INTERNATIONAL SYMPOSIUM ON
DAMS FOR A CHANGING WORLD
-Need for Knowledge Transfer across the Generations & the World
Kyoto, Japan June 5, 2012

Sediment Replenishment on Floodplain Downstream of a Reservoir

Sumi, Tetsuya
University of Kyoto, Kyoto, Japan
sumi.tetsuya.2s@kyoto-u.ac.jp

Lee, Fong-Zuo, Lai, Jihn-Sung, Tan, Yih-Chi & Huang, Chen-Chia
National Taiwan University, Taipei City, Taiwan

ABSTRACT:

The annual mean loss of reservoir storage due to sedimentation has been higher than the increase of capacity by construction of new reservoirs in many countries around the world. The sustainable usage of the reservoir is always an important issue for reservoir long-term operation. By dredging or excavation, sediment deposits may be mechanically removed from reservoirs due to lack of low-level outlet or flushing facilities. The characteristics of deposits, available disposal site, reuse options and environmental criteria will affect the feasibility of sediment deposit removal. Recently, the replenishment technique has been implemented to prevent downstream river from bed degradation and increase suitable living habitat for aquatic animals downstream of the dam. The replenishment should be set before flood discharge released from reservoir. The released discharge and location of replenishment should be investigated before the operation. A physical model was constructed to investigate the flow and replenished cohesive sediment transport downstream of the Afterbay weir. In this research, the experimental results show that the flushing discharge does not dominate the flushing ratio of sediment replenishment volume. More important parameter of flushing ratio is the flushing duration. Besides, the affection duration of water quality is about 1 hour and the investigated suitable replenishment volume is also presented in this study.

Keywords: Flushing, reservoir sediment, replenishment

1. INTRODUCTIONS

When typhoon and heavy rainfall coming, the watershed possesses steep slope would lead to soil washout and land collapse. Artificial development would make soil be disturbed and increases frequencies of huge sediment be flushed. Taiwan is situated at a such geographical location with special climatic condition that brings to the island 3.6 typhoons per year on the annual average. These typhoons often result in flood disasters that can cause serious damage to properties and sometimes with severe casualties, especially after 1999 year Chi-Chi earthquake. Large sediment would be flush out due to collapses. However, Typhoons also bring heavy rainfall as a valuable water resource in Taiwan. The Shihmen reservoir acted as the primary and most important infrastructure of water resource development over the past forty years in northern Taiwan. As livelihood and industrial water needs are increasing, the water supply demand of the Shihmen reservoir is rising. The Shihmen reservoir has a natural drainage area of 762.4 km^2. It is formed by the Shihmen dam located at the upstream reach of the Dahan River and flows westward to the Taiwan Strait. A map of the watershed area of the Shihmen reservoir is presented in Fig. 1 (Lee et al., 2007). The Shihmen dam constructed in 1963 is a 133.1m high and 360m wide embankment dam with spillways, permanent river outlet, power plant intakes and flood diversion tunnels controlled by tailrace gates. The elevations of the spillway crest, permanent river outlet, power plant intakes and flood diversion tunnels are EL.235 m, EL.169.5m, EL.173m and EL.220m, respectively. The design capacity of the three spillways is 11,400m^3/s, the permanent river outlet is 34m^3/s, the power plant intake is 137.2m^3/s, and flood diversion tunnel is 2,400m^3/s. With a maximum water level of EL.245m, the reservoir pool is about 16.5km in length and forms a water surface area of 8.15km^2. The initial storage capacity was 30,912x 10^5 m^3, and the active storage was 25,188x 10^5 m^3. In 2010, the capacity of Shihmen reservoir remained 67% storage.

In 2004, Typhoon Aere attacked Taiwan and generated more than 973 mm rainfall within 4 days in the watershed of the Shihmen reservoir. Highly turbid inflows affected the water supply system seriously and the water supply suffered from a shortage for 14 days. Sediment concentration of the inflow water during

Typhoon Aere rose to 326,700 mg/L and this value was far-exceeded water treatment capacity which can only handle 6,000 ppm (Tan et al., 2009). Following, typhoons such as Typhoon Haitang (2004) and Typhoon Talim (2005) also brought high sediment concentration inflow into reservoir to cause serious deposition problem and water supply shortage. Therefore, the Water Resources Agency of government had established a temporary pumping station with capacity $3x10^5$ CMD (m^3/day) on the top of the Shihmen dam to divert near surface lower-turbidity water that the water treatment plant can accommodate people with clear water. Recently, The temporary pumping station was installed after Typhoon Aere(2004) and until now it also can be worked for emergency operating. In addition, due to serious sediment deposition problem from 2004 induced by Typhoon AERE, the stratified withdraw facility was built at dam site to avoid the lack of public water and the one of tunnel of power plant was designed to vent turbidity current. The stratified withdraw facility with three elevations (El. 220m, 228m, 236m) was finished at Dec. 2009. In order to implements the sediment flushing operation using existed and modified outlet structures, the feasibility study of Lake JhongJhuang engineering at downstream reach of Yuanshanyan water intake for backup water resources during Typhoon event was executed in following years.

Due to unique geological condition with extreme hydrological climate and lack of venting facilities in Shihmen reservoir, massive sediment would deposit in reservoir. Field survey showed the particle size in reservoir was small (Fig. 2) except backwater region. The sediment classified sand at delta and during dam site was silt and clay which diameter is less than 0.075 mm. Therefore, the fine sediment deposition which near dam site would reduce reservoir storage and affect intake operating period. In general, the excavation is adopted to deal with coarse material which located at upstream and dredging is adopted to deal with fine sediment which located after delta. But, the characteristics of deposits, available disposal site, reuse options and environmental criteria will affect the feasibility of sediment deposit removal. Based on transportation and treatment efficiency, these two treatments spend much money to move out sediment and drainage volume is limited.

Recently, the replenishment technique has been implemented to prevent downstream river from bed degradation and increase suitable living habitat for aquatic animals downstream of the dam. So, found out sediment movement phenomenon in reservoir and improved the occasion to desiltation were important. This study based on the literature review in Japan and Taiwan to investigate replenished efficiency and the effects of flushed sediment concentration.

Figure 1. Watershed area of Shihmen reservoir(Lee et al., 2007)

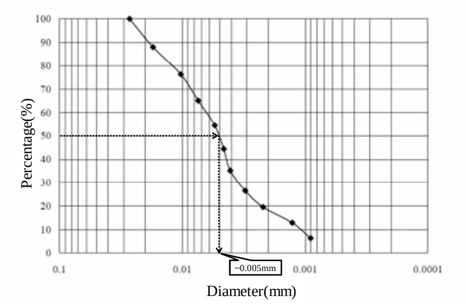

Figure 2. Sediment grain size diameter

2. EXPERIENCE IN JAPAN AND TAIWAN

In Japan, the replenishment technique had been implemented to prevent downstream river from bed degradation and increase suitable living habitat for aquatic organism at downstream of the dam. Okano et al. (2004) also started to study reservoir sedimentation management by coarse sediment replenishment below dams and summarized sediment replenished project in Japan. Such as Tenryu, Otakine, Abukuma, Ara, Oi, Naka, Kuzuryu, Yodo, Kanna, and Tone had been constructed by Ministry of Land, Infrastructure and Transport (MLIT). Seto et al. (2009) investigated replenished sediment effects on the downstream river of Yahagi dam. Sumi et al. (2009) produced appropriate grain size with less turbidity using sediment treatment system. Kantoush et al. (2010) analyzed the interaction of relative flow field and morphological evolution during replenishment experiments in Kizu River. Fig. 3 shows the field test of replenishment in Kizu River.

Figure 3. Evolution of sediment replenishment experiment in Kizu river[Kantoush et al. 2010]

Before flood was coming, the sediment had been constructed at the downstream of Nunome reservoir and after flood was passing, the replenished sediment was flushed to the sea. Such field test in Japan focused on coarse material that deposition in the reservoir and replenished at downstream for preventing bed degradation and creating suitable environment for aquatic livings. Furthermore, the replenishment strategy needed huge discharge to flush replenished sediment, therefore, replenished sediment always constructed before flood coming and implemented during wet season. In Japan, it is common to practice and remove accumulated coarse sediment by excavation and dredging in reservoir. Making effective use of the removed sediment possesses economic value and sediment replenishment method is one of new measures of sediment management. In this method, deposited sediment in reservoir can be periodically excavated and then transported to be placed temporarily downstream of the dam at floodplain. Replenished volume decided according to the sediment transport capacity of the channel and the environmental conditions.

In Taiwan, replenishment was implemented in Shihkang reservoir in 2009 (Central water resources bureau, 2009). It is the first time to test replenishment strategy in field of Taiwan. Shihkang reservoir was choose to test due to efficient water discharge and replenished environment. Fig. 4 shows the sketch of replenished arrangement around Shihkang reservoir. The excavation area located at upstream which area is provided with coarse material and replenished area located at 200m downstream reach of Shihkang dam. Total replenished volume is about $50*10^3 m^3$ and replenished duration is about 14 days. Before typhoon was coming, the replenishment was started to set up at flood plain as show in Fig. 5. Fig. 5 shows that the replenished sediment would not affect the water quality at normal duration and during flood period, the replenished sediment would be flushed. According to the field observation, 1 month later, a huge rainfall was occurred from typhoon Morakot and generated 5,400 m^3/s peak flow discharge around this area. Figure 6 shows the hydrograph of inflow discharge and the sediment concentration. It is about two weeks later, based on the field survey results, there is about 3% sediment remained and the diameter of most remained material is more than 30cm (Fig. 7). Based on the monitoring data of sediment concentration, before typhoon was coming, the turbidity in main channel was not changing at measurement point 1 and 2 (Fig. 6). But, during typhoon duration, the turbidity was reach to 3500 ppm and 4000 ppm at water quality measurement point 1 and 2, respectively. However, 1 week later, the turbidity at point 2 of water quality measurement was decreasing to 10% of peak turbidity during typhoon Morakot event. The field experiment shows that replenished sediment can be flushed to the downstream reach by natural flood which peak discharge is higher than 5,400m^3/s and replenished sediment which constructed at flood plane would not cause water quality changing during normal time. Refer to the experience of replenished volume in Japan is about 10% of annual deposition volume in reservoir, the similar replenished percentage of coarse material in Shihkang reservoir is adopted to replenish which value is about 8%. Until now, up to 10% of replenished sediment is been proof that it can be implement and the action does not affect water quality before flood comes due to discharge control by reservoir during normal condition.

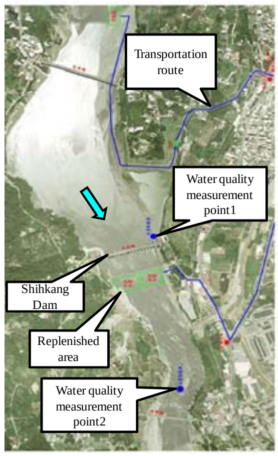

Figure 4. Replenished area and observation points

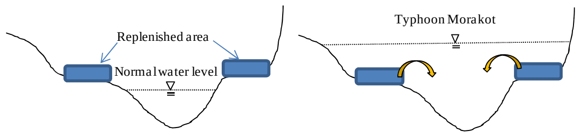

Figure 5. Sketch map of replenished sediment situation

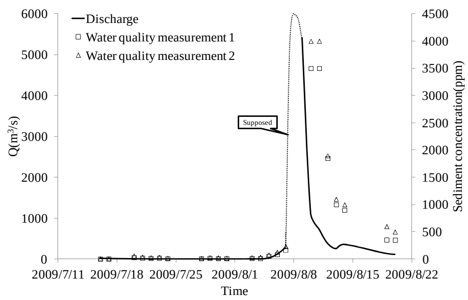

Figure 6. Impacts of replenished sediment and discharge hydrograph

Figure 7. Remained sediment after Typhoon Morakot

3. PHYSICAL MODEL TEST

Although the replenishment of coarse material is successes to implement, but, in Shihmen reservoir, it is difficult to execute due to transportation limit and coarse material is more valuable to be construction material. As a result, only dredging material could be employed and the other reason is course from the deposition pools (Fig. 8) which below the reservoir is almost filled up. In order to solve the disposal area problem of dredging material, replenishment strategy was considered to create a new method for dealing with fine sediment due to limited disposal space. According to the literature review, fine material which possesses colloidal property is difficult to flush and move. Fig. 9 (Fortier and Scobey, 1926) and Fig. 10 (Vanoni, 1977) show the results of threshold velocity for various sediment. Based on the results of literature experiment in Fortier and Scobey (1926) and Vanoni (1977), the fine sediment (Fig. 2) which from the Shihmen reservoir belongs to silt and clay needs more than 1.5 m/s velocity to flush. Besides, the dragging material is in liquid state which includes water and fine sediment. Therefore, the replenished material needs filter structure to make sure that replenished material could not affect the water quality of main channel during normal duration. According to the field survey of upstream material, the diameter is about 4.5mm that belongs to accumulative 80% volume of coarse sediment at Lofu excavation area. Refer to the threshold velocity of 4.5mm, the flushed velocity is about 1m/s which value is small than colloidal material. Therefore, the coarse material of Lofu was adopted to construct filter structure around replenished area. In addition, according to the numerical simulation results, the flow velocity reaches 1 m/s during 1700m^3/s discharge at planned replenishment area (Fig. 8) which value belongs to 2 year return period.

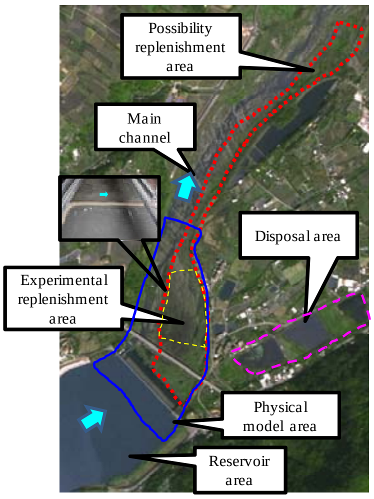

Figure 8. Experimental area and surrounding environment

	Velocity† (ft/s)		
Original material excavated for canal (1)	Clear water, no detritus (2)	Water-transporting colloidal silts (3)	Water-transporting noncolloidal silts, sands, gravels, or rock fragments (4)
Fine sand (noncolloidal)	1.50	2.50	1.50
Sandy loam (noncolloidal)	1.75	2.50	2.00
Silt loam (noncolloidal)	2.00	3.00	2.00
Alluvial silts when noncolloidal	2.00	3.50	2.00
Ordinary firm loam	2.50	3.50	2.25
Volcanic ash	2.50	3.50	2.00
Fine gravel	2.50	5.00	3.75
Stiff clay (very colloidal)	3.75	5.00	3.00
Graded, loam to cobbles, when noncolloidal	3.75	5.00	5.00
Alluvial silts when colloidal	3.75	5.00	3.00
Graded, silt to cobbles, when colloidal	4.00	5.50	5.00
Coarse gravel (noncolloidal)	4.00	6.00	6.50
Cobbles and shingles	5.00	5.50	6.50
Shales and hard pans	6.00	6.00	5.00

1.52 m/s

† For channels with depth of 3 ft or less after aging.

Figure 9. Threshold velocity [Fortier and Scobey, 1926]

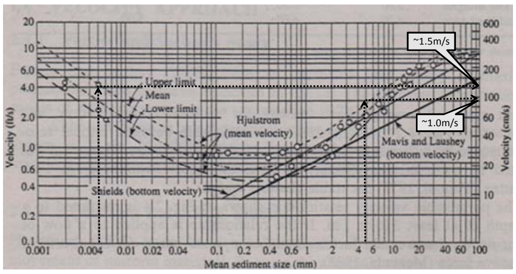

Figure 10. Incipient velocity [Vanoni,1977]

Therefore, 500 m^3/s, 1700 m^3/s, 3500 m^3/s and 6100 m^3/s were selected to be inflow discharge cases and those value were 2 year, 5year and 20year return period, except 500 m^3/s. On the other hand, the water depth is from 2.1m to 2.36m in replenishment area by numerical simulation result. The height of filter structure sets to 2.0m and replenished height sets to 1.6m. Fig. 8 shows the arrangement of replenishment and sketch of around environment and physical scale ratio is 1/64. The possibility replenishment area was choosing at flood plain and experimental replenishment area was adopted at suitable location. Protection bank and possesses enough space to replenish are two reasons to select physical model area. The solid line shows the replenishment area is within physical model area, the upstream boundary is from some part of afterbay to generate uniform inflow discharge and downstream boundary is at narrowest section which flow mechanism belongs to super critical condition.

From the report of Northern water resources bureau (2010), the water content of dredging material is from 39.9% to 45.2% after disposal 1 year. Therefore, 40% of water content was adopted to test the replenishment. Moreover, based on flushing similarity, the flushing mechanism of physical model can be calculated by following equation (Lai, 2001):

$$u_c = a\rho_d^{\ b} \qquad (1)$$

Where, u_c =critical flow velocity and ρ_d = dry density. Lai (1998, 2001) investigated parameter a and b using fine sediment of Akungtien reservoir, and result in 1.65 and 1.96. This result is used for this study due to similar diameter of fine material between Shihmen and Akungtien reservoir. Besides, according to the hydrograph of historical flood, the duration of discharge 500 m^3/s, 1700 m^3/s, 3500 m^3/s and 6100 m^3/s were considered in this research. Fig. 11 shows the arrangement of replenished area. The sediment filter which constructed by coarse material from Lofu excavation was set around replenished area to keep the water quality of main channel.

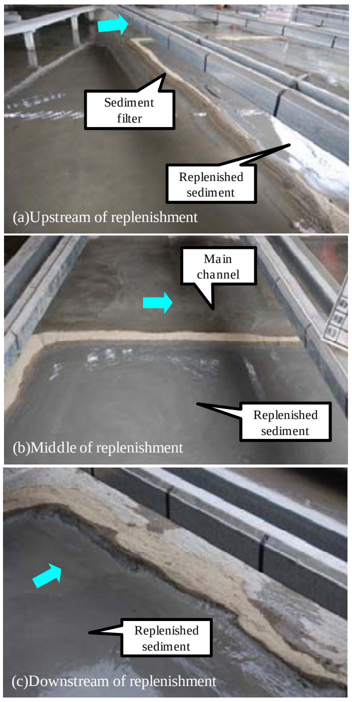

Figure 11. Sketch of experimental set up and arrangement

4. RESULTS AND DISCUSSION

Table 1 lists the information of experience items. Flushing durations of experimental values in table 1 were based on the analysis of historical record. But, it is better flushing efficiency cases, the same test duration was choose to analysis from discharge 500 m^3/s, 1700 m^3/s and 3500 m^3/s due to the limited duration of 3500 m^3/s is 8 hours. In addition, according to the recent 10 years, more than 6100 m^3/s is only 1 hour, therefore, such case only implemented for 1 hour in this experiment. However, the estimated value was also presented in Table 1 from 8 hours results.

Table1 Flushing efficiency and experimental items

Items	500 m^3/s Flushing duration (hr)	500 m^3/s Flushing ratio(%)	1700 m^3/s Flushing duration (hr)	1700 m^3/s Flushing ratio(%)
Experimental values	8	42	8	67
Estimated values	38	96	14	81
Items	3500 m^3/s Flushing duration (hr)	3500 m^3/s Flushing ratio(%)	6100 m^3/s Flushing duration (hr)	6100 m^3/s Flushing ratio(%)
Experimental values	8	84	1	87
Estimated values	5	79	1	87

Fig. 12 presented the variation of flushed sediment volume and it shows that after 3 hours, the flushed sediment ratio possesses liner tendency.

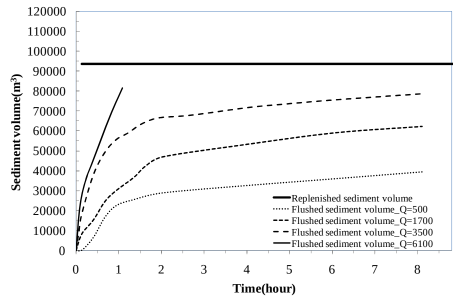

Figure 12. Variation of flushed sediment volume

The first 3 hours dominates the main flushing process and possesses higher erosion efficiency. Therefore, the estimated flushing ratio was estimated from 4 hours to 8 hours. Fig. 13 shows the equations of regression results between discharge 500 m^3/s and 1700 m^3/s.

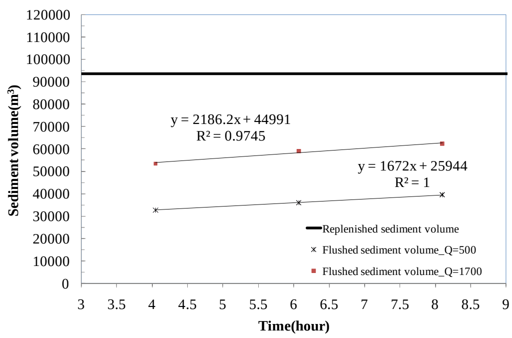

Figure 13. Tendency of flushing rate

The table 1 lists the estimated values of discharge 500 m^3/s and 1700 m^3/s. The data of table 1 presents the higher flushing ratio due to higher flushing discharge in experimental values. But, according to the happened duration of each discharge, the flushing ratio possesses different sequence. The best flushing efficiency is discharge 500m^3/s, the second is discharge 6100 m^3/s, the third is discharge 1700 m^3/s and the worst is discharge 3500 m^3/s. This means that the first suitable discharge is 1700 m^3/s due to more confidence and easier to reach the objective. Fig. 14 shows the variation of outflow sediment concentration from 500 m^3/s to 6100 m^3/s. Due to the sediment filter which as an armour effect, the earliest peak sediment concentration is discharge 6100 m^3/s and the latest is discharge 500 m^3/s due to water discharge energy. However, due to water quantity, the highest sediment concentration is discharge 500 m^3/s and the lowest is discharge 6100 m^3/s. Besides, the hydrograph shows that the main variation was obviously happened in first hour. After 1 hour, the sediment concentration is lower than 6000ppm which value can be treated by water treatment facilities. Combining the results of Fig. 12 and Fig. 14, the flushing impacts presented obviously effects at first two hours. The Fig. 12 also shows that during the test period, the replenished sediment cannot be flushed 100%. Therefore, the suitable replenished volume should be reduced to 60000 m^3 to reach optimal flushed ratio.

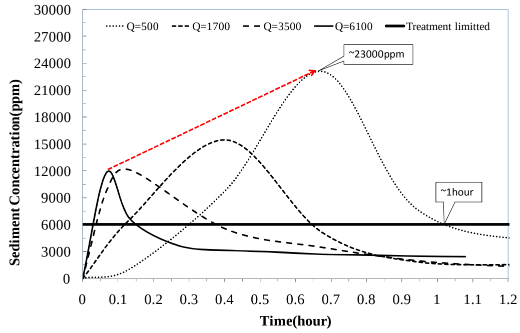

Figure 14. Tendency of flushing sediment concentration

5. CONCLUSIONS

According to the experience of replenishment strategy in Japan and Taiwan, coarse material was usually adopted to implement for preventing downstream river from bed degradation and increase suitable living habitat for aquatic organism at downstream of the dam. In recent years, up to 10% of replenished sediment was been proof that it can be executed and the performance did not affect water quality before flood coming due to replenished area was at flood plain. However, in this study, the fine sediment was first time to try to be replenished in physical model of Shihmen reservoir. The flushing similarity, flushing discharge, replenished area, replenished volume and operation duration were both considered in this study. Based on the experimental results, the peak sediment concentration timing is result from water discharge. On the other hand, due to water quantity, the highest sediment concentration is discharge 500 m^3/s and the lowest is discharge 6100 m^3/s. Besides, combining the results of variation of flushed sediment volume and tendency of flushing sediment concentration, the main effect of water quality was obviously happened in first 2 hours. After 2 hours, the sediment concentration was reduced to 6000ppm and such water turbidity can be treated by water treatment facilities. From flushing efficiency and the variation of flushed sediment volume, the suitable flushed discharge was suggested to 1700m^3/s and replenished sediment volume was presented to 60000m^3 due to more confidence and more easy to reach the objective.

ACKNOWLEDGEMENT

The presented study was financially supported by the Northern water resources bureau, Water Resources Agency Ministry of Economic Affairs. Writers wish to thank the National Taiwan University Hydrotech Research Institute and Disaster Prevention Research Institute of Kyoto University in Japan for manpower and technique supporting.

REFERENCES

Central water resources bureau, Water resources agency, Ministry of economic affairs (2009) : Report of implemention and efficiency of replenishment in Shihkang dam downstream river (Chinese).

Fortier, S., and F. C. Scobey (1926) : Permissible Canal velocities, Transactions of the ASCE, Vol. 89, No. 1, pp. 940-956.

Kantoush, S. A., Sumi, T. and Kubota, A. (2010) : Geomorphic response of rivers below dams by sediment replenishment technique, River Flow 2010 - Dittrich, Koll, Aberle & Geisenhainer (eds), pp. 1155-1163.

Lai J. S. and Chang F. J. (2001) : Physical modeling of hydraulic desiltation in Tapu reservoir, Intl. Jour. of Sediment Research, IRTCES (International Research and Training Center on Erosion and Sedimentation), Vol. 16, No. 3, pp. 363-379.

Lai J. S., Chang F. J. and Yang, H. C. (2001) : Movable bed physical modeling of flushing cohesive reservoir deposits, Journal of the Chinese Institute of Civil & Hydraulic Engineering, Vol. 13, No. 1, pp. 99-109.

Lai, J. S. (1998) : 「Research of threshhold velocity on fine sediment in Akungtien reservoir, Journal of Taiwan Water Conservancy, Vol.46, No.3, pp.76-83.

Lee, F. Z., Lai, J. S., Hwang G. W. and Tan, Y. C. (2007) : Influence of High-turbid Inflow on Irrigation and Water Supply in the Shihmen reservoir, 2007_58th ICID IEC Meeting and Fourth International Conference on Irrigation and Drainage.

Northern water resources bureau, Water resources agency, Ministry of economic affairs (2010) : Report of arrangement and planning on depsition silt in Shihmen Reservoir.

Okano, M., Kikui, M., Ishida, H. and Sumi T. (2004) : Reservoir sedimentation management by coarse sediment replenishment below dams, Proceedings of the Ninth International Symposium on River Sedimentation, Yichang, China, Volume Ⅱ, 1070-1078.

Seto, K., Sakamoto, T. and Suetsugi, T. (2009) : Sediment control measures and improvement effects of physical condition and environment by sediment flushing – a case study in the Yahagi dam. International Congress on Large Dams, Brasilia, Q.89-R.3.

Sumi, T., Kobayshi, K., Yamaguchi, K. and Takata, Y. (2009) : Study on the applicability of the asset management for reservoir sediment management, International Congress on Large Dams, Brasilia, Q.89-R.4.

Tan, Y. C., Lai, J. S. and Lee, F. Z. (2009) : A study of typhoons induced high serious sediment concentration deposition into a reservoir and reduced the water supply in Taiwan, 60th IEC Meeting and 5th Asian Regional Conference, New Delhi, India.

Vanoni, V. A. (1975) : Sedimentation Engineering, ASCE Task Committee for the Preparation of the Manual on Sedimentation of the Sedimentation Committee of the Hydraulics Division(Reprinted 1977).