5th International Symposium on Hydraulic Structures
Hydraulic Structures and Society: Engineering Challenges and Extremes
ISBN 9781742721156 - DOI: 10.14264/uql.2014.20
Brisbane, Australia, 25-27 June 2014

Stepped Spillway Model Pressures Characteristics, Susu Dam Malaysia

E.J. Lesleighter[1], B.P. Tullis[2], and D. Andrews[3]
[1]Hydraulic Engineering Consultant
Cooma NSW 2630
AUSTRALIA
E-mail: lesleighter@yahoo.com
[2]Professor of Civil and Environmental Engineering
Utah State University
Logan, Utah 84322
USA
[3]Senior Dams Design Engineer
SMEC International
AUSTRALIA

Abstract: *Susu Dam is an RCC Dam under construction in Peninsula Malaysia. The dam design has been carried out by SMEC International in its offices in Kuala Lumpur. The dam is some 90 m tall. The overfall stepped spillway provides for discharges to enter a hydraulic jump stilling basin for energy dissipation, prior to passing through a culvert under a roadway. The spillway was subject to hydraulic model testing at the Utah Water Research Laboratory of Utah State University (USA), at a length scale of 1:30. The hydraulic performance of the spillway design was evaluated up to the 4,700 m^3/s Probable Maximum Flood (PMF) discharge (almost 1,000 L/s model scale). The spillway was tested through a number of configurations, prior to the development of the final arrangement. The purpose of the paper is to describe the modelling detail, and then focus on the flow behaviour at the stair-stepped spillway chute with 2.4 m high steps, in particular the piezometric pressures and transient pressures on the tread and riser of the steps. The spillway chute converged from ~100 m at the crest to 78 m at the bottom at entrance to the stilling basin; the unit discharge entering the stilling basin was ~ 60 m^2/s for the PMF. Of particular interest was the occurrence of negative pressures on the steps, and the paper will describe the transients for several discharges from the AEP 1 in 1,000 up to the PMF; the results indicating very low pressures into a cavitation region. The design provides for an aerator across the spillway in order to counter the effects of possible cavitation. Results will be presented with and without the aerator operating. The paper provides useful design information for the hydraulic design of stepped spillways.*

Keywords: *Stepped spillways, models, pressures, transients, cavitation, aerators, stilling basins.*

1. INTRODUCTION

Susu dam is part of the Ulu Jelai Hydroelectric Project (UJHEP) under development by Tenaga Nasional Sdn Berhad (TNB) in the Cameron Highlands of Malaysia. Susu dam will be a 90m tall, 500m wide roller compacted concrete (RCC) gravity dam featuring a stepped spillway chute converging from approximately 100 m at the crest to 78 m at the entrance to the stilling basin. The original design featured adjacent service spillways on the downstream face of the stair-stepped RCC dam. The service spillway aligned directly with the stilling basin; the auxiliary spillway (crest located 5 m higher than the service spillway crest) discharge entered the stilling basin through a side channel spillway that consisted of a lateral stair-stepped transitioned channel or apron located at the toe of the chute. The hydraulic jump stilling basin is 50m long. A culvert road crossing is located immediately downstream of the stilling basin, which, in addition to accommodating an access road, acts as a tailwater control structure for the stilling basin. The tailwater control structure is required due to the steep nature of the discharge channel.

The service spillway originally was to cater for the Annual Exceedance Probability (AEP) 1 in 1,000 discharge, with larger floods to pass over the main service spillway and an auxiliary stepped spillway on the left side of the dam. Together, the service and auxiliary spillways were designed to pass the

Probable Maximum Flood (PMF) of 4,700m^3/s, with the auxiliary spillway passing approximately 20% of the total PMF discharge.

2. DETAILS OF THE MODEL

A 1:30 scale model of the Susu spillway was constructed at the Utah Water Research Laboratory at Utah State University (USA). Figure 1 is a general view of the model. The scope of the first model study phase included evaluating the spillway behaviour at the AEP 1 in 100, 1 in 1,000, 1 in 10,000, and the PMF flood peak discharges, evaluating piezometric pressures at 50 pressure tap locations distributed over the spillway and stilling basin, evaluating dynamic pressure at 6 different pressure tap locations in the basin invert and on a step and the basin sidewall, evaluating the flow transition from the ogee crest to the stair-stepped spillway chute, evaluating the design and function of the aerator, measuring water surface profiles along the spillway chute, and evaluating the stilling basin performance.

Key spillway components, including crest structure, training walls, stilling basin, stair-stepped spillway chute, aerator, and outlet control structure were fabricated using clear acrylic material to facilitate flow visualization, minimize flow resistance at the model scale, and facilitate pressure tap installation. Other model components, such as the head box, tail box, and structural support members, were fabricated using plywood, dimensional lumber, and/or steel. Downstream river channel topography was replicated as a fixed-bed in the model using data provided by the client.

Following preliminary testing of the dual spillway concept, the spillway design was modified from two spillways to a single converging spillway. Due to budget and schedule constraints, the original full-width spillway model was changed to a half-width sectional model of the modified design. The original right training wall represented the centreline of the spillway chute and a new converging left chute wall was added as shown in Figure 2. The two-barrel box culvert outlet structure downstream of the stilling basin was reduced to one opening for the half-width model. In order to properly simulate the single spillway discharge characteristics, the spillway chute centreline wall was extended into the reservoir to eliminate flow contraction at the reservoir/spillway crest transition. A further design modification included doubling the step height from 1.2 m to 2.4 m prototype below the aerator and installing an 8^o ramp aeration step with air entry ducts located in the chute sidewalls.

Figure 1 – General view of the two-spillway concept model

Figure 2 – Convergent chute half model

3. DESCRIPTION OF STEPPED SPILLWAY

The original arrangement utilized 1.2 m high steps on the gravity section spillway (slope 0.8:1), excepting those over the crest profile where smaller steps, gradually increasing in height to the 1.2 m, were used to avoid large jets being projected from the surface and to "ease" the flow onto the main profile. An aerator was incorporated with a ramp slope initially of 6:1 relative to the general slope of the spillway. For that arrangement the air was supplied to the underside of the nappe via a duct across and below the spillway with ten circular openings leading through the downstream vertical face of the step. Remnants of the openings are visible in Figure 2.

Three key discharges were used for the study of the aerator behaviour on the spillway. The AEP 1 in 1,000, 1 in 10,000, and the PMF discharges were approximately 1,400 m^3/s, 2,350 m^3/s and 4,700 m^3/s, respectively. The equivalent unit discharges at the aerator in turn were approximately 15 m^2/s, 25.3 m^2/s and 50.5 m^2/s. The y_c/h values, where y_c and h refer to the critical depth (at the aerator ramp) and the step height, respectively, were then 1.18, 4.03 and 6.38.

For the design of the aerator, in particular its location, it was necessary to consider the "critical velocity" related to a selected design discharge, where cavitation could be expected to initiate. A number of studies have been presented in the Literature. Suffice for our purposes to state that, for the consideration of the critical velocity at which cavitation could occur, the work of Amador et al, 2009, was applied. They applied data from research in which they measured static and hydrodynamic pressures on spillway steps using a wide range of y_c/h values in the skimming flow range – from 0.89 to 3.21. They suggest for design purposes that the minimum pressure with an 0.1% probability ($p_{m0.1\%}$) is the representative extreme negative pressure for cavitation tendency in macroturbulent flows. The "critical" velocity to apply can depend on a number of factors which are difficult to quantify, and selection needs to take into account the overall probability of the discharge and negative pressure probability being considered, as well as the duration of the occurrence of the negative pressures. Without detailing our design analysis, for our purposes a cavitation inception point was calculated at 33 m lower (EL 507) than the spillway crest (EL 540). At that location the average velocity was estimated to be 19 m/s.

4. HYDRAULICS OF THE STEPPED SPILLWAY

4.1. General description of flow behaviour over the steps

Proper design of the transition between the ogee crest and the stepped spillway, which usually features smaller intermediate steps, is important for establishing proper flow profiles on the stepped spillway. At smaller discharges, well below the 10-yr flood event, there were some flow “irregularities” through that transition. Figure 3 shows flow conditions at the crest and past the aerator for the 1-yr flood event. At small discharges, nappe flow and aerated flow can be seen passing over the 1.2-m high steps above the aerator – no doubt an indicator of extremely aerated (emulsion and spray) flow in the prototype. With the additional air introduced by the aerator, nappe flow was maintained over the 2.4-m steps below the aerator.

Figure 3 – Low-discharge aerated flow at the crest and just downstream

The aerator provided efficient flow aeration across the entire spillway width (approximately 90 m wide at the aerator). Figure 4(a) shows an overview of the spillway chute passing the 1-yr flood event. Figure 4(b) shows the spillway passing the 1000-year flood event; the aeration inception point (the location where the boundary layer first reaches the water surface) is visible upstream of the aerator.

(a) (b)

Figure 4 – Chute aerated flow for AEP 1 in 1 (a) and 1 in 1,000 (b)

For the 10,000-year flood event (Figure 5), the inception point does not occur prior to reaching the aerator. From the aerator down, however, significant flow aeration can be seen below the aerator, and Figure 6 shows similar flow aeration characteristics for the PMF. Figures 5 and 6 illustrate the relative uniformity of the flow aeration provided by the aerator ramp and sidewall ducts.

Figure 5 – Chute flow conditions at the AEP 1 in 10,000 discharge

Figure 6 – Chute flow at PMF discharge

4.2. Spillway chute flows without air induction

For comparison, the air duct in the chute sidewall was closed off and the same discharges evaluated. Figure 7 shows the flow conditions for the 10,000-yr and PMF discharges. For these discharges, there was some difficulty in eliminating all air entry, making the location of the aeration inception point less visually obvious. Nonetheless, the green water conditions prevailed for the PMF up to around 8 steps below the aerator; the masking of the aeration inception point was less significant for the 10,000-year flood event (the inception point occurred just downstream of the aerator).

(a) (b)

Figure 7 – Chute flow conditions for AEP 1 in 10,000 (a) and PMF (b) with air duct closed

5. STEP PRESSURES

An important facet of the model studies was to determine the actual pressures prevailing on the steps. Piezometers were used in a number of locations on the steps on both the treads and the risers. In addition, pressure transducers were used to determine the transients at one location. Figure 8 is a part plan showing the piezometers on the steps and in the stilling basin, and the transducers in red. The step transducers, T7 and T8, are on the tenth step below the aerator. Their location relative to the step geometry is shown in Figure 9. Ideally, more locations including positions closer to the edges of steps would be desirable. However, what we present herein is significant in revealing conditions which are not found from piezometers alone.

Figure 10 is a summary of the maxima and minima of the transient pressures at T7 and T8, with the T7 plots in blue and the T8 plots in red. H represents the pressure head in metres and h the step height (2.4 m). The solid lines refer to the pressures obtained when the air duct to the aerator was open. The dash lines show the data for when the air duct was closed off, so that the nappe at the aerator was starved of air. While the plots show some scatter, the trends are clear. The no-air situation had little effect on the pressures for the AEP 1 in 1,000 discharge. This is explained by the fact that there was natural uptake of air from the atmosphere as the boundary layer had reached the surface for the AEP 1 in 1,000 case – and the mixing created by the turbulence by the aerator itself.

The results for the AEP 1 in 10,000 discharge show some deviation in the pressures for the air and no-air case. Some air was being entrained into the flow from the atmosphere (compare Figure 7). For the PMF case there are two important findings. First, the absence of the air reveals appreciably larger pressure fluctuation magnitudes, with peak to peak excursions of more than 12.5 step heights for the tread surface transducer (T7), and around 9 step heights for T8. The range is less than 8 step heights when air was being inducted.

The second finding of note, especially in relation to the potential for cavitation, is the pressure negatives down to vapour pressure both with and without air admission. Note: with a step height of 2.4 m, vapour pressure is represented by an H/h ratio of approximately -4. The pressure trends indicate that vapour pressures would also occur for discharges less than the PMF. The presence of air in the flow is considered as the counter to any concern about cavitation damage, despite the occurrence of vapour pressures.

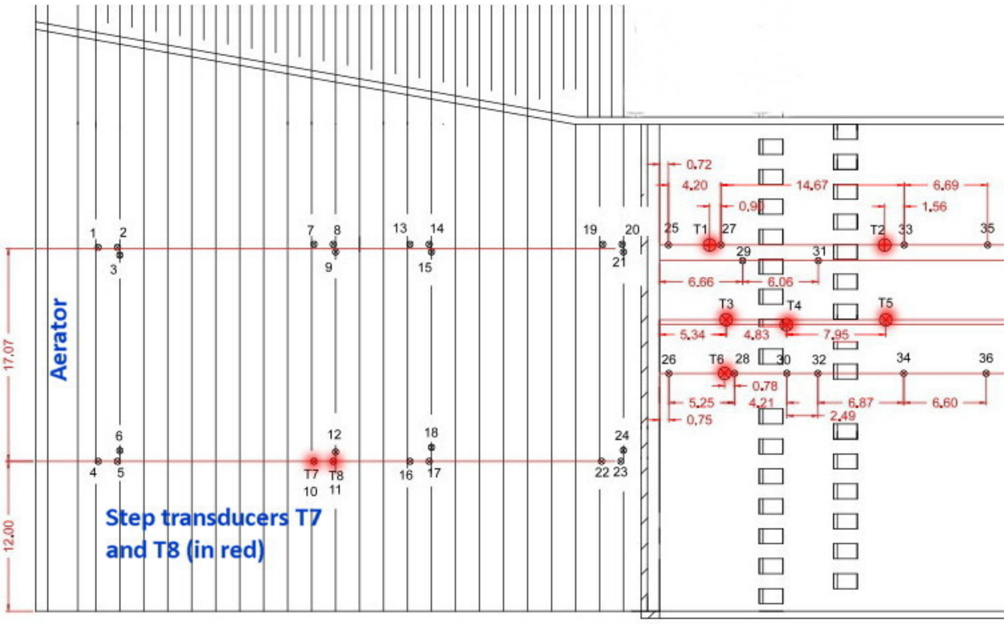

Figure 8 – Piezometer and transducer locations

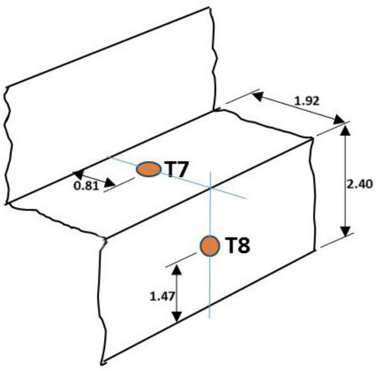

Figure 9 – Location of step transducers

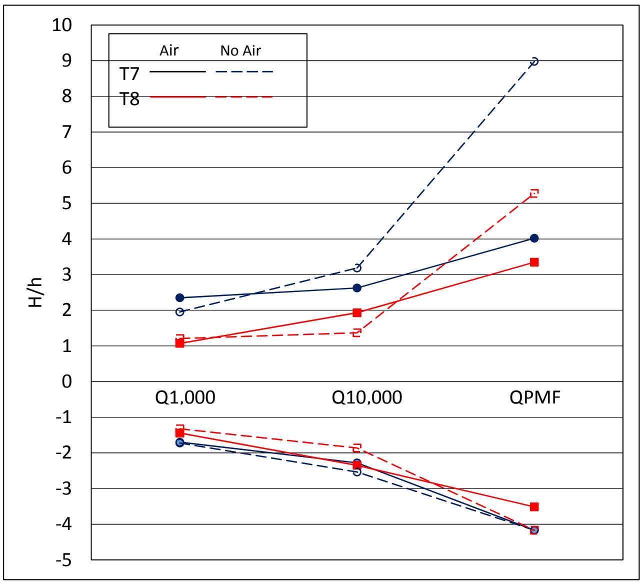

Figure 10 – Pressure head maxima and minima on step

In addition to the pressure range data in Figure 10, Figures 11 and 12 show the ratios of the mean pressure head (H_m) and standard deviation (rms, H_{rms}) data from the measurements. For these data, a comparison was made to the data shown in Amador et al, 2009, in which he relates useful data about the pressures on spillway steps. He presents data for more than one ratio of the length to the step (L) to the step height (h). His data for the step tread for an L/h of 22.64 corresponds closest to the step where T7 and T8 were located on the model (L/h ~ 18). In positions closely corresponding to those of T7 and T8, his ratio of the mean and rms to the step height is approximately 1.2 to 1.4 and 1.0, respectively. Figure 11, for no air as in Amador's case, reveals a value close to zero except for the PMF ratio (y_c/h = 2.75). (Refer to Figure 10 for the legend). The notable difference from the Amador et al data is that the mean head on the tread is negative at -0.3 step heights. Figure 12 for the rms reveals ratios of around 0.3 to 0.4 for the two lower discharges but a value of 1.4 for the PMF.

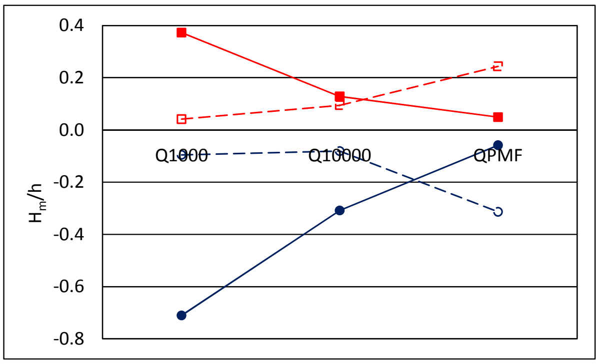

Figure 11 – Mean pressure head ratios

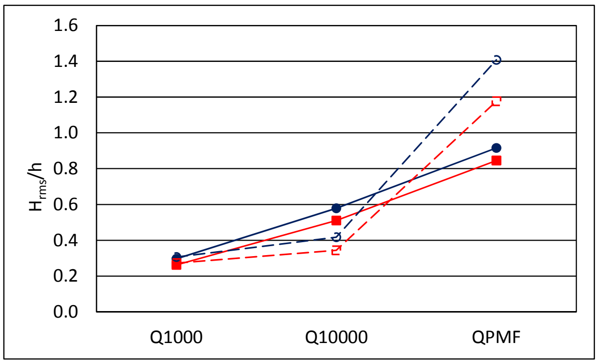

Figure 12 – RMS pressure head ratios

For the pressures on the vertical face, the riser (T8), the mean and rms ratios from Amador et al are approximately 0.2 and 0.4 to 1.0, respectively. Figure 11 (for T7 no air) shows mean ratio ranges from a little above zero to 0.2 – near enough to the values from the reference. Figure 12 for T7 reveals a value of the rms ratio of 0.3 to 0.4 for the lower discharges and 1.2 for the PMF, almost replicating the values obtained by Amador et al.

Figure 13 provides a sample of the transients at the AEP 1 in 10,000. The units relate to conversion from model values to the prototype. Figure 14 provides a sample of the spectra for T7 and T8, again with prototype units. The frequencies at the peak (7.5 Hz and 8.5 Hz) are 41 Hz and 46.6 Hz, model.

As noted, the data are for two transducer locations only. The comparison of results with those of Amador could suggest that nothing new has been identified. This is not the case, and it is relevant to the design of stepped spillways to note the occurrence of negative mean pressures on the tread. Coupled with that are the data shown in Figure 10 – in particular the transients to vapour pressure at the PMF but with a strong likelihood of vapour pressures at a lower discharge than the PMF. Furthermore, there is every likelihood that those same pressures would be found at other locations both on the step treads and the risers.

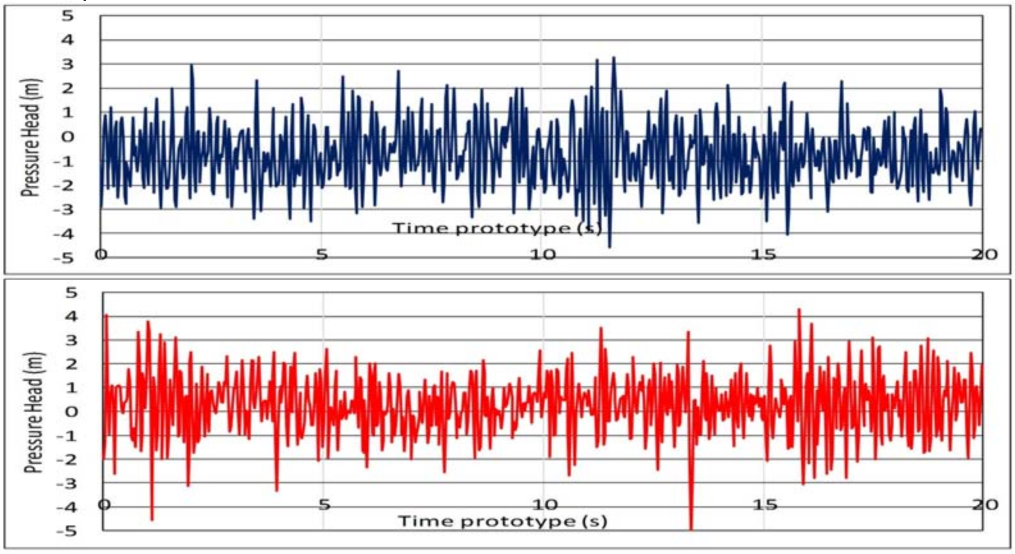

Figure 13 – Sample signals for T7 (top) and T8 for AEP 1 in 10,000 with air induction

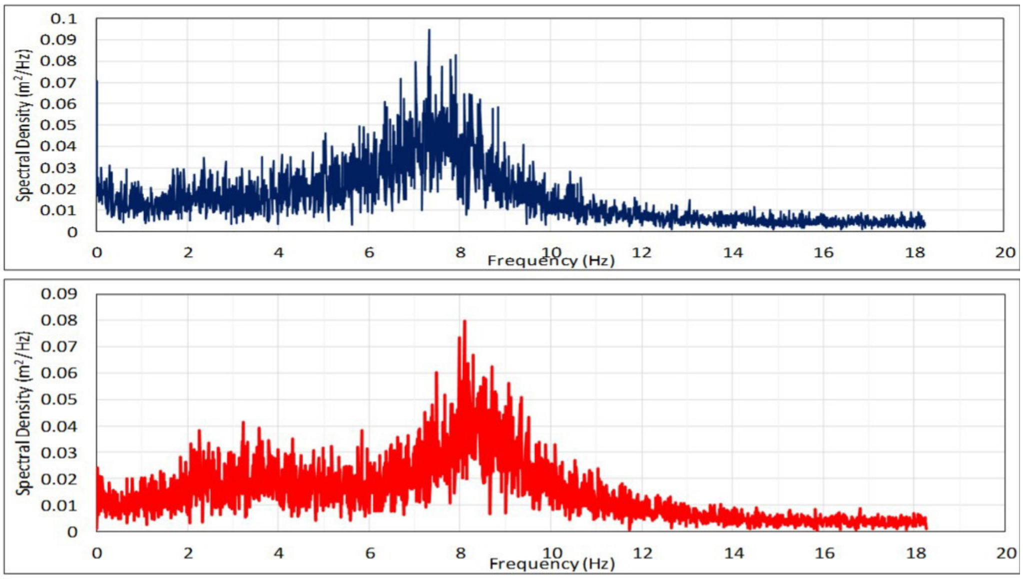

Figure 14 – Sample spectral density plots for T7 (top) and T8 for AEP 1 in 10,000 with air induction

6. CONCLUSIONS

The Susu Spillway model covered numerous aspects of the hydraulics behaviour that needed to be assessed as part of the design process. The paper has focused alone on the characteristics of the transient pressures on the spillway steps. Debate has centered on the need or otherwise for aerators in a stepped spillway, with some suggesting that the characteristic turbulent and mixed flow behaviour assures of sufficient aeration to avoid cavitation damage. We suggest otherwise on the basis of the data. The results of our investigation show the occurrence of very low pressures on some areas of the steps – sufficient to indicate that vapour pressures are reached and the cavitation possibility is indicated. This confirms that the overall design process is well-advised to incorporate an aeration facility into the stepped spillway chute for dams above certain heights.

7. REFERENCES

Amador, A, Sanchez-Juny, M, and Dolz, J. (2009) *Developing flow region and pressure fluctuations on steeply sloping stepped spillways,* Jl Hyd. Eng., ASCE, 135(12), 1092–1100.

8. ACKNOWLEDGMENTS

The authors wish to acknowledge the Tenaga Nasional Sdn Berhad (TNB), Malaysia, the owner of the Ulu Jelai Project, of which Susu Dam is a major component, for its permission to present the model findings.