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Technical Issues on Detailed Design of RCC Dam for the Dasu Hydropower

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ABSTRACT:
In spite of chronic load-shedding due to lack of electric power, which is one of the most serious socio-economic issues of Pakistan, there is huge hydropower potential originating from glaciers in the north-west region of Pakistan where the Himalayas, the Karakorams and Hindu Kush Mountains meet. Already, Tarbela Hydopower Project (3,478 MW) built in 1976, one of the largest hydropower stations in Pakistan, utilizes the flow of the Indus River originating in the north-west mountainous area. Pakistan Water and Power Development Authority (WAPDA) plans Dasu Hydropower Project located 200 km upstream of Tarbela or 350 km north of Islamabad, the capital city. It is composed of a concrete gravity dam and an underground powerhouse with 12 generators with each 360 MW capacity, 4,320 MW in total. Main specifications of the dam are 242 m height, 570 m length and 4.1 million m^3 volume of RCC. This paper describes the challenging design concept of the RCC dam due to issues such as: i) dynamic analysis and countermeasure for safety against large earthquakes, ii) design of flushing facility for sedimentation, iii) RCC mix proportion with natural pozzolan. 2D/3D dynamic analyses were conducted to evaluate safety for the maximum credible earthquake (MCE). Low Level Outlet (LLO) in the dam and two flushing tunnels on the right bank for flushing of sedimentation was designed based on sedimentation analysis along the Indus River. Natural pozzolan from gracial deposits will be used as the cementitious material instead of flyash or blast-furnace slag.

***Keywords:** 3-Dimensional Dynamic Analysis, Dam Reservoir Sedimentation, Natural Pozzolan*

1. INTRODUCTION

Pakistan has rich hydropower potential, and a total of 54,000 MW of potential power has been identified. However, only a small proportion, about 6,500 MW (12 %), has been developed to date. A peak power deficit reached to around 5,000 MW in 2010 due to the rapid increase of power demand by some 10% per annum. Given such a power crisis, a series of large hydropower developments have been studied in the northern part of Pakistan in the Indus River, which has the greatest potential in the country to achieve energy security and subsequent economic growth.

The Dasu Hydropower Consultants (DHC) in Lahore is undertaking the detailed design and bid preparation services for the Dasu Hydropower Project (Dasu HPP). The services started in September 2011 with a target completion time of 18 months.

Dasu HPP is the third among the five major planned hydropower projects in the cascade along the upstream stretch of the existing Tarbela HPP (Installed capacity: 3,478 MW) in the Indus River. Ordering from the north, these are Bunji HPP (7,100 MW), Diamer-Basha HPP (4,500 MW), Dasu HPP (4,320 MW), Pattan HPP (2,800 MW) and Thakot HPP (2,800 MW).

The Dasu dam site is located in a deep and narrow gorge having the existing Karakoram highway (KKH) on the left bank. The proposed RCC dam will be 242 m high and 570 m long, will have an RCC volume of 4.1 million m^3 and a reservoir capacity of 1,410 million m^3. The annual average discharge at the dam site is expected to be 2,100m^3/s that will bear an annual generation of 18,432 GWh with an installed capacity of 4,320 MW (12 x 360 MW). There will be an underground powerhouse with four 2.2 km long waterways. In order to limit the initial costs, the Project will be phased. Each of the four Phases will consist of one waterway and three units, thus 12-unit in total.

The paper describes the design concepts in order to overcome the major challenges of the Project, such as (i) the dynamic analysis of the severe earthquake loading, (ii) the installation of the low-level outlets (LLOs) and the flushing tunnels for the large sedimentation loads, and (iii) the RCC mix design using local natural pozzolan to achieve the high strengths required.

2. OUTLINE OF THE DASU DAM

2.1. Profile of the RCC Dam

The Project is located 7 km north of Dasu Town in the Kohistan District of the Khyber Pakhtunkhwa Province. It is 350 km north of Islamabad, the capital city of Pakistan. The dam site is 74 km downstream of the proposed Diamer-Basha dam site along the Indus River, and the elevation of KKH near the dam site is about El.840 m. The Dasu reservoir extends to just downstream of the proposed Diamer-Basha dam site.

The Dasu dam is to be constructed as a RCC dam at the middle point along a straight stretch in a narrow valley of the Indus River. As there is no sufficient space to divert the river through an open channel or culvert at the dam site, the flood will be diverted through two diversion tunnels on the left bank during the dam construction period of about six and a half years.

Fig. 1 shows the general view of the Dasu dam and the appurtenant structures. Although the main RCC dam is of a concrete gravity type, the dam axis forms arcs of 525 m in the overflow sections and 1,000 m in the non-overflow sections. The cross section of the dam is composed of slopes of 1:0.72 (Vertical: Horizontal) on the downstream (d/s) face, 1:0.10 on the upstream (u/s) face and fillets with 1:0.2492 and 1:0.80 slopes, which are determined through static stability analyses and dynamic stress analyses for the operation based earthquake (OBE) and maximum credible earthquake (MCE).

2.2. Hydraulic Structures

As for the hydraulic design, Safety Check Flood (SCF) requires eight spillway gates and nine low-level outlets (LLOs). Additionally, two flushing tunnels will be installed in the right bank of the dam for sedimentation control by annual flushing operation under free-flow conditions. The power intake structures with four tunnels and the powerhouse cavern will be arranged on the left bank. Table 1 also shows the salient features of the Project.

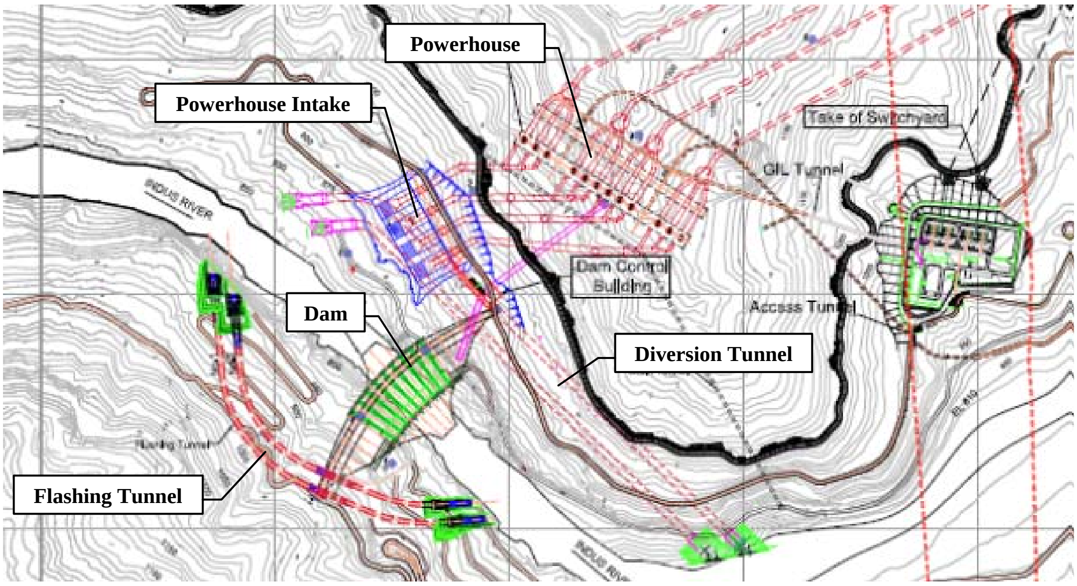

Figure 1. General view of the Dasu dam and appurtenant structures

Table 1. Salient Features of the Project

River & Reservoir		Dam & Appurtenant Structures	
Catchment area	158,800 km^2	Dam type	Concrete gravity dam (RCC)
Average discharge at site	2,102 m^3/s	Dam height	242 m
Safety check flood (SCF)	51,957 m^3/s	Dam crest length	570 m
Basic design flood (BDF)	24,932 m^3/s	Dam RCC volume	4.1 million m^3
Dam crest elevation	El.957.0 m	Spillway	8-radial gate, 16.5 m W x 22.4 m H
Flood water level under SCF	El.959.46 m	Low-level outlet	9-radial gate & pipe 6.4 m dia.
Flood water level under BDF	El.951.28 m	Flushing tunnel	2-tunnels of 9.5 m dia.
Full supply level (FSL)	El.950.00 m	Generator	4,320 MW (360 MW x 12)
Minimum operation level	El.900.00 m		
Gross reservoir storage	1,410 million m^3		

Three LLOs are supposed to be installed during phase 1 at first, while it depends on finance availability, then other six sets will be installed during phases 2. The spillway with eight radial gates is capable of releasing the SCF/PMF (51,960 m^3/s) with the flood overtopping the 1.1 m high parapet wall on the central nine RCC blocks (a length of 225 m) with a 1.4 m water depth with all the spillway gates in operation and the three LLOs but without using the flushing tunnels. The SCF can be released from the eight spillway gates with using all LLOs (i.e. nine LLOs) after their completion with 1.33 m freeboard from the crest elevation of the dam at El.957.0 m. The Basic Design Flood (BDF: 26,640 m^3/s) can be released by the spillway safely with sufficient freeboard at the water level of El.951.28 m with one gate non-operational (i.e. through only seven gates) without the use of the LLOs and flushing tunnels. As mentioned above, the LLOs will be installed to release SCF with the spillway gates, however, can be also opened frequently during a high-flow season in order to discharge the sediments from the reservoir.

The number of spillway gates (W16.5 m x H22.0 m) has been increased by two from the six gates in the F/S report. The number of LLOs was also increased by two (circular: D6.4m) from seven (rectangular: W5.0 m x H7.2 m) in the F/S report. The cross-sectional area of the LLOs was thus increased by 14.9 %, as the maximum total flow capacities is required for sediment flushing under free-flow conditions.

3. COUNTERMEASURE AGAINST LARGE SCALE OF EARTHQUAKE

3.1. Requirement of Analysis against Large Scale Earthquake

The Dasu Project is located in the Kohistan Island Arc physiographic province. Tectonically, it is classified as an active earthquake region, because it is sandwiched between the converging Indian and Eurasian tectonic plates. According to the grouping of the Geological Survey in Pakistan, the Project area belongs to the "Serious Seismic Danger Zone". The Dasu dam, which is 242 m high, is a critical component of the Project. Thus, the dam should maintain safe under strong seismic activity based on the guidelines of ICOLD regarding selecting seismic parameter regarding for large dams. That is large dams must be capable of resisting severe earthquake motion without uncontrolled release of the reservoir water, namely, damage to the dam due to the severe earthquake motion may be acceptable as long as no catastrophic flooding occurs in the downstream river.

3.2. Selection of applied Earthquake

The acceleration time history of the earthquake ground motion by "1971 San Fernando" was selected for the analysis, as it has the most strong ground motion among three alternatives, which has the longest wave motion period of h=11.28 sec and v=14.72 sec. The most severe ground motion affecting to a dam is referred as Maximum Credible Earthquake (MCE) of which Peak Ground Acceleration (PGA) is h = 0.54 (max. 531.2 gal) and v = 0.36 (max.354.1 gal), respectively.

3.3. Methodology of 2D/3D Dynamic Dam Analysis

The 2D and 3D dynamic FEM analyses were executed to assess the seismic risks against a large earthquake observed in serious situations. In the case of the Dasu dam, under consideration of the concrete gravity RCC dam with an arch shape and a height to length (H/L) = of 0.47 locating at the narrow valley in the strong earthquake zone of Pakistan, the analysis was applied not only for 2D but also 3D dynamic FEM. In the case of tensile cracks opened through the whole dam body, it will require some countermeasures against the cracks.

3.4. Results of Analysis and Countermeasures

Zoning with two grades of RCC such as "RCC1" with characteristic cylinder compressive strength of 25 MPa in the lower zone below El.850.2 m and "RCC2" with 20 MPa strength in the upper zone above El.850.2 m (see Fig. 2) was applied as a safe design without any crack penetrations for MCE in the dam body through 2D dynamic analyses. However, the response accelerations at the dam crest 3D analyses were quite different from those of the 2D analyses. As shown in Table 2, the maximum horizontal acceleration by 3D linear analysis is 4,417.7 gal, while that of 2D analysis is 1,984.4 gal. It is considered to be affected by the seismic motion from both abutments under the topographic condition of the narrow gorge. As a result, the inferred cracks by 3D non-linear analyses spread over the whole dam body of the upper zone (see Fig. 2).

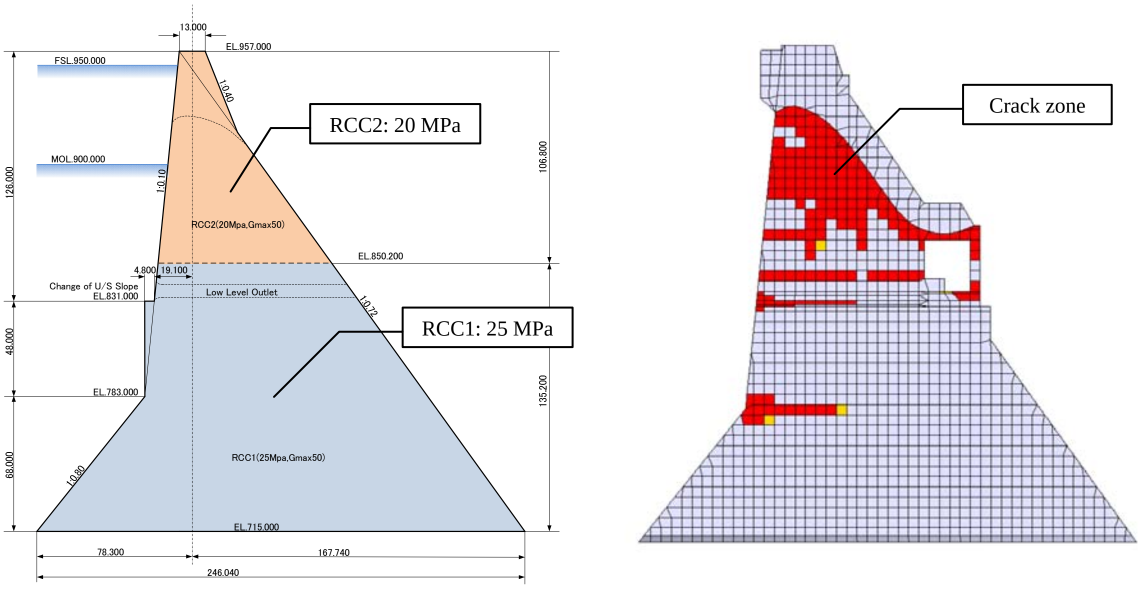

Figure 2. Initial dam shape determined through 2D stability analysis/2D dynamic analysis and estimated crack zone for MCE by 3D non-linear dynamic analysis

Table 2. Maximum Response Acceleration at the Dam Crest for MCE

	Horizontal		Vertical	
	2D analysis	3D analysis	2D analysis	3D analysis
Acceleration at bottom of the dam	531.2 gal	421.0 gal	354.1 gal	312.2 gal
Acceleration at crest of the dam	1,984.4 gal	4,417.7 gal	996.0 gal	1,401.8 gal
Response magnification rate	3.7	10.5	2.8	4.5

The final zoning of RCCs to minimize crack penetration is proposed as shown in Fig. 3. A high-strength 30 MPa RCC will be applied for a 10 m depth on both the u/s and d/s slopes in above El.770.0 m and for the whole width of the dam above El.920.4 m. The shape of the fillets is also improved from the initial shape. The estimated crack zone in the dam body was remarkably reduced from the previous case.

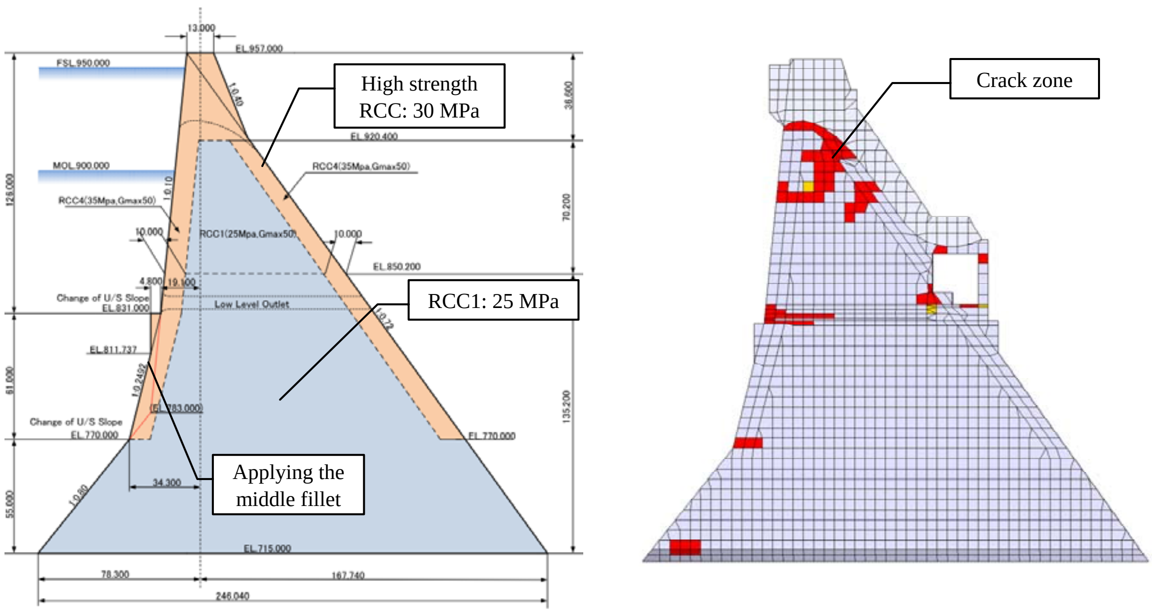

Figure 3. Improved dam shape and zoning of RCCs, and estimated crack zone by 3D analysis

However, a local crack yet penetrates even for the final shape and the RCC zoning mentioned above. The stability on the penetrated crack surface (El.890.0 m) was examined through stability analyses by the earthquake time history mentioned below to assess a possibility of a large collapse of separated dam body which might give catastrophic damages to the downstream area. Fig. 4 shows the safety factors for sliding on the penetrated crack through the time history, where seismic inertia, static/hydrodynamic water pressures and uplift on the crack surface are given as the sliding forces, and frictions on the penetrated crack surface and on the dam joint surfaces with both adjacent blocks act as resistance forces. The minimum safety factor is 1.06 for Block-11, therefore the separated dam body on the penetrated crack will not be assessed to collapse. The arc shape of the dam will provide a effective resistance force against the seismic movement.

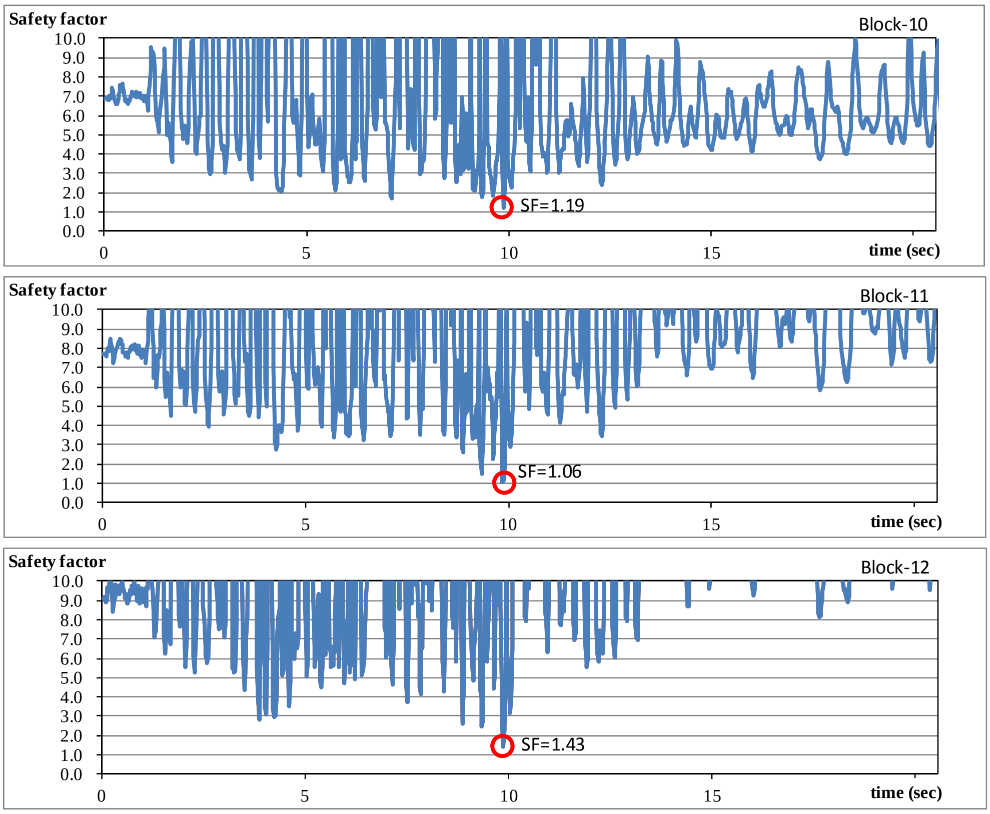

Figure 4. Safety factor for sliding of separated dam body on the penetrated crack

4. COUNTERMEASURE AGAINST LARGE SEDIMENTATION VOLUME

4.1. Sedimentation Mechanism in the Dasu Reservoir

In order to grasp the sedimentation mechanism in the reservoir over a defined operation period, the scour/deposition was analyzed while maintaining the reservoir water level at FSL without any flushing operations. Fig. 5 shows the longitudinal profiles of the sedimentation delta at each 5-year interval without flushing.

As the results of annual sediment inflow, outflow and trapped sediment in the reservoir without flushing, the one-dimensional HEC-RAS model confirmed that the trapped sediment volume is 58 % of sediment inflow and 61 % by Brune's formula. The performances of sediment profiles suggest the following points:

- According to the longitudinal profiles of the sedimentation delta, it is expected for the LLO inlets and the power intakes to be blocked with sediment within 20 to 25 years after the start of operation.
- After 15 years, the foot of the sedimentation delta is developed only up to El.780 m (50 m below LLO inlet) 9 km upstream of the dam with its El.910 m (130 m depth on top), which conforms to the stable slope of 5.3 m/km of the Tarbela reservoir's guideline.
- It is likely that the sedimentation delta will rapidly approach the dam exceeding the stable slope. This might bring the sudden collapse of the delta and could result in the blockage of the LLO inlets.

Consequently, the non-flushing operation might be allowed for only 15 years if there will be no dam development in the upstream river. The project may prolong flushing operation up to 15 years after the start of operation, since it would contribute not only for maximization of annual energy production in the 15 years but also mitigation of annual sediment inflow in the Tarbela reservoir. After a dam development in the upstream river, flushing operations would not be required for further 30 years.

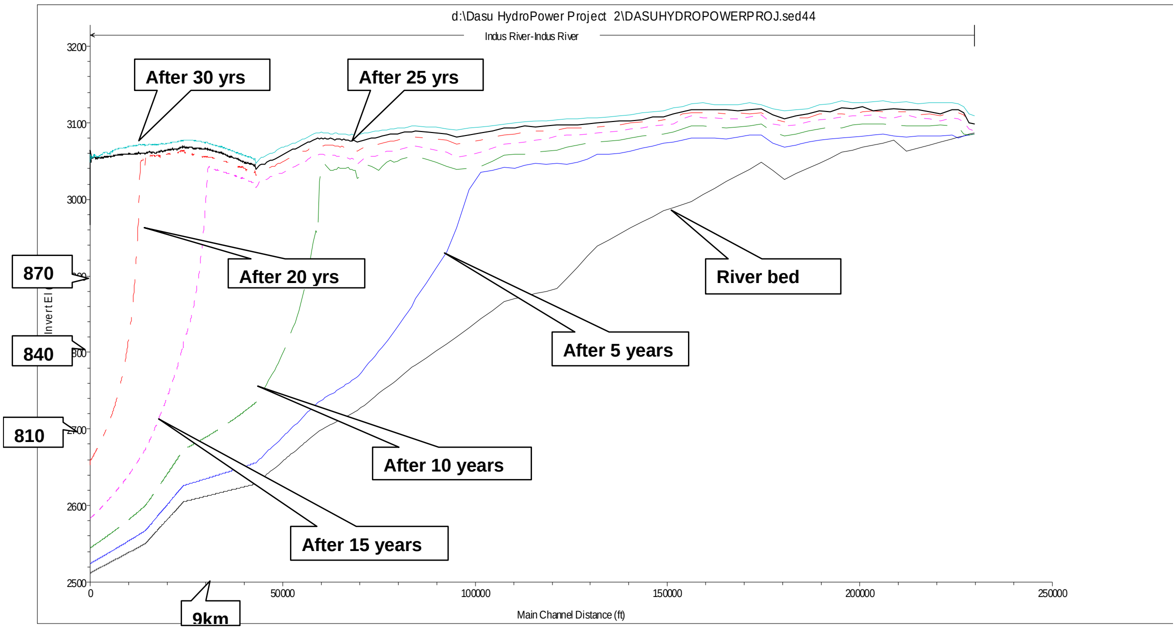

Figure 5. Longitudinal sediment profiles without flushing (Ackers-White Formula)

4.2. Design of Flushing Facilities

In general, the flushing operations are divided into two types; pressure-flow and free-flow operation. After the hydraulic simulation regarding the moving performance of the sediment delta profile under hydraulic conditions by both methods, the free-flow flushing operation was judged to be adopted as the most suitable method.

Nine LLOs with 6.4 m diameter are provided under the spillway bays and their total flow capacity is 2,280 m^3/s under free-flow conditions. However, the detailed sediment management study reported in the previous section indicates that a larger discharge for sediment flushing is preferable and results in maintaining the sustainability of the reservoir. Then, the flow capacity of 4,400 m^3/s through the LLOs and the flushing tunnels is determined by the following considerations:

- The flushing discharges are generally recommended to be twice of the annual mean flow. It is worldwide experience on the large dams being flushed at regular basis. As the annual mean inflow is 2,102 m^3/s, the required discharge capacity will become more than 4,200 m^3/s.
- It is appropriate to flush the sediment in June before entering in a peak high flow season (July to August), since the monthly average inflow discharge of June is 4,329 m^3/s. The high flow season is crucial for power generation to maximize the annual energy outputs.
- A circular section with 6.4 m inner diameter is recommended for the LLOs as the maximum size in a view of peripheral tensile and shear stresses around the LLO pipes. Then, as the total discharge capacity of the nine LLOs is limited to 2,280 m^3/s under free-flow conditions, other facility is required for flushing external to the dam.
- To overcome the above situations, the balance of the required discharge, 2,120 m^3/s (i.e = 4,400 - 2,280), will be released through two flushing tunnels to be excavated in the right bank of the dam. This is on the opposite bank to the diversion tunnels and the power intakes.

4.4. Recommended Flushing Operation

A drawdown for flushing should be executed in May to June, since such operation will allow refilling the reservoir immediately after the drawdown flushing in mid-June, for a quick starting of power generation with high flows due to snow melt. A rapid refilling of the reservoir would achieve greater power generation during the rest of the season. Once the reservoir water level is lowered to El.842.55m by the LLOs, the free-flow flushing operation through the LLOs and flushing tunnels should be started simultaneously.

The tentative operation manual for the flushing operations is described below: The flushing operations are divided into the following two periods with consideration of the discharge capacities of the LLOs and the flushing tunnels, and the indispensable period for an annual inspection at the flushing tunnels:

- 1st flushing schedule: May 20 to June 20 operated together with LLOs and flushing tunnels, and
- 2nd flushing schedule: Sep.10 to Oct.10 operated by LLOs only.

When no flushing is being undertaken, the flushing tunnels should be closed by both the guard and the main gates in the gate chamber at just d/s of dam axis, whilst the stoplogs at the tunnel inlets are removed. Just after starting of LLOs operation under free-flow conditions, the flushing tunnels are closed by stoplogs and the inside of the tunnels is dryed by opening the guard and main gates. The inspection of the flushing tunnels would then immediately be started. If significant damages were to be found in the flushing tunnels, necessary repair and remedial works should then be commenced. Conversely, if no damage was observed, the stoplogs should be removed for flushing operation through the flushing tunnels.

5. RCC MIX DESIGN USING LOCAL NATURAL POZZOLAN

5.1. Development of the Mixture Proportion for the RCC

The only practical pozzolans that are available in any quantities in Central and Northern Pakistan are natural pozzolans; flyash and blast-furnace slag are only available in small quantities and only in Southern Pakistan and are too far from the Dasu site. It is also not practical to import materials in the quantities required for the Dasu dam.

An extensive search was made for natural pozzolans within an accessible range from the Dasu site. Although six different locations were investigated as sources of natural pozzolans, only one was proved to be practical in terms of quality, availability and distance from the site, which is located in Gini, around 128 km upstream from the Dasu site along the KKH. Several Portland cements were also tested, however, only two productions were proved to be practical at this moment. The aggregate is quarried from a diorite area which is located at around 8 km upstream from the Das site within the dam reservoir area.

The Trial Mix Programme was undertaken in three stages, Stage 1 in April 2012 to assess the performance of the various cementitious materials, Stage 2 in September 2012 to refine the mixture proportions of the RCC and to develop the leveling concrete (that will be used to create a platform onto which the RCC can be placed) and Stage 3 to study the high-strength RCC (see Section 3) applied for the surface of the dam. Fig. 6 shows the 182- and 365-day best-fit relationships from the Stage 1 and Stage 2 Trial Mix Programmes (both Stages were used to develop the 182-day relationship, Stage 1 was used for the 365-day relationship). Also shown in the Fig. 6 are the design strengths required for the RCC1 (25 MPa) and RCC2 (20 MPa).

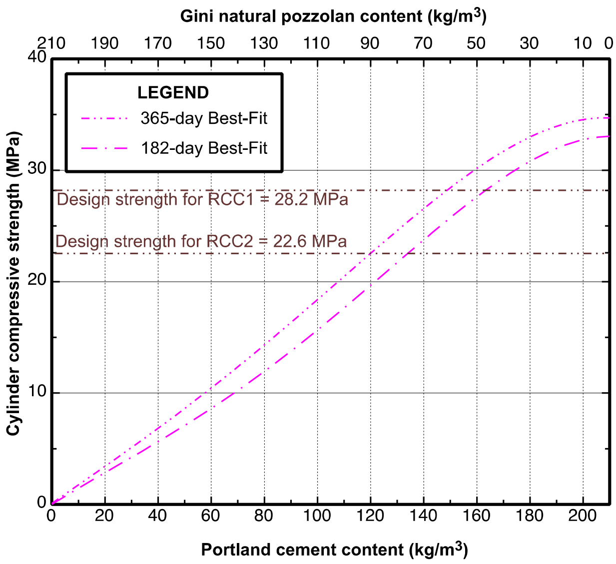

Figure 6. Relationship between 182- and 365-day cylinder compressive strength and Portland cement and natural pozzolan contents of RCC

The determined mixture proportions of these RCCs are shown in Table 3, although those for RCC5 (30 MPa) will be refined after the Stage 3 Trial Mix Programme. Although the natural pozzolan from Gini does not have a particularly good performance in concrete, it has proved to be possible to develop high-strength RCCs.

Table 3. Proposed Mixture Proportion of RCC for the Dasu Dam

	Characteristic cylinder compressive strength @356 days (MPa)	Mixture Proportion (kg/m^3)		Note
		Portland Cement	Natural Pozzolan	
RCC1	25	150	60	Used for lower part of the dam body (below El.850.2 m)
RCC2	20	120	90	Used for upper part of the dam body (above El.850.2 m)
High strength RCC	30	260	50	U/S and D/S surface of the dam body (Under mixture test)

5.2. Proposed Simple Construction Methodology for the Placement of RCC

Due to the power crisis in Pakistan, the construction of the Dasu Project is implemented as rapidly as possible. It is intended that the 4.1 million m^3 of RCC in the dam body be placed in 27 months at an average rate of 150,000 m^3/month. This would be slightly faster than the fastest average placement rate yet achieved in an RCC dam (142,750 m^3/month at the Longtan dam in China). In order to achieve this rate of placement, the concrete and other plant will have to have sufficient capacity and the method of construction will have to be as simple as possible, because with simplicity will bring speed and speed will bring quality and economy. Consequently at Dasu, it is proposed that the layers of RCC will be placed horizontally from one abutment to the other on a continuous basis.

The defining factor that can determine the placement rate in the Dasu dam may be the delivery rate of materials such as cement, aggregate and natural pozzolans. During the peak months, maximum placement of RCC per month might be expected to be 300,000 m^3, or even more (less than the 400,000 m^3: peak at the Longtan dam) and this will require some 650,000 tonnes of aggregate and 65,000 tonnes of cementitious materials (over 100 trucks per day) to be delivered to the site. Essentially the Project will become a material-handling exercise.

6. CONCLUSION

A challenging seismic design using 2D/3D dynamic analyses was adopted on the design of the Dasu dam. Different response accelerations were seen in the results between the 2D and 3D analyses, considered to be caused by the topographic condition at the site. Though crack penetration was supposed in the upper zone of the dam body, it is verified that safety will be maintained without any collapses on the dam body. As for the hydraulic structures, model tests especially for the flushing tunnels are being undertaken at present to ensure the well performances of their functions. As for the RCC, further test mix for high strength RCC will be also undertaken. After the finalization of the design based on these studies, the procurement process is going to start in 2014.

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