3 \cdot s^{-1}$ for sediment bypasses and also up to 600 $m^3 \cdot s^{-1}$ for diversion tunnels. Since larger design discharge, e.g. larger tunnel cross section, and longer tunnel length make tunnel design harder, sufficient cost/benefit analysis is needed considering the maximum design flood that should be totally bypassed through the tunnel.

It should be also understood that careful design should be necessary if steeper bottom slope, e.g. higher velocity, and larger grain size will be expected. Regarding design velocity and slope, 10 $m^3 \cdot s^{-1}$ -15 $m^3 \cdot s^{-1}$ are expected in case of 3% - 4 %.

Generally, the main problem of bypass tunnels is abrasion along the invert (Visher *et al.*, 1997). In Switzerland, to counter abrasion, linings of steel or plates of granite, or even molten basalt have been used. Moreover, selected concretes such as micro-silicate concrete, roller-concrete, steel-fiber concrete, polymer-concrete and standard concrete(for reference) are tested. In Japan, several materials have been also tested in case of Asahi dam. These materials show better performances against abrasion damages than conventional concrete, while it will need more study to use them on wider areas because these works are very much expensive. In Japan, from the view points of initial construction cost and easy maintenance, selecting high strength concrete and preparing enough abrasion depth on top of necessary tunnel invert depth is recommended at the moment.

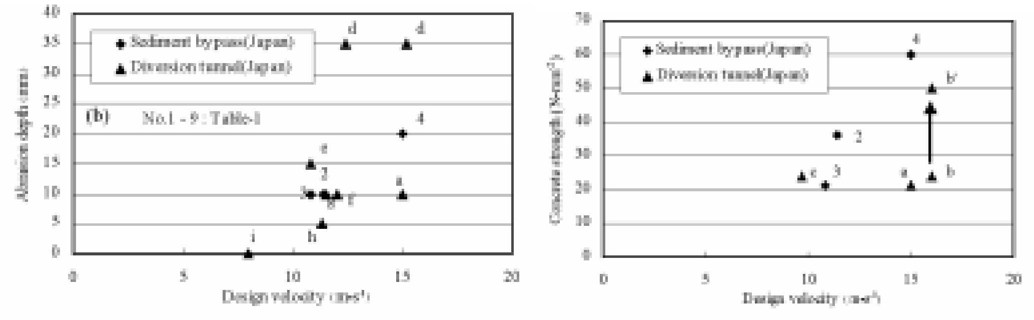

Fig. 8 Bypass Tunnel Design against Abrasion Damages

Figs. 8 (a) and (b) show concrete strength and abrasion depth designed for sediment bypasses and diversion tunnels in Japan. In case of design velocity higher than 10 $m^3 \cdot s^{-1}$, it can be found that concrete strength higher than 30 $N \cdot mm^{-2}$ and abrasion depth deeper than 10 mm-35 mm have been selected. Since necessary abrasion depth is, off course, depend on the interval of repairing works, more experiences for real operation and maintenance are needed.

4 CONCLUSION

The conclusions can be listed as follows:

Sediment bypass system in the Nunobiki dam and Asahi dam in Japan are contributing to sustain reservoir lives, and completion and realization of other projects are highly desired.

Data of existing sediment bypass tunnels in Japan and Switzerland are as follows: the tunnel lengths are between 250 m and 4,300 m; the section areas are between 10 m^2 and 60 m^2; the general bottom slopes are between 1 and 4%; the design discharges are between 40 and 300 $m^3 \cdot s^{-1}$; the design velocities are between 9 $m^3 \cdot s^{-1}$ and 15 $m^3 \cdot s^{-1}$.

The main problem of sediment bypass tunnels is abrasion along the invert. To counter abrasion, selecting high strength concrete and preparing enough abrasion depth on top of necessary tunnel invert depth are recommended from the view points of initial construction cost and easy maintenance.

In order to operate the sediment bypass system effectively, it is important to predict and to perform real-time monitoring not only the flow discharge but also the concentration of sediment in the inflowing water. Since Miwa dam has the flood control function, such kind of operational challenges is now under studying, and will be reported in the near future.

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