Stilling Basin Length Optimization for Hvammur Hydro Electric Project

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Abstract

The scope of the study conducted is to verify and optimize a low inflow Froude number stilling basin at Hvammur Hydro Electric Project, in southern Iceland, in a physical model. The model is built according to Froude similitude with a scale ratio of 1/40 and represents the approach flow area to the spillway, the spillway, downstream stilling basin and a discharge channel conveying the flow back to the original river channel. The quality of the rock conditions downstream of the stilling basin is expected to be good and therefore the effect of a shorter and less expensive stilling basin is investigated. In total 4 stilling basin lengths were tested at various operating discharges to identify aspects of performance for the basin and downstream channel. Results indicate that a too short basin has limited capability to form a hydraulic jump and produce turbulent kinetic energy for energy dissipation. A longer basin forms a more conventional hydraulic jump and is better able to handle the extreme fluctuations of forces before returning the flow back to the riverbed. Furthermore, with decreasing stilling basin length a fluctuating component is measured at the downstream end of the stilling basin indicating sweep out of the hydraulic jump.

Introduction

Landsvirkjun is planning the construction of three power plants in the lower section of the Thjorsa River, Hvammur Hydro Electric Project (HEP), Holt HEP and Urridafoss HEP. All three will be run of the river power plants with small intake ponds. Hvammur HEP is the uppermost project of the three utilizing the head between elevations 116 m a.s.l. and 84 m a.s.l. The design discharge is 310 m^3/s providing installed power of approximately 80 MW and energy generating capacity of 665 GWh/a with two Kaplan turbines.

A gated spillway is proposed to bypass floods and regulate pond elevation. The gated section of the spillway is ogee shaped with a crest elevation of 107 m a.s.l. and equipped with three 10 m high and 12 m wide radial gates. A concrete stilling basin downstream of the spillway dissipates excess energy and protects the dam and spillway from erosion. The design assumes a hydraulic jump to form within the basin for all gate openings and discharges up to the design flood, Q_{1000} (2150 m^3/s). The water is routed back to the original river channel downstream of the stilling basin by a 50 m long excavated channel with a hydraulic control at the end to ensure necessary tail water (backwater) elevation to support the formation of a hydraulic jump in the stilling basin. The design criteria states that the gated structure must pass the design flood without any damage to the spillway and the flow in the downstream discharge channel shall be subcritical for all conditions.

The inflow Froude number is 3.3 for the design flood. The design of a short and efficient hydraulic jump stilling basin for Froude numbers below 4-5 is challenging because the jump that forms is weak, with low energy dissipation and high degree of fluctuating components. For low inflow Froude numbers the USBR recommends stilling basin IV with chute blocks and a sloping end sill. (USBR, 1987).

In this study, a physical model is built according to Froude similarity with a scale ratio of $\lambda = 1/40$ to study the effect of stilling basin length and properties of the weak hydraulic jump that forms in the fluctuating system. The energy removed in a hydraulic jump is dissipated with generation of large scale turbulence and the resultant conversion of turbulence to heat. In view of this and in an effort to quantify the flow behavior and hydraulics of the system, the measured fluctuations of pressure and velocity are used to quantify the turbulence characteristics of the system.

Based on preliminary investigations, the quality of the rock downstream of the stilling basin is believed to be good. Therefore the effect of a stilling basin shorter than generally recommended in the literature is investigated, as reduced length of the basin will contribute to less construction cost.

All values in this article are prototype values.

METHODS

The model study was conducted in the hydraulics laboratory of the Icelandic Maritime Administration during a 6 month period. The gated structure and stilling basin are made of industrial plastics and the stilling basin has plexiglas side walls. The topography of the model is made out of fiber reinforced mortar.

Figure 1 *– Overview of the physical model of Hvammur HEP in the laboratory.*

The discharge in the system is regulated with two pumps with frequency inverters. Two reservoir tanks, one downstream and one upstream, collect the water which is circulated in a closed loop as is shown in Figure 2.

The three spillway gates are operated at equal openings (interlocked operation) for all flow scenarios investigated. The gates regulate the discharge up to approximately 1500 m^3/s but for higher discharges the spillway enters a transition regime to un-gated flow which stabilizes at around 1600 m^3/s. A control section is constructed 50 m downstream of the stilling basin end sill to ensure necessary tail water depth to prevent sweep out of the jump. Three discharges were investigated, 1050 m^3/s (annual flood, gated regulated flow), 1650 m^3/s (50 year flood, un-gated flow) and 2150 m^3/s (1000 year flood, un-gated flow).

High accuracy ultrasonic sensors measure the discharge in the system and manual gauges are used to verify the upstream pond elevation. Pressure sensors at various locations in the pond are used to measure the pond elevation and monitor stability.

A Sontek Acoustic Doppler Velocimeter (ADV) measures the three velocity components. ADV's are capable of reporting accurate mean values of water velocity in three dimensions (García, Cantero, Nino, & García, 2005), (Liu, Zhu, & Rajaratnam, 2002). Each measurement lasts for 60 seconds at 5 Hz, collecting 300 data points. The ADV, which is down looking and has a blind zone of 50 mm from the sensors probe (Sontek, 1997), does however have some limitations. Because of the blind zone, measurements are limited to a depth exceeding 2 m (prototype depth) from the surface. Also, in complex flow regimes with high air entrainment, such as in a hydraulic jump, the instrument’s capability to accurately resolve flow turbulence is uncertain. The ADV resolution is however believed to be sufficient to capture a significant fraction of the turbulent kinetic energy of the flow (Nikora & Goring, 1998). By filtration of the acquired time series the data can be corrected for spikes in the data caused by air bubbles in the sampling volume. Measurements with the ADV are made along the center line of the stilling basin and downstream channel. ADV data processing and filtering is done with USBR’s WinADV32 software (Wahl T. L., 2000). Because the sampling volume in the laboratory model is located 5 cm (model value) below the probe of the ADV and fluctuations of the water surface in the stilling basin, the topmost zone in the system has no measurement data.

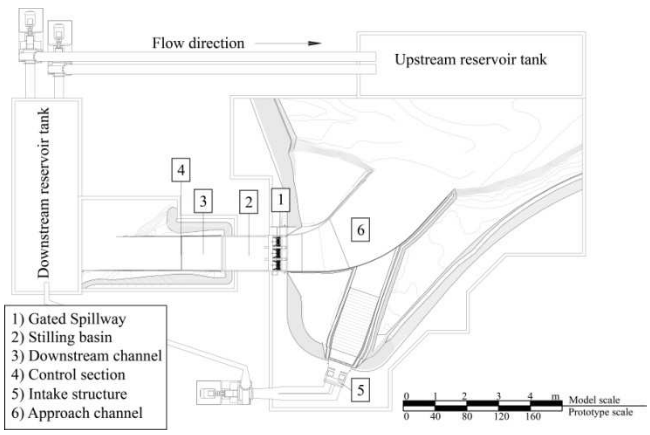

Figure 2 *– Overview of the modeled area: 1) the three gate spillway; 2) stilling basin for energy dissipation; 3) excavated downstream channel to ensure necessary tail water; 4) control section to ensure a hydraulic control for all flow conditions.*

High accuracy pressure sensors (0.05 % full scale) are also flush mounted to the stilling basin and downstream channel invert to measure fluctuations of pressure at 10 m intervals. Data is collected at 10 Hz along the center line of the structure.

The root-mean-square of the turbulent velocity fluctuations about the mean velocity is computed for use in determining turbulence intensities and levels of turbulent kinetic energy. The RMS value is equal to the standard deviation of the individual velocity measurements. The RMS turbulence for each velocity component is calculated as:

$$RMS_i' = \sqrt{\overline{(v_i')^2}} = \sqrt{\frac{\sum v_i^2 - (\sum v_i)^2/n}{n-1}} \quad (1)$$

where *i* is the direction of the velocity component relative to the ADV probe, RMS_i' is the RMS value for the component and *n* is the number of samples (Wahl T. L., 2011).

Turbulence kinetic energy (TKE) is defined as mean kinetic energy per unit mass associated with eddies in turbulent flow. The turbulent kinetic energy is characterized by root-mean-square (RMS) velocity fluctuations in the longitudinal, lateral and vertical directions. Generally, the TKE is quantified by the mean of the turbulence normal stresses:

$$TKE = \frac{1}{2}\left(\left(\sqrt{\overline{u'^2}}\right)^2 + \left(\sqrt{\overline{v'^2}}\right)^2 + \left(\sqrt{\overline{w'^2}}\right)^2\right) \quad (2)$$

where TKE is turbulent kinetic energy per unit mass and $\sqrt{\overline{u'^2}}$, $\sqrt{\overline{v'^2}}$ and $\sqrt{\overline{w'^2}}$ are root mean squares of the velocity fluctuations in the longitudinal, lateral and vertical directions, respectively (Urban, Wilhelms, & Gulliver, 2005). Turbulence intensity in a plane identified by *i* is:

$$\sqrt{\overline{(V_i')^2}}/U_m \quad (3)$$

where U_m is the mean value of velocity in plane *i* and $\sqrt{\overline{(V_i')^2}}$ is the root mean square of the turbulent velocity fluctuations in plane *i*.

The layout of the system is shown in Figure 3. The difference in the coordinate system defining the stilling basin length between USBR and this study is 7 m. A 55 m long stilling basin in this study thus corresponds to a 62 m long stilling basin according to the USBR convention.

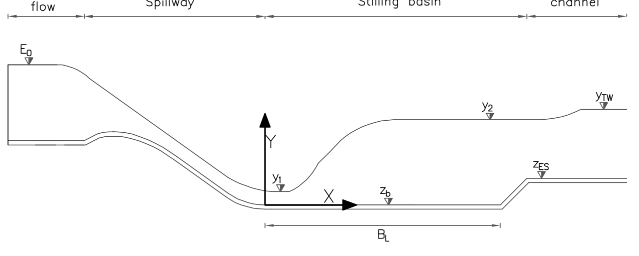

Figure 3 *– Overview of the model coordinate system. E_0 is the total upstream energy, y_1 is the pre jump depth, y_2 is the conjugated depth of the hydraulic jump, y_{TW} is the corresponding tailwater elevation in the downstream channel. Z_b is the stilling basin invert elevation and Z_{ES} is the end sill height. B_L is defined as the length of the stilling basin.*

For each of the three discharges investigated velocity data is acquired at 5 elevations within the stilling basin and at 3 elevations for each section in the downstream channel. Four stilling basin lengths are tested, as is summarized in Table 1.

Table 1 *– Description of layouts tested to optimize stilling basin length (B_L). For all cases the spillway crest elevation is 107 m a.s.l., stilling basin floor elevation (Z_b) is 100 m a.s.l. and end sill elevation (Z_{ES}) is 103.1 m a.s.l.*

Case	A2	A2.1	A2.2	A2.3
BL (m)	55	45	35	25

EXPERIMENTAL RESULTS

Figure 4 shows the mean velocity distribution in the central plane for the 4 lengths tested at the design flood discharge, as measured by the Sontek ADV. The figure shows that the velocity profile changes gradually from a plane wall jet-like profile within the stilling basin to a standard open channel flow velocity profile in the downstream channel. For the longest stilling basin a vertical velocity component is apparent immediately downstream of the end sill. For the second longest stilling basin a standard velocity profile has developed immediately downstream of the end sill and for the two shortest stilling basins the observed character from the longest stilling basin is observed but only stronger, i.e. a vertical velocity component immediately downstream of the end sill. After station 60 a standard distributed velocity profile has stabilized for all the cases tested.

Figure 5 shows the measured velocity fluctuations (RMS) for the four basin lengths. Scattering of the data is largest within the stilling basin and decays downstream of the end sill. For 45 m and 55 m stilling basin lengths the mean values are similar, while for the 25 m and 35 m stilling basin lengths the average is higher within the stilling basin, with an absolute maximum at the end sill, but decaying more rapidly in the downstream channel. The 25 m and 35 m stilling basins yield the lowest measured and average values in the downstream channel.

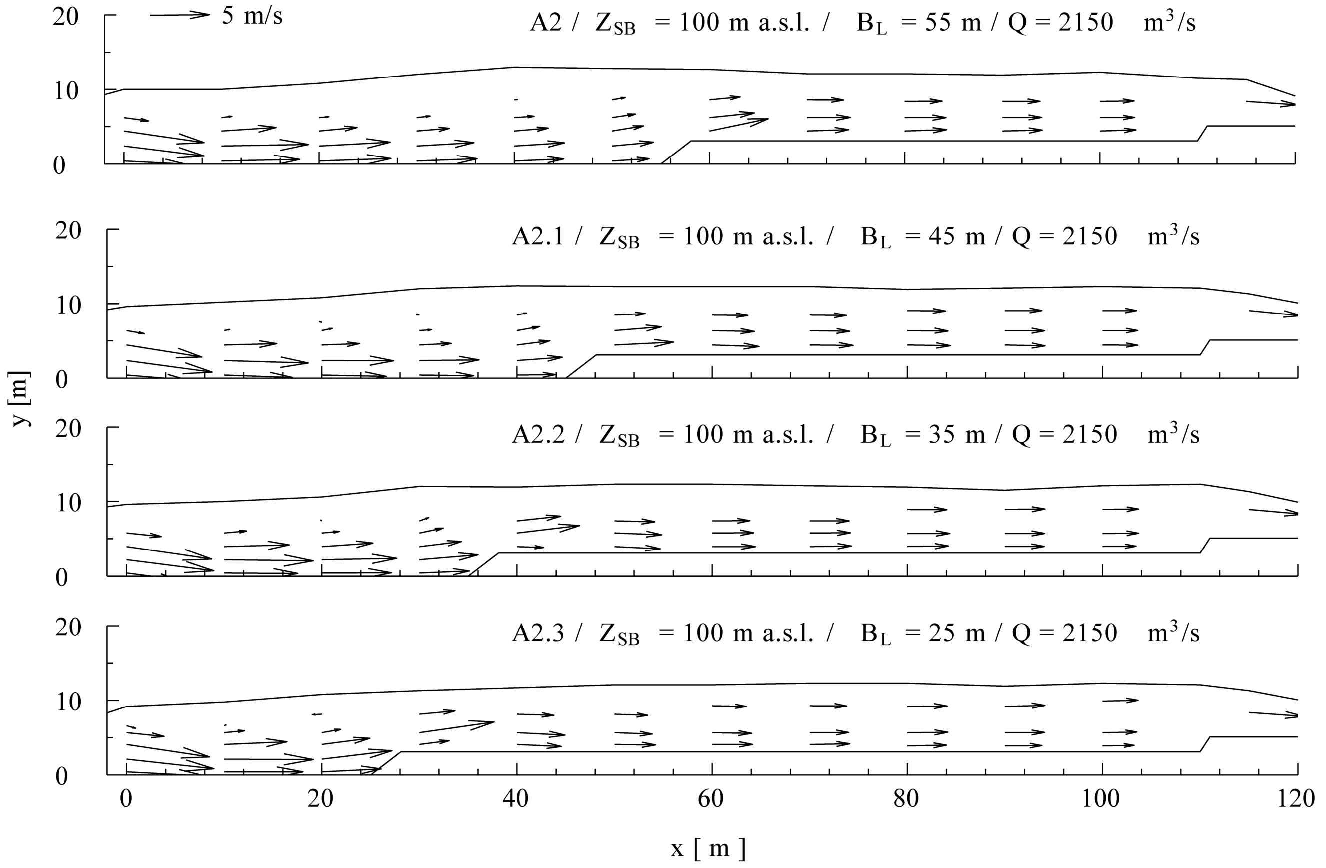

Figure 4 *– Velocity distribution along the central vertical plane for the four basin lengths tested. Data is shown for Q = 2150 m^3/s*

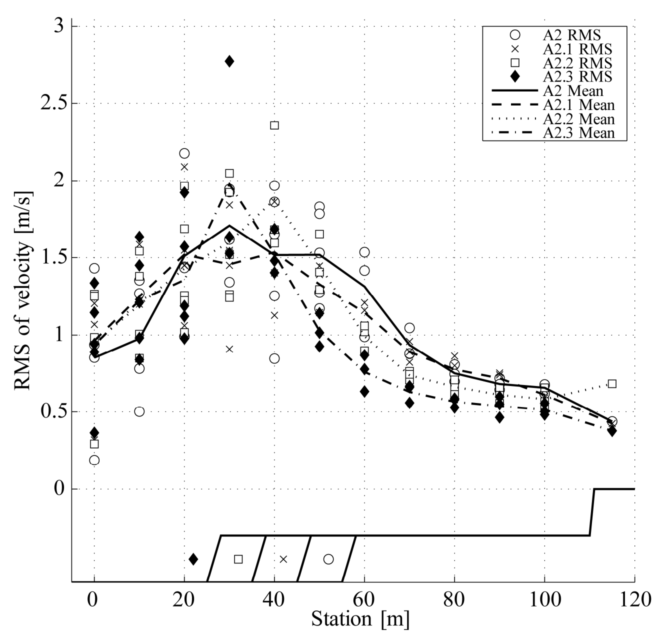

Figure 5 *– Measured RMS values of velocity along the central vertical plane. Data is shown for Q = 2150 m^3/s. The bottom legend shows the corresponding stilling basin length.*

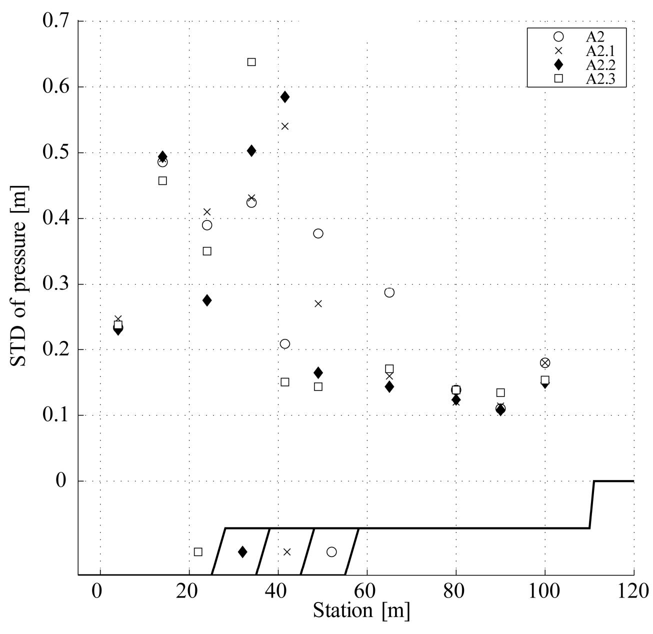

Figure 6 *– Standard deviation of pressure measured in the central line on the invert of the stilling basin and downstream channel. Data is shown for Q = 2150 m^3/s. The bottom legend shows the corresponding stilling basin length.*

Figure 6 shows the standard deviation of measured pressure at the invert of the structure. The highest measured values are at top of the end sill for the 25 m, 35 m and 45 m stilling basin lengths while for the 55 m basin a peak value in pressure deviation at the end sill in observed but much lower than for the other three cases. This correlates somewhat to the measured velocity fluctuations in Figure 5. In the stilling basin the lowest RMS velocities are where the jet enters the basin, but increases towards the expected location of the hydraulic jump. In the downstream channel the pressure deviations decay rapidly for all cases.

In Figure 7 the longitudinal turbulence intensity is plotted while Figure 8 shows the vertical turbulence intensities. For the two shortest basins, 25 m and 35 m, a peak in longitudinal turbulence intensity is observed immediately downstream of the end sill but for the 45 m and 55 m basin lengths no outliers are detected. The vertical turbulence intensity scattering is overall lower than the longitudinal one, but in the downstream channel the 55 m stilling basin lengths has the highest measured values.

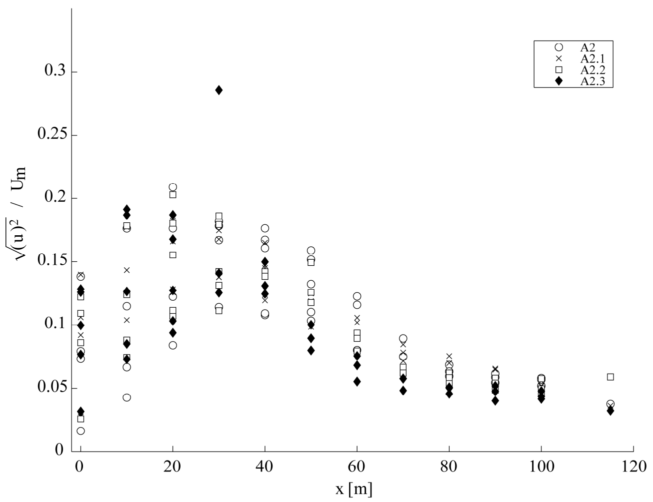

Figure 7 *– Variations of normalized measured longitudinal turbulence intensities in the central vertical plane. Data is shown for Q = 2150 m^3/s.*

Figure 9 shows a side view of the stilling basin at the design flood. The oscillating waves and instability of the system can be observed. Up to 3 m wave height is observed in the stilling basin for the design flood. The oscillating behavior and wave height are similar for all cases tested. For the two shortest stilling basins, the overall hydraulic character at the end of the stilling basin seems to indicate a “sweep out” character of the weak hydraulic jump, as the incoming jet to the stilling basin does not have the necessary stilling basin length to facilitate a necessary velocity reduction of the inflow velocity of the jet before leaving the stilling basin.

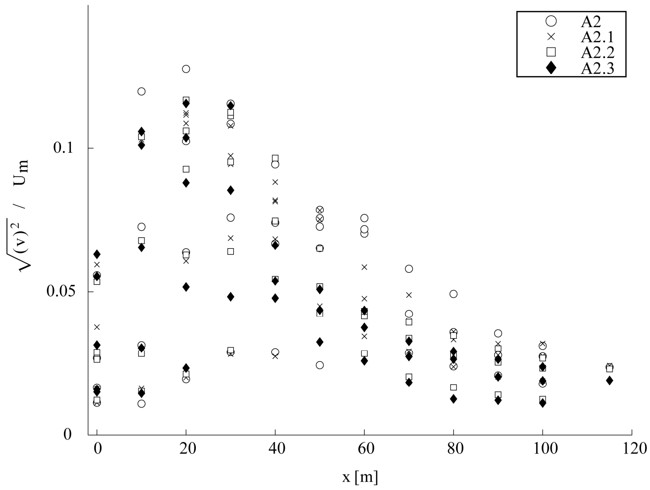

Figure 8 *– Variations of normalized measured vertical turbulence intensities in the central vertical plane. Data is shown for Q = 2150 m^3/s.*

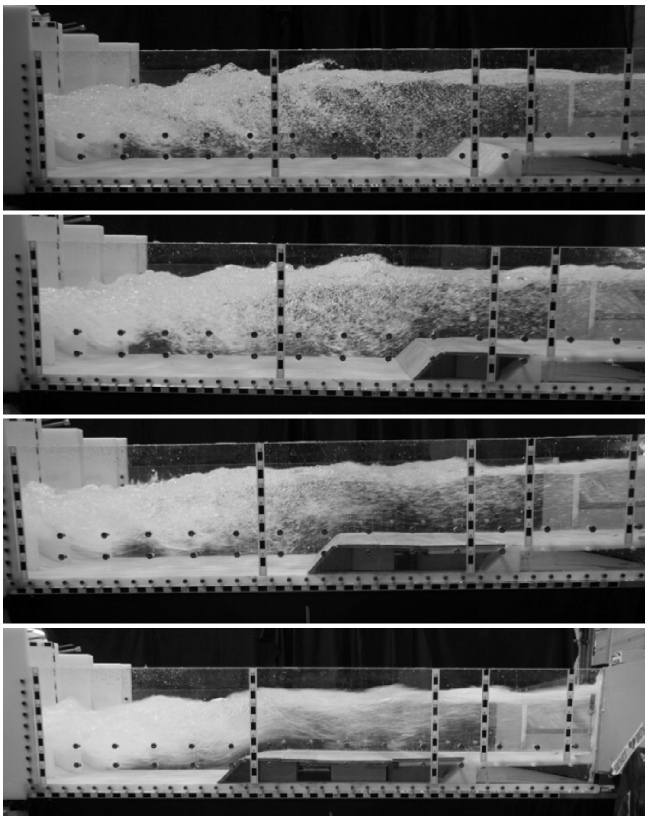

Figure 9 *– Side view of the stilling basin in the physical model for Q = 2150 m^3/s for the four stilling basin lengths*

CONCLUSION

The measurement results indicate that a critical location in the system is at the end sill and immediately downstream of it (5 – 10 m downstream). By decreasing the stilling basin length, fluctuating components are observed at this location. For the two longer stilling basins, 45 m and 55 m, no outliers or abnormality in the measurements are observed at the end sill location while for the two shortest stilling basin lengths, 25 m and 35 m, a different character is identified. Immediately downstream of the end sill location, a strong fluctuating component of pressure and velocity is observed for the two shorter stilling basins, indicating possible erosion potential which might result in structural damage or complete failure of the structure if the rock quality downstream of the concreted stilling basin is not high enough. Therefore, by reducing the stilling basin length to cut down the construction cost, careful assessment needs to be made on the downstream rock quality, as part of the dissipating energy is moved to the downstream channel.

ACKNOWLEDGMENTS

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