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# Experimental survey of static pressure in stepped chutes with inclined and horizontal steps equipped with end sills in nappe and skimming flow regimes

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## Abstract

A spillway is one of the most important parts of a dam for controlling floods. Among different types of spillways, stepped spillways are one of the best energy dissipaters. Due to technological advances and the satisfaction of two elements for safe and low-cost construction, the use of stepped spillways has increased widely. Due to this, more studies are focused on stepped spillways. Researchers have made some efforts and proposed different methods to improve structural efficiency to dissipate energy. Modifications on step geometry, regarding flow regime type, are one of these efforts. Flow pressure and its fluctuations on the steps of the stepped spillways is one of the main factors affecting structural design and safety. In this experimental research, reverse inclined steps combined with the end sills have been applied in four degrees [0o (horizontal), 5o, 8o, and 11o] to obtain static pressure in both the nappe flow and skimming flow regimes of stepped spillways. Static pressure obtained from reverse inclined steps with end sills have been compared to the amount in the horizontal step. Results indicate a slight increase in the energy loss rate when reverse inclined steps have been applied in the nappe flow regime of stepped spillways.

**Keywords:** Static pressure; Stepped spillway; Nappe and skimming flow; Inclined step together with end sill

## 1. Introduction

In the last two decades, extensive experimental research has been developed to characterize many aspects of stepped spillways. Some research has been conducted on the pressure of steps in the stepped spillway to determine the amount of pressure fluctuations and pressure distribution on the vertical and horizontal sides of steps. Gangfu Zhang et al. (2016) conducted new experiments in the developing flow region on a large 1V:1H stepped spillway model with a step height h=0.10 m. The flow properties in the developing flow region were carefully documented. In the developing boundary layer, the velocity distributions followed a 1/4.5th power law at the step edges. Detailed velocity and pressure measurements showed some rapid flow redistribution between step edges and above step cavities. Results suggested that the spatially averaged dimensionless shear stress was comparable in the developing flow and fully aerated flow regions. Also, Gangfu Zhang et al. [1] studied total pressure fluctuations and two-phase flow turbulence in self-aerated stepped chute flows. The results demonstrated the suitability of miniature total pressure probe in both monophase and two-phase flows. Both interfacial and water phase turbulence intensities were recorded. Present findings indicated that the turbulence intensity in the water phase was smaller than the interfacial turbulence intensity. Lesleighter, Ej. et al. [2] studied flow behaviour at the stair-stepped spillway chute with 2.4 m high steps, in particular the piezometric pressures and transient pressures on the steps' treads and risers. The spillway chute converged from 100 m at the crest to 78 m at the bottom of the entrance to the stilling basin; the unit discharge entering the stilling basin was 60 m2/s for the PMF. One particular area of research interest was the occurrence of negative pressure on the steps, and the paper described the transients for several discharges from the AEP 1 in 1,000 up to the PMF; the results indicated very low

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pressures in the cavitation region. The design provides for an aerator across the spillway to counter the effects of possible cavitation. Results were presented with and without the aerator operating. The paper provided useful design information for the hydraulic design of the stepped spillways. Hamedi et al. has conducted experiments on the stepped chute with reverse inclined steps to observe the efficiency of energy dissipation for the stepped spillway [3]. Kamyab Moghaddam et al completed a series of experiments to determine the energy loss in different step modifications in the same physical model used in this research [4-5]. The results show a slight increase in the energy loss rate when a reverse inclined step is applied. Significant research has been conducted to observe the effect of inclined steps degree on the energy dissipation rate. Moreover, Ohtsu and Yasuda (1997) considered the characteristics of flow conditions on stepped channels [8]. Many studies have addressed different aspects of stepped spillways; and they are known as an efficient energy dissipater. Chamani & Rajaratnam (1994) conducted extensive experiments on the Nappe flow regime and developed experimental formulas to determine energy loss in this flow [9]. Kamyab Moghaddam et al. also conducted an experimental static pressure analysis in stepped chutes with inclined steps. The results show inclined steps increasing the static pressure on the steps [11].

## 2. Material and method

### 2.1. Experimental Set up

The research was conducted at the Water Research Institute in Iran on a stepped spillway. The steps and walls were made of Plexiglas and mounted on a steel frame. The chute spillway was a broad-crested weir with 60 steps. In the present investigation, only four steps were reverse inclined; all were placed after the middle of the chute (steps 39-42). The horizontal length of the steps was 14 cm; the step height was 4.66 cm, and the chute width was 1.33 m. The height of the broad-crested weir to the first step was 5 cm. Measured parameters during the test included depth and velocity. The experiments were conducted for 20 and 25 liters per second (the nappe flow regime) and 95 and 100 liters per second (the skimming flow regime). Flow depth and velocity were measured using a point gauge (with a precision of 1 millimeter) and a pitot-tube, respectively. Flow discharges were measured by the sharp crested weir at the end of the downstream chute. Three slopes were used: 5°, 8°, and 11° during the current investigation. The depth measurement included three depths for Jet 1 (only water), Jet 2 (a mixture of water and air), and Jet 3, which is flow spray. Finally, the average of the three depths across each line of the piezometer was used as the step depth.

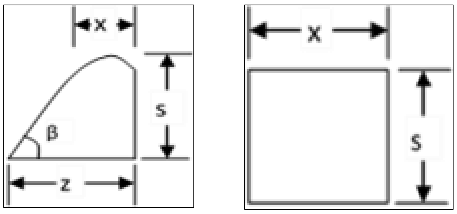


**Figure 1** Schematic representation of rectangular and cycloid end sills

**Table 1** Specification of rectangular end sills

| S. No. | (s-x) mm | |
|---|---|---|
| 1 | 6-10 | 6-5 |
| 2 | 8-10 | 8-5 |
| 3 | 10-10 | 10-5 |
| 4 | 15-10 | 15-5 |

**Table 2** Specification of cycloid end sills

| S. No. | (s-x) mm | |
|---|---|---|
| 1 | 10-5-15 | 10-5-10 |

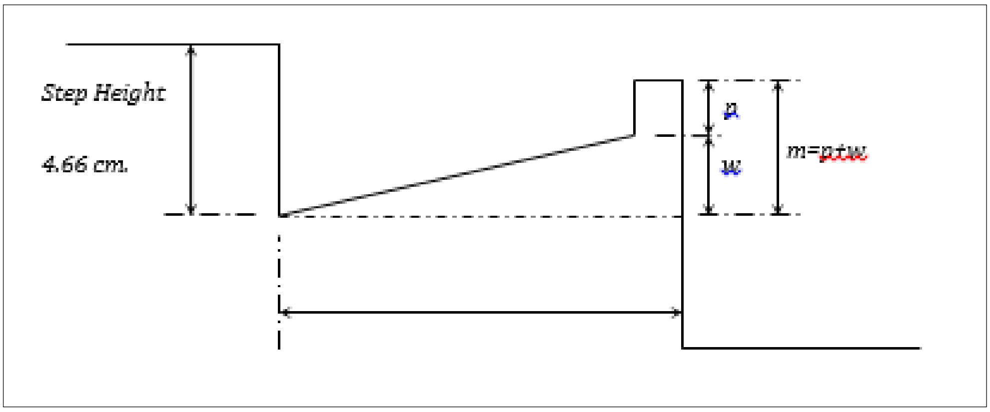


**Figure 2** Schematic representation of the step

Static pressure was measured using piezometers installed in the bottom of the model connected by hoses to the board of piezometers. Three piezometers were installed at each step and there were 3 rows of piezometers within each step: right, left, and center. In fact, on each step, nine piezometers are available. In each test, a picture was captured from the board of piezometers, to determine the height of the flow column more accurately. To accurately measure pressure fluctuations, a transducer was used. Thus, the tip of the piezometer's hose was connected to sensors and the sensors were connected to the amplifier to boost the signal, and the amplifier in turn is also connected to a computer and related software. The time for the test was 30 seconds and the data was recorded at a rate of 200 per second. In this chute, only four steps (39-42) were reversely inclined. The depth and velocity and static pressure values were measured at these steps, as well as at the 38th step for ease of use.

## 3. Results and Discussion

Results show that by increasing the discharge rate (with a constant slope), the static pressure increases. Moreover, the static pressure at the middle of the step is higher than the static pressure on the right and left side of the steps for all discharge rates (Figures 3 and 4).

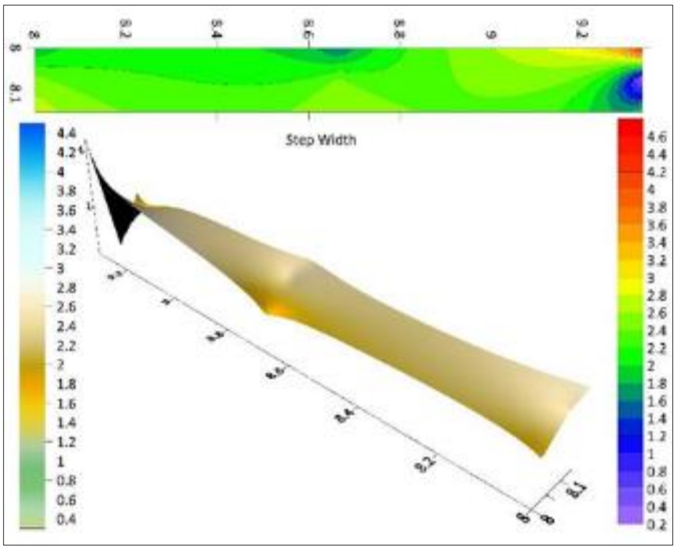


**Figure 3** Pressure on the bottom of the steps for a Discharge of 25 liters per seconds with a slope of 0 degrees (Horizontal)

Results indicate that by increasing the slope of the steps with a constant discharge and adding end sills, the pressure is increased. In this case, as shown on the slope contours (Figures 5 and 6), the pressure on the right side has the lowest pressure value. In the nappe flow regime and with horizontal steps with increasing discharge rate, the pressure is increased.

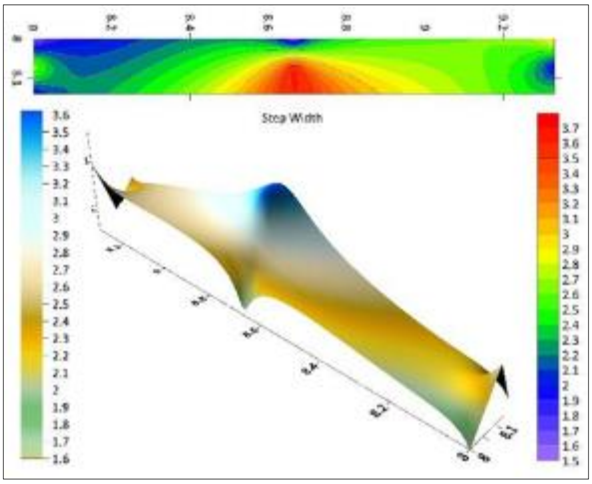


**Figure 4** Pressure on the bottom of the steps for a Discharge of 100 liters per seconds with a slope of 0 degrees (Horizontal)

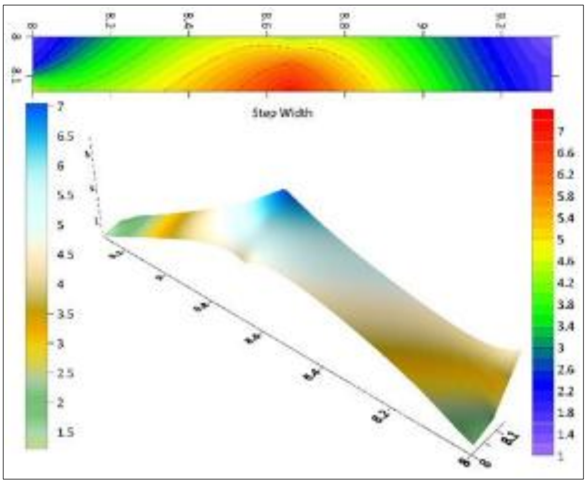


**Figure 5** Pressure on the bottom of the steps for a Discharge of 25 liters per seconds with a slope of 5 degrees

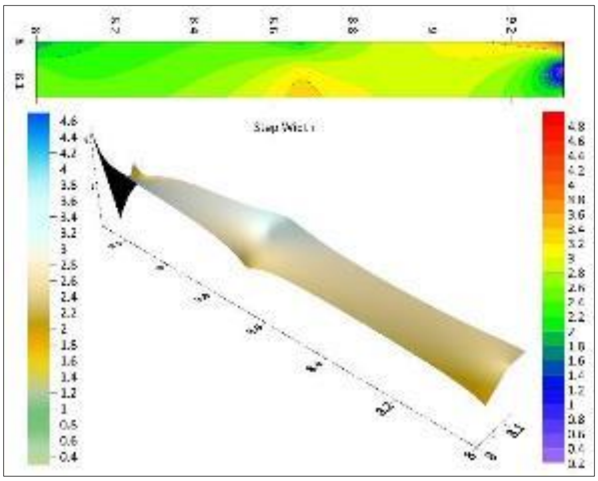

**Figure 6** Pressure on the bottom of the steps for a Discharge of 25 liters per seconds with a slope of 8 degrees

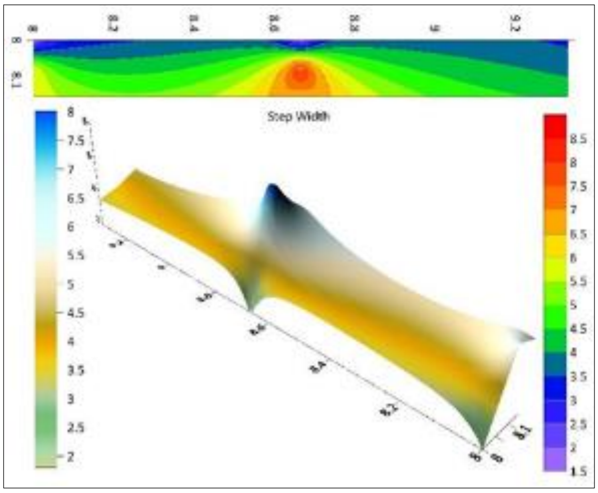


**Figure 7** Pressure on the bottom of the steps for a Discharge of 100 liters per seconds with a slope of 5 degrees

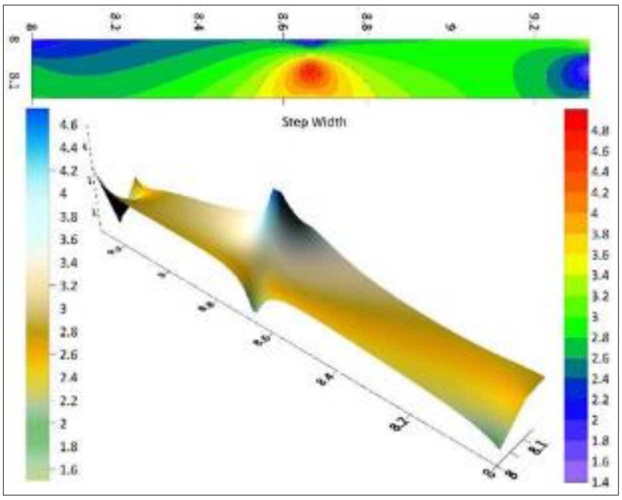


**Figure 8** Pressure on the bottom of the steps for a Discharge of 100 liters per seconds with a slope of 8 degrees


**Figure 9** Nappe flow regime for a Discharge of 20 liters per second with flat steps


**Figure 10** Nappe flow regime for a Discharge of 25 liters per second with flat steps

Pressure on the front row of the piezometers in the steps (the furthest row from the edge) is less than the amount of pressure on the other two rows at all steps during the chute. After the first row, the third row has the lowest pressure. The maximum pressure occurs in the second row at the middle of the steps regardless of end sills. This is due to the jet on the steps which almost collided in the central area of the steps. Moreover, the pressure on the width of the steps in the chute is not constant and fluctuates. Pressure fluctuations within the width of the chute could have occurred since the current instability in the first few steps of the chute with an air discharge phenomenon causes surface instability throughout the whole structure.

In the skimming flow regime with horizontal steps with an increasing discharge rate, pressure increased. Pressure on the front row close to the end sill location has the maximum pressure value since the jet collides at the bottom of the steps in this area. The unstable vortex at the end of the steps (the furthest from the edge of the steps) creates little pressure on the bottom of the steps in this area.

In inclined steps in both the nappe and skimming flow regimes and a constant angle with increasing discharge, pressure increased. In the nappe flow regime, the pressure increases gradually along the slope. This means that the least pressure from the first row will be transferred to the second row. In the skimming flow regime, the pressure also increased gradually along the slope. The lowest pressure occurs in the first row of the piezometers and the maximum pressure in the third row (the edge of the steps) can be seen.

## 4. Conclusion

Experiments have been conducted for four discharges (20, 25 l/s) in the nappe flow regime and (95,100 l/s) in the skimming flow regime. Results show that with end sills increasing the flow rate in the stepped spillway increases the pressure on the bottom of the steps. By adding a reverse slope and end sills to the steps, the pressure increases on the bottom of the steps compared with horizontal steps and the steeper slopes generate higher pressures.

## Compliance with ethical standards

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### *Disclosure of conflict of interest*

The authors have no conflict of interest.

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