Conversion of Diversion Tunnels to Bottom Outlets at Xiaolangdi Dam on Yellow River

Sheng T. (Paul) Hsu

Abstract

During planning stage, Xiaolangdi Dam on the Yellow River faced with a problem of how to convert diversion tunnels to large-scale bottom outlets without causing excessive erosive velocity. A closely-spaced multiple orifice scheme was proposed by Bechtel and implemented in the design. High lights of the scheme and the developing process as well as initial testing and operation of the converted bottom outlets are presented.

Keywords: Xiaolangdi Dam, bottom outlet, orifice, energy dissipation

1 Background

Yellow River is known as a ""suspended river"" in China because in the downstream reach for several hundred kilometers its river bed is higher than the surrounding ground, some by as much as 10meters. It had been estimated that on the average, the river bed rises at a rate of 10 cm/yr. To slow down the ever rising water level in the river, Sanmenxia Reservoir, Figure 1, was constructed in 1960. The designed maximum water level was El. 335 m, but initial operation revealed severe siltation occurred in the upstream end of the reservoir and flow structures also experienced extensive erosion by sediment-laden flow. To prevent continuing siltation, the dam went through two phases of renovation, by constructing two new silt-sluice tunnels on the left abutment and by opening up 8 plugged diversion outlets as well as by converting power penstocks to silt-sluice conduits. The dam is now operated as a run-of-river structure. The reservoir level is controlled from El. 305 m in flood season to El. 310 m in dry season.

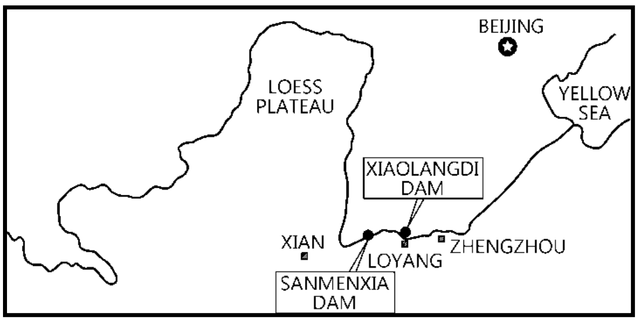

Figure 1: The Yellow River Basin

The failure of Sanmenxia Reservoir to manage sediments from loess plateau prompted Chinese authority to plan on the development of the 154m high Xiaolangdi Dam at 130km downstream from Sanmenxia. Based on experiences at Sanmenxia, the following criteria were established for Xiaolangdi by the Yellow River Conservation Commission (YRCC).

- The dam shall have large bottom outlets. Spillway shall be used only during extreme flood events.
- Surface abrasion can be expected for carbon steel in excess of 10m/s and for regular concrete in excess of 12 m/s.
- Diversion tunnels shall be converted to bottom outlets to save construction cost and schedule.

From 1984 to 1987 Bechtel Civil Corporation was contracted by the Ministry of Water Resources and Electric Power of the PRC to jointly work with YRCC on a conceptual design of Xiaolangdi Dam Project. This paper presents the concept and investigations leading to the conversion of three 14.5 m diameter diversion tunnels to three unique bottom outlets and results of initial operation.

2 Scheme proposed by Bechtel for Xiaolangdi bottom outlet

The Xiaolangdi Reservoir was designed to have a maximum water level of El.275m and normal low water level of El. 230 m during raining season. The tail water level at low flow is El. 130 m. Thus the head difference created by the dam is in the range of 100-140 m. If the potential energy is converted to kinetic energy, the maximum velocity would be nearly 50 m/s. Potential problems induced by high velocity erosion became unavoidable.

The scheme recommended by Bechtel to YRCC to alleviate erosion potential is the installation of a series of closely-spaced 2m-thick orifice rings in the diversion tunnel to form a step wise energy dissipator, as shown on Figure 2. Figure 3 depicts flow pattern and hydraulic gradeline variation immediately upstream and downstream from an orifice. The presence of an orifice causes flow contraction along centerline of the tunnel and separation between the central region and the tunnel wall. The separation induces intense shear and energy dissipation.

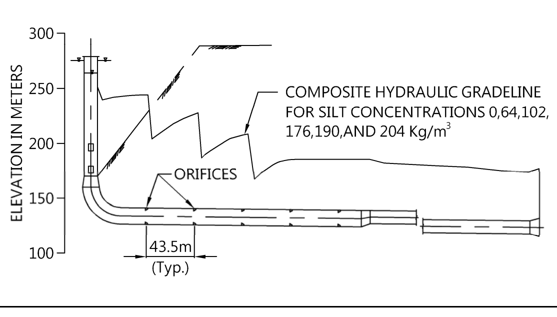

Figure 2: Original conceived multiple orifice scheme for Xiaolangdi Project

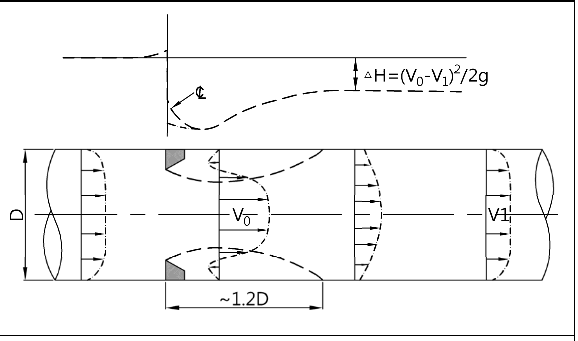

Figure 3 Flow pattern & hydraulic gradeline variation in the vicinity of an orifice

Extensive experiments had been conducted by many researchers to define do/D vs K relationship. Figure 4 depicts the effect of spacing between two orifices L on K, where do: orifice diameter; D: conduit diameter; $K = \Delta H / V^2 / 2g$; △H: headloss induced by orifice; V: average conduit velocity; g: gravitational acceleration. It is seen that with L/D = 3.0 proposed by Bechtel, the amount of energy dissipation is nearly complete. Details of headloss data on orifice were pressented by Ball, Sweeney and Hsu.

Yellow River is known for its sediment-laden flow. The maximum recorded sediment concentration was 941 kg/m^3. Flow with high sediment concentration tends to exhibit the behavior of Bingham Plastic Fluid. As shown on Figure 5, the fluid is characterized by the presence of Bingham shear stress τ_β at zero velocity gradients and a coefficient of rigidity η instead of dynamic viscosity, μ, in Newtonian Fluid. Thus the applicability of clear water results to high-concentration sediment-flow needs to be verified. Naik and Roberson found that behavior of sediment laden-fluid is a dependent on its flow velocity. As velocity and inertial effect increases, fluid will transform from that of Bingham Plastic to that of Newtonian. This conclusion was verified in various Xiaolangdi model tests.

Model test results suggested that closely-spaced orifices can be installed to achieve a △H of about 20 m at each orifice ring, and for D = 14.5 m, the spacing of successive orifice L can be set at L=3D = 43.5 m.

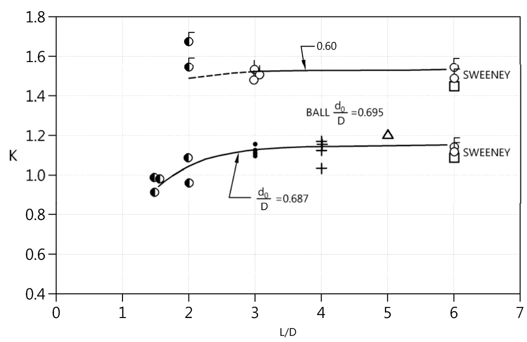

Figure 4: Headloss coefficient- orifice spacing relationship

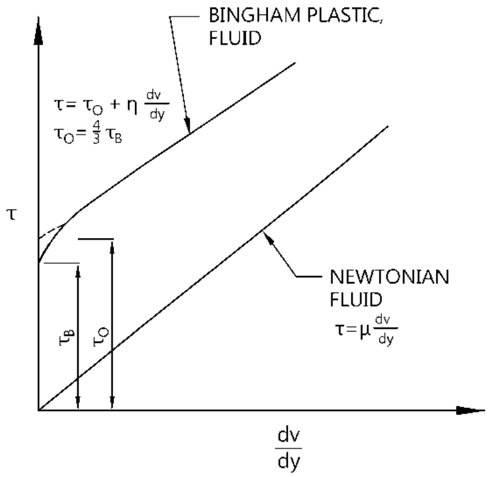

Figure 5: Stress-strain relationship of Bingham Plastic and Newtonian Fluids

3 Bekou silt sluice tunnel tests

Facing with a new energy dissipation scheme for a key structure on Yellow River, YRCC decided to perform a large scale field test to confirm the feasibility of the proposed layout. During June-July 1987, tests were conducted in a 3.8 m diameter tunnel at Bekou Power Project on the Bailong River in Gansu Province, China.

Tests were conducted at a maximum silt concentration of 550 kg/m^3. Tests indicated that:

- Headloss induced by both orifices were very close to those predicted in a small-scale model.
- Stresses on concrete and reinforcing steels were small.
- No vibrations on the tunnel walls and surrounding rocks.

The results of the tests greatly enhance the level of confluence for the use of the scheme at Xiaolangdi.

4 Adopted bottom outlet

In the final design Xiaolangdi Dam consists of three 14.5 mϕ diversion tunnels, one with invert of intake at El. 132.0 m and the other two at El. 141.5 m. The corresponding outlet flip bucket are at El. 129.0 m, El. 138.5 m and El. 138.5 m, respectively. Each tunnel was installed with 3 orifices. As shown in Table 1, the orifice/tunnel diameter ratio is 0.689 for the upstream one and 0.723 for the second and third one. Flows are discharged into a man-made plunge pool.

Table 1: Details of diversion tunnels and multiple-orifice bottom outlets

Diversion Tunnel			Bottom Outlet				
No.	Intake Invert Elevation	Tunnel Diameter	No.	Intake Invert Elevation	Tunnel Diameter	Orifice/Tunnel Diameter Ratio	Outlet Flip Bucket Elevation
1	El.132.0m	14.5m	1	El.175.0m	14.5m	$d_1/D=0.689$ $d_2/D=0.723$ $d_3/D=0.723$	El.129.0m
2	El.141.5m	14.5m	2	El.175.0m	14.5m	$d_1/D=0.689$ $d_2/D=0.723$ $d_3/D=0.723$	El.138.5m
3	El.141.5m	14.5m	3	El.175.0m	14.5m	$d_1/D=0.689$ $d_2/D=0.723$ $d_3/D=0.723$	El.138.5m

Table 2 shows the final design capacity of all outlet structures. It is seen that outlets with the lowest intake are the silt-discharge tunnel and the converted multiple-orifice bottom outlets, all with intake invert at El. 175.0 m. Their combined discharge capacity is 6,607 cms, which is 39.2% of the total capacity, as compare to the spillway capacity of only 22.3%.

Table 2: Summary of Xiaolangdi Dam outlet structure dimension and capacity

Name of Structure	Intake Invert Elevation	Tunnel Dimension	Number	Discharge Capacity	Capacity Ratio
Silt Discharge Tunnel	El.175.0m	D=6.5m	3	2,025 cms	12.0%
Multiple Orifice Bottom Outlet	El.175.0m	D=14.5m	3	4,582 cms	27.2%
Open Channel Bottom Outlet	El.195.0m	10.5m(W)×13.0(H)	1	2,714 cms	38.3%
	El.209.0m	10.0m(W)×12.0(H)	1	1,936 cms	
	El.225.0m	10.0m(W)×11.5(H)	1	1,800 cms	
Spillway	El.260.0m	-	1	3,764 cms	22.3%
Sum	-	-	-	16,821 cms	100%

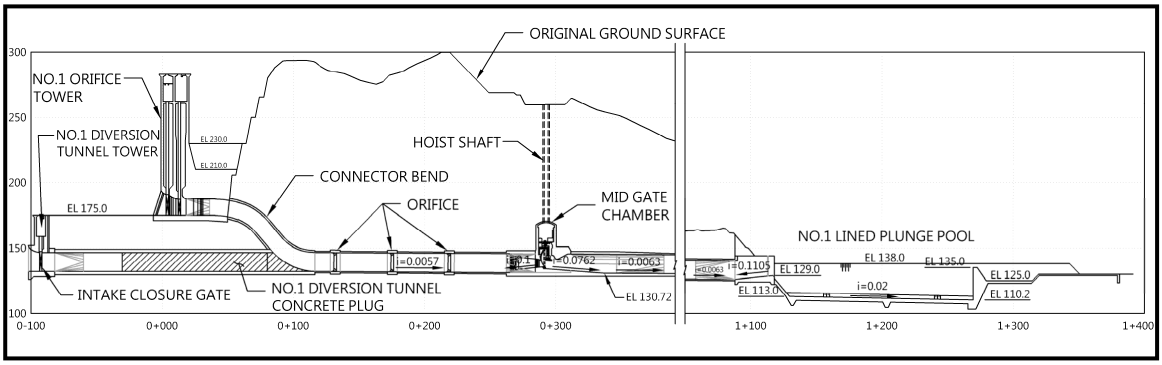

Figure 6: Adopted no.1 bottom outlet

5 Results of initial operation

In April and November , 2000 following the completion of the first multiple -orifice bottom outlet, two field tests of the as-built structure were conducted when the reservoir water level reached El. 210.0 m and EL. 234.0 m. Data on wall mean and pulsation pressures, noises, gate vibrations, ground vibrations, amount of air-entrainment and structured stresses were obtained. The maximum tested discharge was 1,290 m^3/s. It was determined that when the radial gate was nearly fully open, noise level from the microphone increased suddenly, indicating a possible initiation of incipient cavitation. Other parameters showed that the structure behaved pretty much expected. Details of the tests were described by Lin.

The Xiaolangdi Project was completed in 2002. To prove the design concept, man-made flood was created through operations of upstream reservoirs. Photos 1 and 2 depicts difference in discharge between upper level open channel and lower level multiple-orifice bottom outlets. The efficiency of the low-level outlet in discharging reservoir sediment is quite evident, indicating a successful conversion of diversion tunnels to bottom outlets, both from the viewpoints of structural function and sediment sluicing.

	
1. Top View	2. Side View
Photos: Xiaolangdi discharge structure in operation, 2002	

Acknowledgement

The author was the project coordinator and partially responsible for the initial development of the multiple-orifice energy dissipator scheme during the YRCC/Bechtel conceptual design phase in 1984-1987, while working at Bechtel Civil Corporation. Subsequent data were obtained from YRCC publications.

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Author

Sheng T. (Paul) Hsu
Chairman, G T International, 2F, No.215, Section 3, Nanjing E. Road, Taipei, Taiwan
Email: paulhsu@gtint.com.tw