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Physical Model Studies of Energy Dissipation Systems to Rehabilitate Jinnah Barrage

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Abstract

A subsidiary weir was proposed by feasibility consultants to rehabilitate and modernize Jinnah Barrage. This weir is to be constructed across the river, at a distance of about 800 ft, downstream of the barrage. Subsidiary weir location and crest level was finally fixed on the basis of a detailed physical model study. This model study was carried by Irrigation Research Institute (IRI) at their Lahore laboratory under the technical guidance of "Feasibility Consultants".

The "Detailed Design Consultants" while finalizing rehabilitation structure (either subsidiary weir or its alternative) requested IRI for another model study, which was carried out at Nandipur Research Station. It seems that the two model studies were under taken for the same project, having almost similar objectives. This paper critically reviews the judiciousness of two model studies carried out for the same project. Furthermore, the experimental results of various rehabilitation alternatives are also discussed in terms of their reliability and effectiveness.

Key Words: Jinnah barrage, physical model study, rehabilitation and modernization of Jinnah barrage, subsidiary weir, two-step stilling basin.

1. Introduction

Physical model study play vital role in planning and designing of hydraulic structures. Design of river training works, stilling basins, spillways and barrages are generally refined on the basis of physical model studies**.** However, physical model studies are expensive, time consuming and resources such as expertise, technical labor etc., are needed in developing and testing the models. Appropriate scale between model and prototype structure plays imperative role in terms of rationality and reliability of the results.

Finalization of rehabilitation and modernization works, for an existing hydraulic structure, on the basis of physical and numerical modeling, is a real challenge for researchers and engineers. Precise identification of hydraulic problems on prototype structure is paramount for the success of rehabilitation projects; otherwise huge investment may go partially or completely in waste [1, 2].

Islam barrage was rehabilitated by constructing a subsidiary weir at about 400 ft at its downstream. The subsidiary weir was constructed to develop hydraulic jump on glacis to dissipate excessive kinetic energy. But soon after rehabilitation the barrage lost its discharging capacity.

Recently rehabilitation and modernization of Taunsa barrage was carried out by constructing a subsidiary weir across the river at about 800 ft of its downstream. The existing concrete floor was overlaid by 2 ft thick RCC slab and replenishment of loose stone apron was carried out. Rationality of this massive rehabilitation project is questionable as model study showed that at prevailing water level conditions, hydraulic jump remained on glacis up to the discharge of 400000 cusec [3]. Furthermore, hydraulic performance of barrage, undersluices, silt excluders and the subsidiary weir are not yet tested, at higher discharges. Hydropower potential at the barrage is almost ended since placing of hydropower project and dismantling of subsidiary weir is very difficult.

Mahboob [4, 5] reviewed the design of Jinnah barrage and found it acceptable. Jinnah barrage energy dissipation study, under prevailing water level conditions noted that excessive retrogression repelled hydraulic jump over horizontal floor [6, 7, 8]. Feasibility Report [8] proposed subsidiary, whereas Chaudhry, et. al, [1] proposed two alternatives to the subsidiary weir as rehabilitation structures.

2. Barrage Details

Jinnah barrage consisted of 42 weir bays; two undersluices each consisting of 7 bays with clear span of 60 ft. Barrage width between abutments is 3781 ft, whereas clear waterway for weir and undersluices sections are 2520 ft and 420 ft, respectively. Weir and undersluices crest and floor levels are at EL678, EL670, EL675 and EL667, respectively. Two divide walls (350 ft long), bifurcate weir and undersluices sections of the barrage. In left and right undersluices, two fish ladders are provided adjacent to the divide walls. Jinnah barrage has 20 ft wide navigation bay and silt exclusion system in its right and left undersluices, respectively.

The barrage is designed for a flood of 950,000 cusec; however, a flood of 1100,000 cusec can be passed as the barrage guide banks have enough freeboard. Normal pond level is at EL692, which will be raised at EL694 to meet 10,000 cusec of remodeled capacity of Thal canal.

3. Physical Model Studies

3.1 First Model Study

Feasibility Consultants in Year 2004 requested IRI, to optimize energy dissipation arrangements, on a physical model. A model study was carried out for the existing structure and various rehabilitation alternatives. As mentioned in the Feasibility Report [8], the model study was intended to achieve following objectives:

a) Hydraulic jump should take place on glacis.

b) Retrogression in river bed d/s of barrage is controlled.

c) Suitable curative measures such as subsidiary weir to restore the position of hydraulic jump on the sloping glacis and consequent energy dissipation.

d) To determine suitable location for the subsidiary weir.

Sectional model of weir section of barrage was fabricated using teak wood on a geometrical scale of 1/45 and fitted in a glass sided flume. Physical model represented one bay in center, enclosed by half bay on either side, separated from central bay by 7 ft wide piers. Three gates made of iron sheet along with their hoisting system were also provided in the model.

This model study seems deficient in following aspects:

- Tail water levels, at higher discharges used in model study were not computed precisely; rather values were on lower side. For example the difference in water level for the discharge of 950000 cusec and 110000 cusec is just 0.5 ft **(Figure 1).** Comparison of tail water levels maintained in first and second model study showed a significant difference at higher discharges **(Figure 1).** For example at the discharge of 950000 cusec, the tail water level (EL690) maintained in second model study was 3 ft higher as compared with the corresponding level (EL687) used in first study. Tail water level is a sensitive parameter and controls the location of hydraulic jump. This model study didn't precisely model the location of hydraulic jump and energy dissipation in the stilling basin at higher discharges.
- Physical model was developed in a laboratory flume at the geometric scale of 1:45. Size of impact and friction blocks became too small in the model and didn't reflect hydraulics of prototype structure precisely.
- Laboratory flume was of rigid bed, whereas river bed is erodible and has potential to scour.
- Undersluices are imperative components of the barrage; draw about 27% of river flows and used for sediment sluicing. Hydraulic performance of undersluices (crest EL675) after the construction of subsidiary weir (crest EL676) on its downstream was not studied on the physical model.

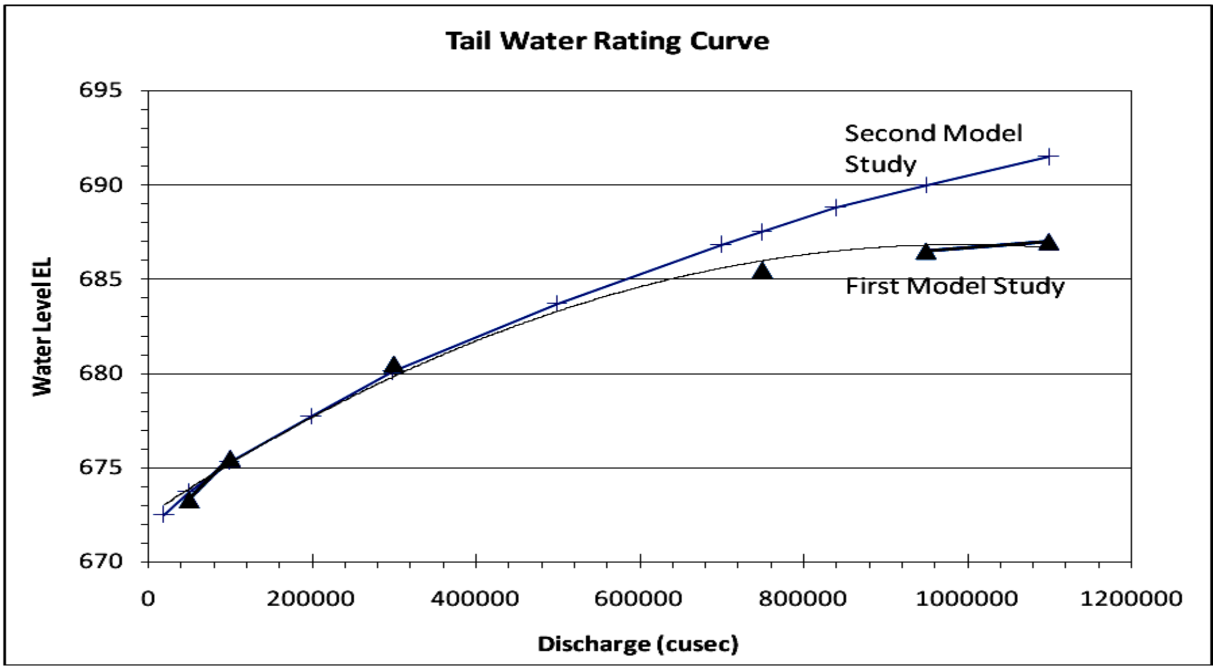

Fig. 1 Tail water rating curves employed in the model studies.

Base test was carried out developing prevailing water level conditions on the model. Upstream water level was maintained at EL694 under gated control flow, whereas free flow conditions were considered in case of higher discharges. Feasibility Report [8] showed that the jump repelled over the floor for all discharges.

To shift hydraulic jump over glacis, a 4ft high solid wall was placed at the location of baffle/impact blocks, but the test failed at very low discharges. In second rehabilitation scenario the wall was shifted at the location of friction blocks. This arrangement worked up to the discharge of 300,000 cusec whereas at higher discharges the jump swept with shooting flow. Feasibility Report [8] noted that the subsidiary weir arrangement with crest at EL676 at a distance from 800 ft to 1200 ft from the barrage crest, developed hydraulic jump over the glacis.

3.2 Second Model Study

Partial model of barrage was developed at IRI Nandipur, at geometric scale of 1:16. One complete bay and two half bays along with piers and gated arrangements were constructed in an already existing channel. The channel bed at upstream and downstream was kept erodible to model scour development and loose stone apron displacement. In base test the loose stone was placed downstream of stilling basin as per its size and dimensions on prototype.

This model study was focused on the assumption that energy dissipation problems persists in weir section of barrage and no rehabilitation works are required downstream of undersluices [1, 2]. Furthermore the subsidiary weir arrangement was also tested on physical model.

This study was intended for the following objectives:

a) *To study hydraulics of weir section of the barrage under prevailing water level condition.*

b) *Alternative 1*

i. To study proposed Gabion size for its stability (Fig 3a).

ii. To optimize gabion size that act as flexible lining and shall not be displaced.

iii. To check whether energy dissipation becomes substantial at the end of loose stone apron.

c) *Alternative 2*

Alternative 2, the two-step stilling basin arrangement as shown in Fig 3b, was tested by changing its crest elevation and location, for the following objectives:

i. Hydraulic jump should form at glacis of main barrage and second stilling basin; consequently the energy dissipation takes place in both the jumps.

ii. Overall energy dissipation should be substantial at the end of second stilling basin.

iii. Variation in water depth over crest of second stilling basin shall be within acceptable limits.

iv. The project is economized by finishing rehabilitation works within the existing divide walls.

d) *Subsidiary Weir at 600 ft From Barrage Crest*

The subsidiary weir arrangement was also tested for the following objectives:

i. Hydraulic jump should take place on glacis.

ii. Loose stone apron downstream of stilling basin should remain stable at the design discharge.

Fig 2a loose stone placed at slope

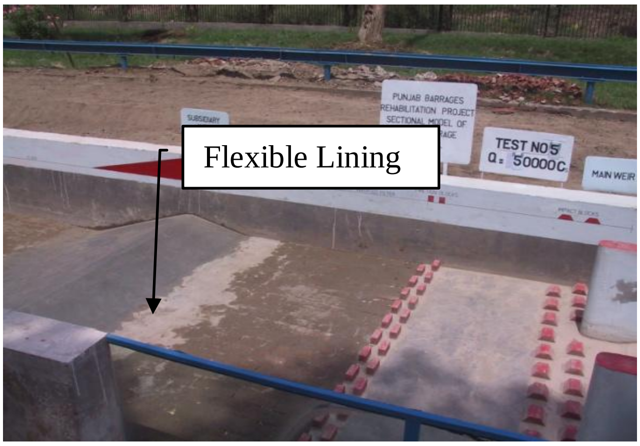

Fig 2b two-step stilling basin

Fig. 2 Structural arrangements of Alternative 1 and 2.

3.3 Second Model Study Results

First test was performed to study energy dissipation arrangements provided at the barrage. Physical model reasonably models energy dissipation mechanism such as location of jump and functioning of impact and friction blocks. Figure 3 shows that the model results were comparable to that of the prototype. Scour pits were developed and loose stone was displaced after passing the floods of various intensities, Fig 4(a).

Fig 3a The model

Fig 3b The barrage

Fig. 3 Energy dissipation systems in operation for the discharge of 100000 cusec.

3.3.1 Alternative I

The Alternative-1 was based on the assumption that existing d/s floor is strong enough and energy dissipation mechanism is working well. Repairs to impact blocks and adjacent concrete floor will be carried out as and when required. Displacement of loose stone is to be controlled by placing stone at stable slope and in proper size.

Alternative-1 as shown in Fig 3 (a) is sloping stone apron laid at the slope of 1V:15H. The stone apron starts from concrete block floor (EL670) and finished at the level EL662, having an overall length of about 120 ft. Stone apron is designed for the velocity of 16 ft/sec which occurs at the discharge of 950000 cusec. On prototype, the stone should be placed in gabions, whereas size of sloping stone apron used at the model is given in Table 1.

Table 2 show the velocity and Froude number with reference to the bed level EL662. The energy dissipation became substantial and Froude number remained even less than 0.34. Furthermore as shown in Figure 5, the flow was reasonably quite and clam with increasing flow depth in the downstream.

Table 1 Loose stone apron characteristics for model and the prototype (Alternative 1).

Design Discharge	950000	Cusec
Velocity downstream of barrage	16.0	ft/sec
Velocity downstream at the model	4.0	ft/sec
Size of stone at the model	2.25	in
Volume of the stone	5.96	in^3
Weight of the stone	0.569	lb
Gabion size on prototype 2ft×3ft×3ft	2970	lb

Table 2 Velocity and Froude number downstream of stone apron (Alternative 1).

Discharge (cusec)	Tail water Level EL	Water depth at the end of loose stone	Velocity ft/sec	Froude number	Energy dissipation
100,000	675.30	13.30	2.26	0.11	Substantial
300,000	680.10	18.10	4.97	0.21	Substantial
500,000	683.70	21.70	6.91	0.26	Substantial
700,000	686.80	24.80	8.47	0.30	Substantial
850000	688.80	26.80	9.51	0.32	Substantial
950,000	690.00	28.00	10.18	0.34	Substantial

Fig 4a existing condition (stone displaced)

Fig 4b Alternative 1 (stone not displaced)

Fig.4 The loose stone apron and development of scour pits after the tests.

Fig 5a Discharge 850000 cusec

Fig 5b Discharge 950000 cusec

Figure 5 model showing reasonably calm flows (Alternative 1).

3.3.2 Alternative 2

Alternative 2, shown in Fig 2(b) is provision of another stilling basin, to be located at about 200 ft from the barrage crest. The crest elevation varies from EL674 to EL676, to be finalized at the model. This is basically a two-step stilling basin in which the energy dissipation takes place in both the jumps. The second stilling basin acts structurally and hydraulically an integral part of the existing barrage structure.

With crest level at EL674, it was noted that the jump repelled for the discharge above 100000 cusec. In the first model study the jump remained over glacis up to the discharge of 400000 cusec when a vertical wall of same height (EL474) placed at the location of friction blocks. This indicates that optimum location of second stilling basin crest is just the end of existing stilling basin floor.

Due to higher water depth in second stilling basin the overall energy dissipation became substantial (Table 3). Subsequently, second stilling basin crest level was raised at EL675 and EL676, keeping its location the same. Results revealed that the hydraulic jump developed over the glacis and energy dissipation remained substantial. Hydraulic performance of two-step stilling basin with crest EL676 was slightly better in terms of jump location on barrage crest. Figure 7 show jump development at the discharge of 850000 and 950000 cusec, respectively.

Fig 6a Discharge 850000 cusec

Fig 6b Discharge 950000 cusec

Fig. 6 Hydraulic jumps at the model with subweir crest at EL676.

3.3.3 Subsidiary Weir

A subsidiary weir at 600 ft from the barrage crest was also tested to reaffirm its hydraulic functioning. The subsidiary weir crest level varied from EL674 to EL676. Chute blocks and end sill were also incorporated in the model study. This crest level was 2 ft low and 1 ft high as compared with the crest level of the weir (EL678) and undersluices (EL685) sections of the barrage, respectively.

Rise in water level upstream of the subsidiary weir with crest level at EL676 was just satisfactory to shift the hydraulic jump over the glacis (Table 3). The decrease in velocity upstream of the subsidiary weir, especially at higher discharges is not promising. Furthermore the velocity remained fluctuating and higher near the bed in region where stone apron was placed. This not only launched loose stone apron but deep scour pits were also developed (Figure 7). The situation became worsen as compared with existing conditions tested on physical model.

Experimental results further indicate that subsidiary weir is an isolated structure and not showing structural support to the barrage.

Table 3 Hydraulics of two-step stilling basin with crest EL674 and 200ft centerline distance between the crests.

Discharge cusec	Pond level (EL)	Froude Number		Remarks		
		u/s	d/s	Jump		Energy dissipation
		second stilling basin		d/s barrage	d/s second stilling basin	
50000	694.00	0.16	0.05	ok	ok	Substantial
100,000	694.00	0.18	0.08	ok	ok	Substantial
300,000	694.00	0.38	0.16	ok	Not ok	Substantial
500,000	694.00	0.50	0.22	Not ok	Not ok	Substantial
700,000	694.00	--------	0.26	Not ok	Not ok	Substantial
850000	694.30	--------	0.28	Not ok	Not ok	Substantial
950,000	694.70	--------	0.29	Not ok	Not ok	Substantial

Table 4: Hydraulic performance of two-step weir with crest EL676 and 200ft centerline distance between the crests.

Discharge cusec	Water level u/s of second stilling basin (EL)	Froude Number		Remarks		
		u/s	d/s	Jump		Energy dissipation
		second stilling basin		d/s barrage	d/s second stilling basin	
50000	678.45	0.11	0.05	ok	ok	Substantial
100,000	679.90	0.17	0.08	ok	ok	Substantial
300,000	683.50	0.32	0.16	ok	ok	Substantial
500,000	686.35	0.40	0.22	ok	ok	Substantial
750,000	689.60	0.46	0.26	ok	ok	Substantial
850,000	690.70	0.48	0.28	ok	ok	Substantial
950,000	691.65	0.50	0.29	ok	ok	Substantial

Table 5 Water depth and velocity variations, with and without the subsidiary weir.

Discharge (cusec) (prototype values)		Water depth downstream of barrage (ft)		Velocity downstream of barrage (ft/sec)	
Total	Per unit width	With subsidiary weir	Prevailing value	With subsidiary weir	Prevailing value
50000	15	8.45	3.70	1.78	4.05
100000	30	9.90	5.30	3.03	5.66
300000	90	13.50	10.10	6.67	8.91
500000	150	16.35	13.70	9.17	10.95
750000	225	19.60	17.70	11.48	12.71
850000	255	20.70	18.20	12.32	14.01
950000	285	21.65	20.00	13.16	14.25

Fig 7a

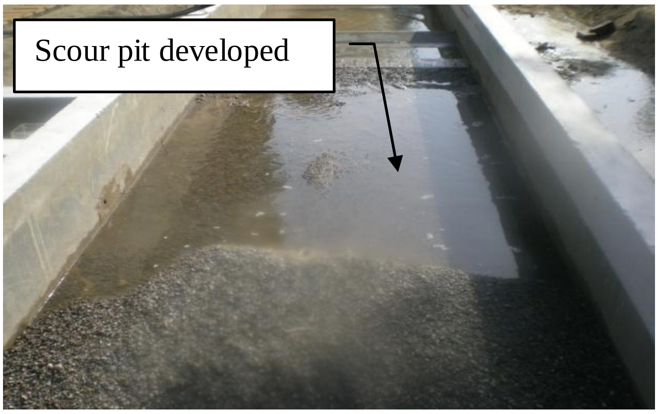

Fig 7b

Fig. 7 The scour pit developed and stone apron launched (Subsidiary weir at 600ft with crest at EL676).

4. Conclusions

For the same discharge the tail water level maintained, varied considerably in both the model studies. For example, at the discharge of 950000 cusec, the tail water level maintained in first model study was 3 ft lower (EL687) as compared with the second model study (EL690). Tail water level is sensitive parameter and controls the location of hydraulic jump. It is observed that in first model study the tail water levels were not computed precisely; rather the values were on lower side.

River bed between barrage and subsidiary weir was made rigid in the first model, whereas it is erodible and has potential to scour. In second model the erodible bed conditions were maintained and loose stone apron was designed accordingly.

Undersluices are important component of the barrage; draw about 27% of river flows and are used for sediment sluicing. Undersluices performance with the provision of subsidiary weir was not tested in the first model study.

The geometric scales 1:45 and 1:16 varied considerably. For such projects, the geometric scale 1:45 used in first model was too diminutive; consequently the size of impact blocks became very small and frictional resistance dominated.

Model results showed that both the alternatives to subsidiary weir worked well as per objectives fixed. Change in water depth upstream of the subsidiary weir/two-step stilling basin even with crest level EL676 is not promising; consequently velocity remains higher and fluctuating. This developed scour pits and displaced loose stone apron. Experimental results further reveal that the subsidiary weir is an isolated structure and not showing any structural support to the barrage.

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