Hydraulic desilting of reservoir in Taiwan

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Abstract

Reservoirs in Taiwan encounter seriously sedimentation problem due to numerous sediment yield production in the watershed during typhoon event. It is estimated that 0.96% of water storage volume is lost annually, siltation result of the upstream river flow carries large amount of sediment from the watershed during floods. To mitigate the sedimentation problems in several major reservoirs, a series of desiltation measures have been conducted to slow down sedimentation and sustain the life of reservoir. Hydraulic desilting is the most effective and economical way to releasing sediment in reservoir, this paper summarized hydraulic desilting projects of Shihmen, Agongdian and Zenwen reservoir in Taiwan, and among of which, abundant sediment was released by desilting operation through the sediment outlet into the downstream river during typhoon.

Keywords: abnormal hydrologic activity, reservoir sedimentation, hydraulic desilting

1 Heavy rainfall causes reservoir to lose capacity rapidly

In Taiwan, there are two major nature hazards always affect the hydrological and geological condition. One is earthquake and the other is typhoon. Earthquake-triggered landslides in mountainous areas accompany with heavy rainfall could supply large amount of sediment to river basin. Sediment produced in upper basins may not immediately deliver to lower basin owing to river aggradations. However, still great part of sediment can be transported and deposited in downstream river particularly during extreme rainfall events, which could generate turbidity current into a reservoir. In 1999, Taiwan suffered from an earthquake which magnitude reaches 7.3 Richter magnitude scale. After that earthquake, the soil and rock of the mountainside were collapsed. Therefore, when typhoon or heavy rainfall occurs in Taiwan, the watershed may generate huge amount of sediment yield. And, the land development in the watershed would accelerate soil erosion. As sediment moves into a reservoir, deposition occurs due to decrease of velocity and makes storage of reservoir decrease.

In addition, climate change caused abnormal hydrologic activities in recent year, which triggered frequent and extreme rainfalls, there is a tendency of reducing rainfall duration and increasing rainfall intensity in Taiwan, large difference in annual precipitation, in wet years, annual precipitation reaches 3,568 mm which is over two times of those in dry years (1,572 mm), climate change and in the last couple of years, Taiwan has suffered the continuous drought in year 2014, 2015 and 2017 (Figure 1).

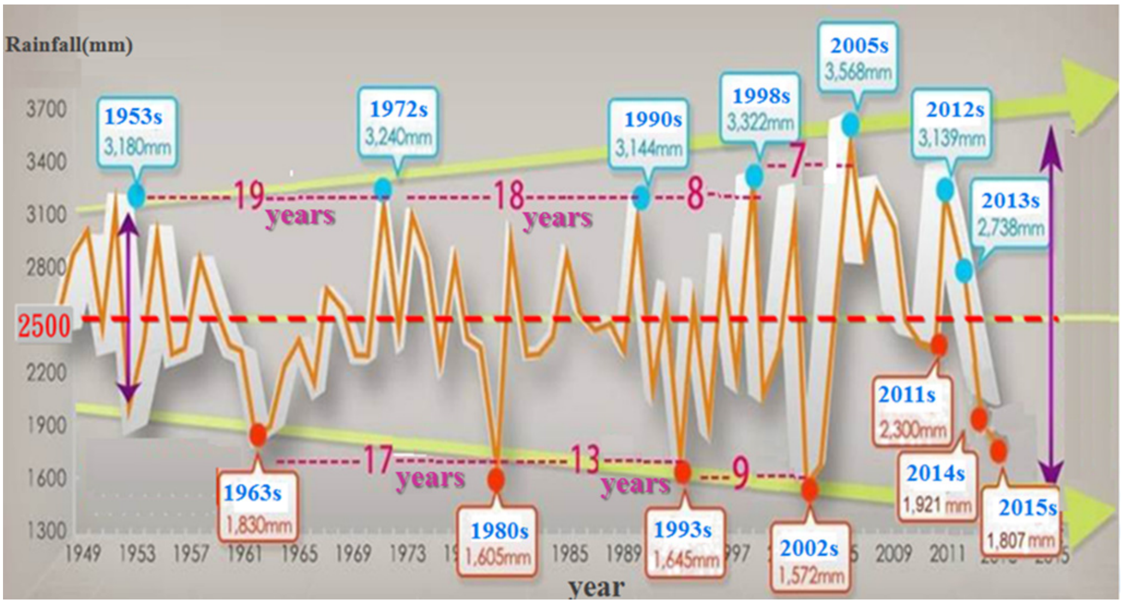

Figure 1: Records of annual precipitation in Taiwan

Moreover, heavy rainfall and landslide had caused reservoir to lose capacity rapidly, such as Arre typhoon in 2004 and Morakot typhoon in 2009, each caused Shihmen, Zengwen and Nanhau reservoirs to lose capacity about 9% to 12% of the total design storage (Table1). In addition, reservoir storage lose reduce water supply reliability, and impacted infrastructure, particularly to outlet works and turbine intakes.

Table 1: Events of heavy rainfall causes reservoir to lose capacity rapidly

Reservoir	Typhoon (year)	Original storage capacity (10^6 M^3)	Siltation caused by each typhoon(10^6 M^3)	Ratio of siltation
Shihmen	Arre (2004)	309.12	27.88	9%
Zengwen	Morakot (2009)	748.40	91.08	12%
Nanhau	Morakot (2009)	158.05	17.06	11%

2 Strategies against reservoir sedimentation

In general, reservoir sediment management methods can be put into three different categories:

- Reduce sediment delivery (watershed management)
- Prevent sediment deposition (route sediments through or around storage)
- Earth increase or recover volume (removal of deposited sediments)

Figure 2 shows a variety of sediment management techniques placed into the three above categories proposed by Kondolf *et al.* (2014). There can be instances where a combination of methods from the above categories is necessary to maintain reservoir capacity and achieve reservoir sustainability. Overall, hydraulic desilting is the most effective and economical way of releasing sediment out of reservoir.

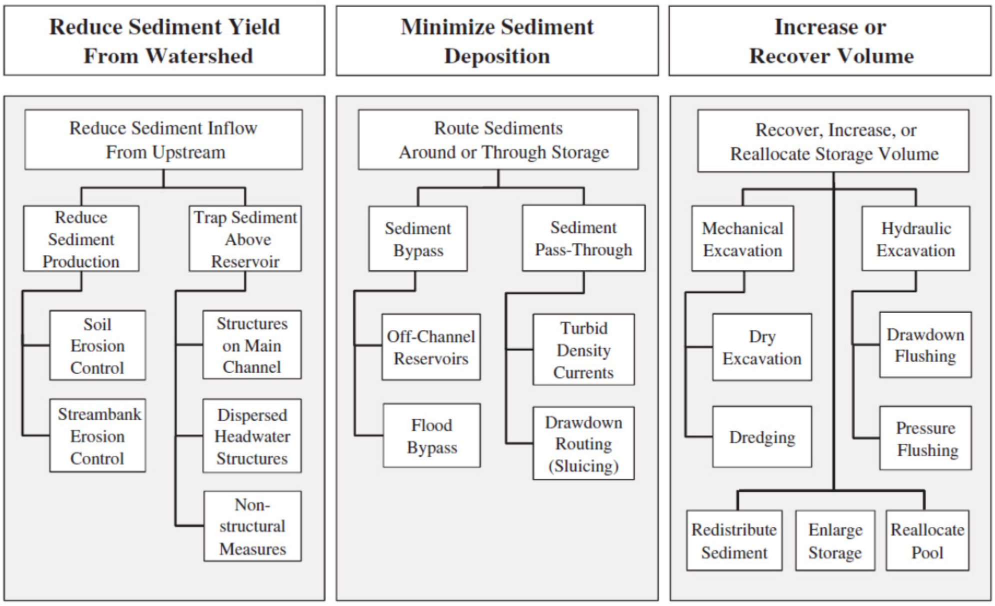

Figure 2: Diagram of sediment management options for reservoir sustainability (taken from Kondolf *et al*. 2014)

3 Hydraulic desilting of reservoirs in Taiwan

As many of you may have known, hydraulic desilting is the most efficient and economical way to reduce siltation in reservoir. In Taiwan, hydraulic desilting projects have been implanted in Shihmen, Baihe, Zengwen, Nanhau and Agongdian reservoirs (Figure 3). Except for Agongdian reservoir which practices “empty flushing sediment”, the others have implanted “turbidity current venting” to discharge ”turbid density currents” through the bottom outlet of the reservoirs. And three hydraulic desilting cases, including Agongdian, Shihmen, and Zengwen reservoirs will be introduced as following.

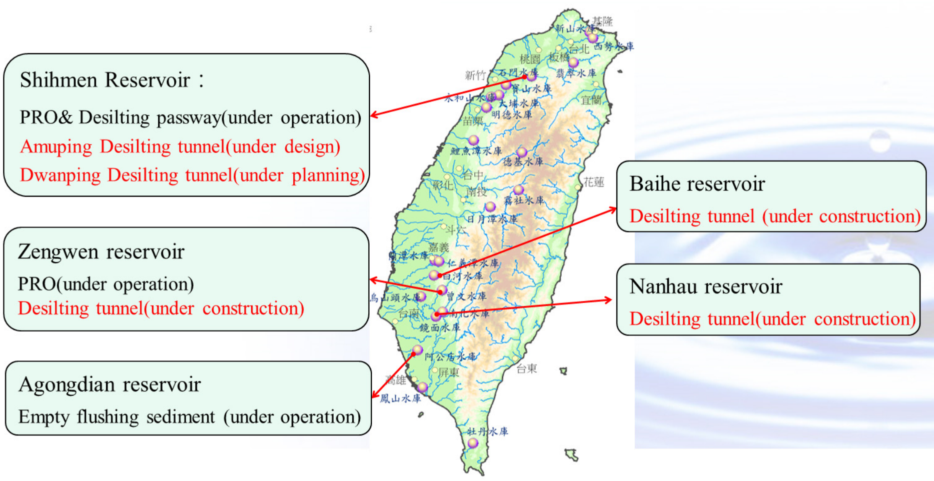

Figure 3: Hydraulic desilting projects in major reservoirs

3.1 Agongdian Reservoir

Agongdian Reservoir was completed and operated in 1953. Sediment deposition and accumulation in reservoir area was a serious problem for lacking of efficient sediment flushing facilities. 73% of reservoir capacity was stored by sedimentation, and capability of flood protection was reduced from 250-year to 50-year flood in 1981. A rehabilitation program was executed for the reservoir from 1997 to 2005. The new sediment countermeasures are "empty flushing sediment" and "storing clear and releasing muddy". The sediment is flushing out of reservoir in flood season, and water diverted from Chishan River is stored in dry season. In order to silting by hydraulic, the water level will drawdown in flood season, which is during June first to September thirtieth, desilting operation of Agongdian in difference typhoons, the ratio of desilting in Agongdian reservoir is about 13% to 74% (Figure 4, 5).

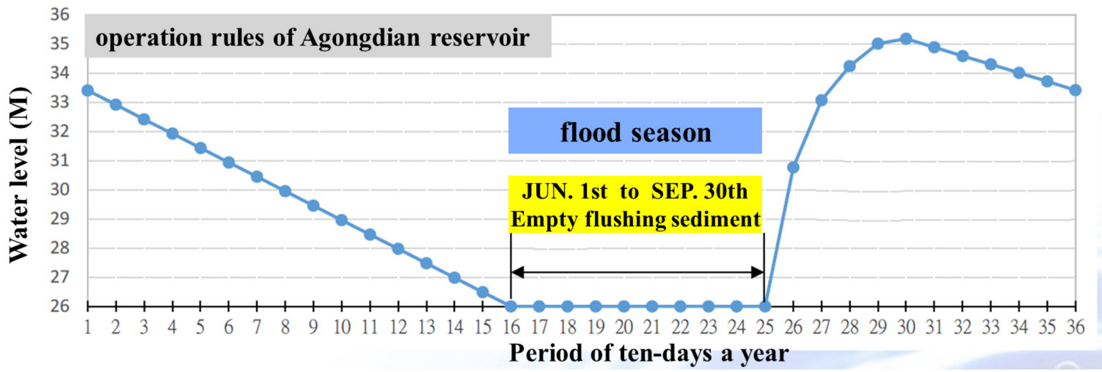

Figure 4: Operation rules of Agongdian Reservoir

Figure 5: Desilting operation in 2016 Typhoon Nepartak in Agongdian Reservoir

Table 2: Ratio of desilting in Agongdian Reservoir

Year	Typhoon	Sediment flow into reservoir(10^3M^3)	Amount of Desilting (10^3M^3)	Raito of desilting in reservoir
2009	Morakot	49	67	13%
2010	Fanapi	55	16	29%
2011	Nanmadol	59	32	54%
2012	0610 heavy rain	15	48	31%
2012	Talim	33	14	42%
2013	Trami	28	6	22%
2014	Matmo	9	7	74%
2014	0810 heavy rain	42	1	24%

3.2 Shihmen Reservoir

Shihmen Reservoir was completed in 1964, an essential water resource in northern Taiwan, operating over 52 years, which is a multipurpose reservoir, serve as water supply, hydro-power plant and flood control. Figure 6 shows the aerial view of the reservoir, which is the largest watershed area in Taiwan, a total of 763 km^2 wide. The soil erosion situation is quite severe in Shihmen Reservoir, over 32% of storage capacity is lost due to siltation. Typhoon Aere in 2004 attacked northern Taiwan, and flood-induced high sediment concentration more than 200,000 Nephelometric Turbidity Unit (NTU) was measured in the Shihmen Reservoir (Figure 6).

Figure 6: Typhoon Aere caused muddy in Shihmen Reservoir in 2004

3.2.1 Reformed penstock to hydraulic desilting passway

There was no bottom outlet to desilting in original design of Shihmen Reservoir, in order to improve the desilting and drainage ability, existing penstock had been reconstructed into a hydraulic desilting passway with a discharge capacity of 300 m^3/s in 2012, and total 3.1 million m^3 of sediment had been desilted through the new passway during typhoon season in 2013-2016 (Figure 7). After the installation of desilting passway, the ratio of desilting during a typhoon event could reaches to about 30% on average in Shihmen Reservoir (Table 3).

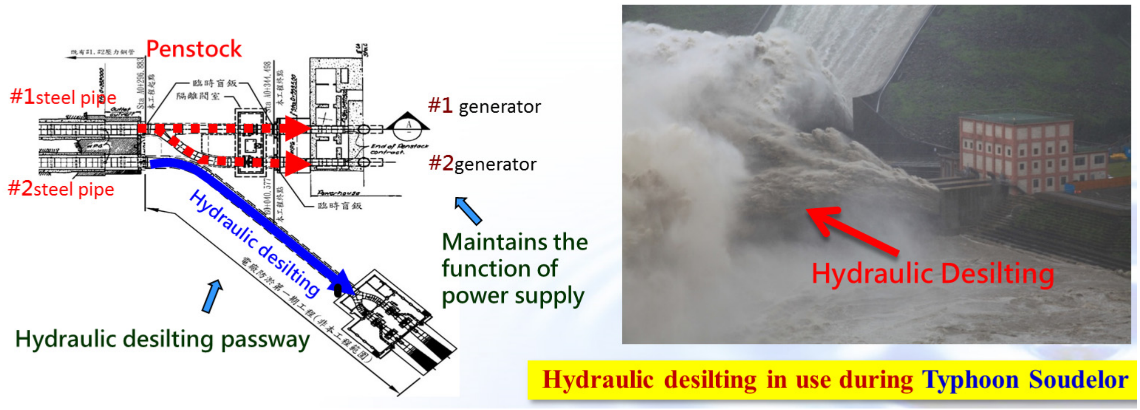

Figure 7: Typhoon Aere caused muddy in Shihmen Reservoir in 2004

Table 3: Comparison ratio of desilting in Shihmen Reservoir

Year	Without desilting passway						With desilting passway				
	2008	2008	2008	2009	2010	2011	2013	2013	2015	2015	2016
Typhoon	Fung-wong	Sinlaku	Jangmei	Morakot	Fanapi	Saola	Soulik	Trami	Soudelor	Djuan	Megi
Ratio of desilting	12.9%	26.5%	17.9%	14.3%	3.0%	15.0%	34.3%	37.2%	36.7%	37.4%	21.1%

3.2.2 Promoting the construction of 2 desilting tunnels

In order to remove coarse sediment from upstream, maintain reservoir capacity, the Amuping and Dawaping tunnels will continue to be promoted (Figure 8). The Amuping tunnel is at its design phase, ready to be constructed in 2018 and estimated to complete in 2021, which functions includes silt transfer, flooding discharge and truck delivery, the use of the tunnel can be divided into three condition (Figure 9).

- In normal time, the tunnel helps delivering the siltation carried by the dredging boat in reservoir. When the siltation comes out the tunnel, further extract the sand and sediment as a usable material. The rest is mud, which then transferred to the flushing basin.
- In flood season, flooding will be discharging through the tunnel; moving all the muds to downstream.

- In drought season, the water level goes down, allowing truck to drive through the tunnel, and rapidly reducing siltation by dry-digging.

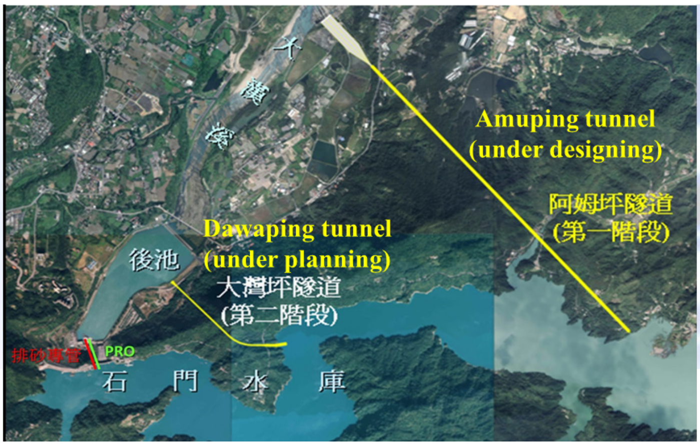

Figure 8: Location of Amuping and Dawaping tunnel in Shihmen Reservoir

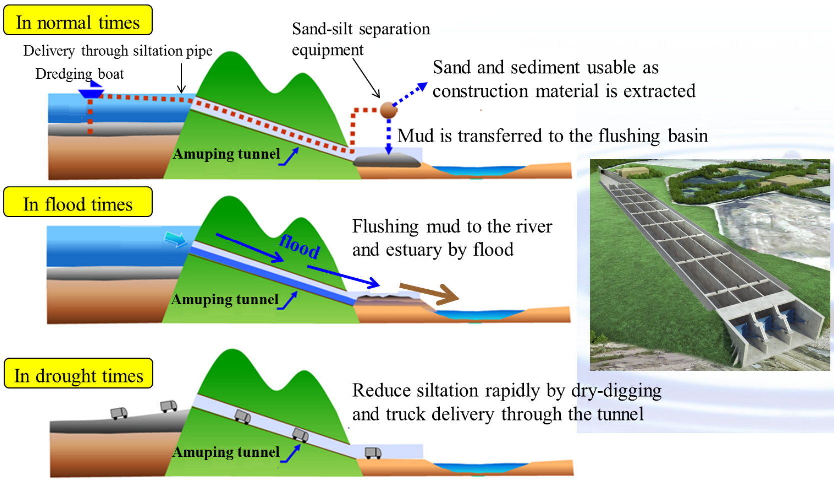

Figure 9: Operation of Amuping tunnel in Shihmen Reservoir

3.3 Zengwen Reservoir

Zengwen Reservoir is important water resource in Southern Taiwan, completed in 1973, which capacity with the largest storage volume of 712 × 10^6 m^3 in Taiwan, and also within functions of water supply, hydro-power, and flood control. Within 40 years of operation, siltation took up 37% of storage capacity due to 9 major typhoons.

In 2009 Typhoon Morakot attacked southern Taiwan, the accumulative rainfall was more than 3,000 mm within 3 days, the inflow sediment concentration was more than 0.2 × 10^6 ppm during peak flow and caused about 90 × 10^6 m^3 sediment deposited in the Zengwen Reservoir. Total amount of the deposition in this event was more than 20 times annual value.

3.3.1 Improving the permanent river outlet (turbidity current venting)

The first stage to increase hydraulic desilting ability of Zengwen Reservoir is to "improving the permanent river outlet (PRO)", the original outlet type was "Howell-Bunger valve" and which had been reconstructed into a "jet flow gate" with a discharge capacity of 177 m^3/s in 2014, and the benefit of desilting ability was estimated reached 0.56×10^6 M^3 per year.

3.3.2 Constructing desilting tunnel (turbidity current venting)

The second stage to increase hydraulic desilting ability of Zengwen Reservoir is to construct desilting tunnel, the tunnel has been constructed from 2013 and will be completed in 2017, The desilting tunnel could increase desilting by 1.04×10^6 M^3 per year, and which flooding capability 995 m^3/s (Figure 10), the layout of tunnel shows as Figure 11.

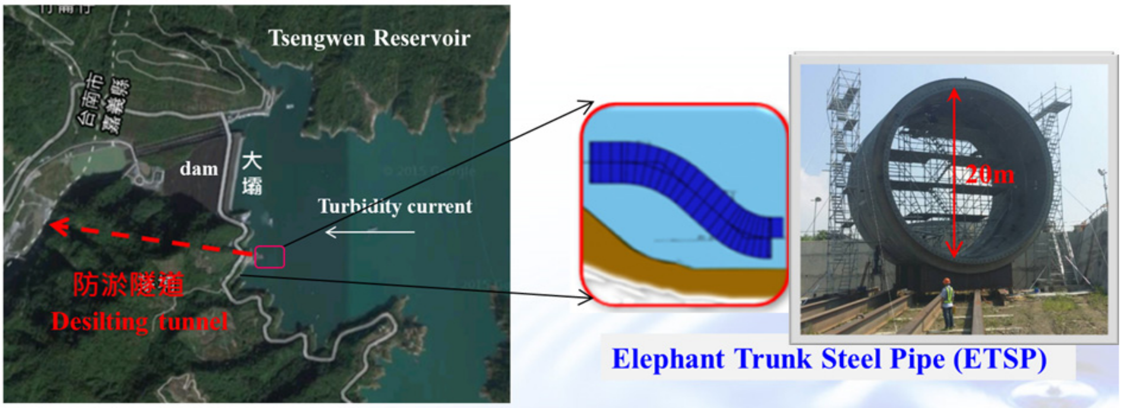

Figure 10: Location of desilting tunnel and construction of ETSP in Zengwen Reservoir

The main structure of tunnel includes intake pipe, vertical shaft, gate chamber, tunnel, plunge pool, and outlet (Figure 11), the length of the tunnel is 1,200 m with slopes from 1% to 3%, and the designed velocity of discharging is 18 to 30 m^3/s in the tunnel. It is worth to mention, the intake design huge steel pipe, also called Elephant Trunk Steel Pipe (ETSP), is designed to connect the tunnel in intake of bottom reservoir, which outer diameter and inner diameter is 23.32 m and 20 m, respective, and that is the first kind case in the world, the ETSP is design to extract the sediment in the bottom of the reservoir, its innovative design allows it to connect the desilting tunnel under water without building the cofferdam.

The size of ETSP is very huge, meaning transportation on the land is nearly impossible. Therefore, it was assembled on the river shore, lunching to the water, dragging on the water to the installation site, and sinking to the bottom to connect the tunnel (Figure 12). Due to the installation of ETSP is the critical part of the whole project. In order to increase the construction safety and understand its motion phenomena during installation, several simulation procedures are needed. Thus, a 1:20 model of ETSP was built for simulating its installation procedures in a towing tank.

Moreover, due to the limited outlet area, there is a need to build up an underground plunge pool. The size of it is 168 m long, 41 m high, and 18 m wide, which is the largest plunge pool underground of Taiwan. As for the outlet, a rock pillar was also designed to prevent the narrow outlet from collapse (Figure 13).

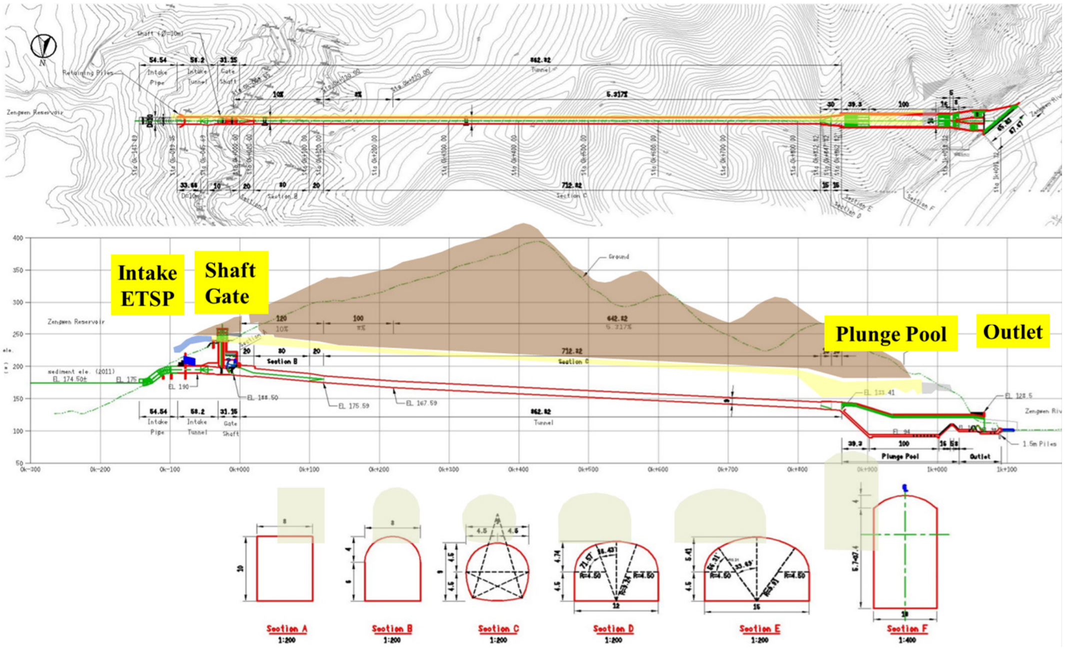

Figure 11: Layout of desilting tunnel in Zengwen Reservoir

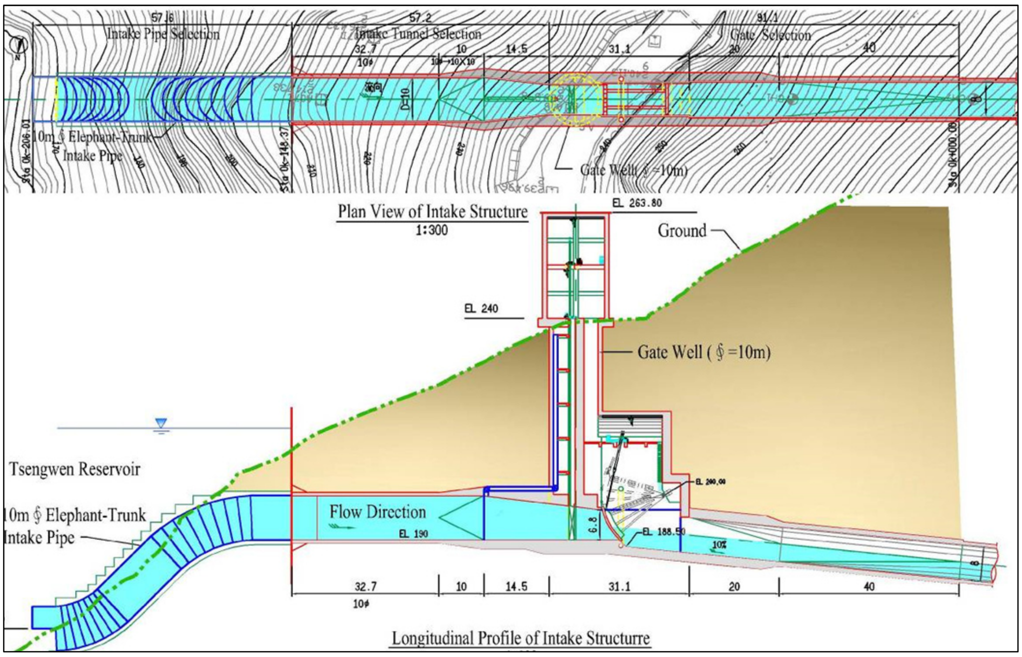

Figure 12: Preliminary intake structure layout

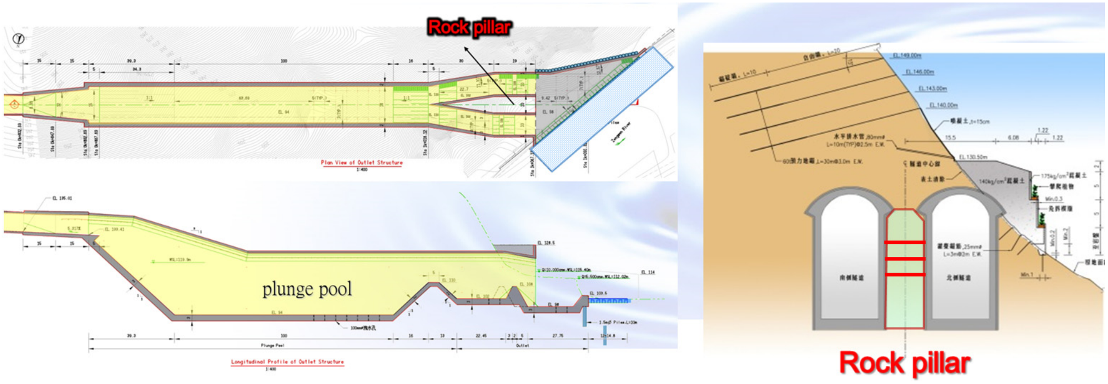

Figure 13: Layout of plunge pool and outlet

4 Conclusions

- It is estimated that 0.96% of water storage volume is lost annually as a result of siltation in Taiwan. In order to achieve reservoir sustainability, sediment management and storage maintenance are necessary.
- Soil erosion control of the upstream areas, digging and dredging, flushing, and sluicing have all been adapted to reduce sediment in the reservoir. However, among all, hydraulic desilting proves to be the most economical and rapid method.
- Depending on conditions of sedimentation, topography and hydrological characteristics, different operations of hydraulic desilting have been established upon reservoirs that develop serious siltation in Taiwan.
- Among Shihmen, Agongdian and Zengwen reservoirs in Taiwan, abundant sediment was released by desilting operation through the sediment outlet into the downstream river during typhoon.

References

Collins, K., Kimbrel, S., Randle, T. (2014). Formulating Guidelines for Reservoir Sustainability. Bureau of Reclamation Review, Research and Development Office, Bureau of Reclamation, USA.

Hsu S.-T. (2016). Renovation of Existing Reservoir in Taiwan for Sustainability. 12th International. Conference on Hydroscience & Engineering Hydro-Science & Engineering for Environmental Resilience November 6-10, 2016, Tainan, Taiwan.

Jyoti, M., Warudkar, A.A. (2016). Comparative Study for Desilting Process of a Reservoir. *International Journal of Research in Engineering, Science and Technologies*, 2(1), 164–167.

Kondolf, G.M, Gao, Y., Annandale, G.W., Morris, G.L. Jiang, E., Zhang, J. Cao, Y., Carling, P., Fu, K, Guo, Q., Hotchkiss, R., Peteuil, C., Sumi, T., Wang, H.-W., Wang, Z., Wei, Z., Wu, B., Wu, C., Yang C.T. (2014). Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. *Earth's Future*, 2(5), 256–280

Lee, F.-Z., Lai, J.-S., Hsieh, H.-M., Huang, C.-C., Tan, Y.-C. (2016). Downstream Impact Investigation of Released Sediment from Reservoir Desilting Operation. 12th International Conference on

Hydroscience & Engineering Hydro-Science & Engineering for Environmental Resilience November 6-10, 2016, Tainan, Taiwan.

Novak, P., Moffat, A.I.B., Nalluri, C., Narayanan, R. (2007). Hydraulic Structures, Fourth Edition. Taylor & Francis, New York, USA.

van Rijn, L.C. (2013). Sedimentation of Sand and Mud in Reservoirs in Rivers. (accessed April 20, 2017). http://www.leovanrijn-sediment.com/.

Wu, P.-H., Chan, H.-C., Chen, W.-F. (2015). Preliminary Model Study of Sediment Reduction in Shihmen Reservoir, *Journal of Soil and Water Conservation*, 47(4), 1495–1510.

Yeh, C.-W., Chen, Y.-C., Chen, Y.-G., Chen, W.-F. (2016). Study on the operation of sediment prevention for Agongden Reservoir, *Journal of Soil and Water Conservation*, 48(1), 1589–1606.

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