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Journal homepage:
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ISSN: 2180-1363

Two-Phase Flow Modelling Based on Roughness Surface Effect of Roller Compacted Concrete

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ARTICLE INFO

Article history:
Received 3 February 2024
Received in revised form 5 March 2024
Accepted 7 April 2024
Available online 31 October 2024

Keywords:
RCC; CFD; air inception; cavitation index; numerical; experimental; VOF; two phase flow

ABSTRACT

One of the most important considerations that are interest to researchers on the stepped spillway in hydraulic structure is the location of the point at which the flow begins to transform into two phase-flow and the development of boundary layers. In this study, an unconventional rough surface was used (RCC materials), which has completely different properties from what is used in previous laboratory studies, which uses smooth surfaces in reality to represent the actual roughness of the surface. Benchmark mixes are evaluated as a reference standard concrete to determine the optimal combination proportions for RCC according to The U.S. Army Corps of Engineers Standard. A laboratory study of different models enhanced by a mathematical model CFD with VOF technics to described the two- phase interaction to investigate the location of the inception point and compare the results with the proposed equations assumed by different researchers in this topic. The results obtained from the study showed a clear effect of surface roughness on the location of the inception point and the formation of the boundary layer for laboratory models. It's clearly found that the two-phase flow starts with closer locations than it is for conventional models and the ratios vary (10 % - 20 %) according to the discharge values (where the effect of surface roughness is evident in the low discharges compared to the high discharges in which the boundary Lear effect begins to fade.

1. Introduction

It has been possible to utilize the tiered spillway for around 3500 years. It is ancient, having existed before the year 500 B.C. Since then, stepped chutes have been used in municipal water supply systems, stepped spillways, and stepped rivers. Because of its straightforward form and capacity to provide the dam wall more structural stability, the stepped geometry was first chosen [1]. Initially, cut-stone masonry and wood were the main materials used to build these stepped chutes; but, as time went on, a greater variety of materials became available [2]. RCC, or zero-slump concrete, is moved, distributed, and compacted using conventional earthmoving machinery in horizontal lifts. RCC is strong enough to hold a vibratory roller while being compacted in its unhardened form. Comparing RCC to conventional concrete has the disadvantage that RCC is less resistant to erosion,

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https://doi.org/10.37934/cfdl.17.3.116

cavitation of the exposed layer, and has a different skin surface roughness (rougher surface) than conventional concrete, Figure 1. These limitations should be studies deeply in case of use RCC stepped spillways systems [3].

RCC is generally known to have a rougher surface texture compared to conventional concrete due to the use of larger aggregates and the absence of a finishing process. Occurrence of cavitation can be a function of pressure and velocity, boundary roughness, operation duration, the amount of dissolved air in the water and strength of materials from which the boundary is constructed, Fadaei *et al.,* [4], the roughness values for Roller compacted concrete (RCC) in open channel flow can vary depending on the surface finish of the RCC. However, as a general guideline, the following roughness values in mm can be used:

i. Smooth surface finish: 0.5 - 1.0 mm
ii. Medium surface finish: 1.0 - 2.0 mm
iii. Rough surface finish: 3.0 - 5.0 mm

It is essential to remember that those values are approximations that might change based on the particulars of the channel flow and RCC surface quality according to U.S. Army Corps [5]**.** The length of boundary layer development and inception point is considered to be one of the most unpredictable elements in the construction of stepped spillways. There are a lot of studies on the air inception location and boundary layers developed in stepped spillway, and many researchers have previously touched on this topic numerical and laboratory ways. What has not been touched upon is the non-use of real models of the Roller Compacted Concrete properties (roughness and texture of surface). non-smooth surface of RCC used in the current study to demonstrated the flow characteristics according to cavitation index and self-aeration pattern. Cavitation damage manifests on the surface of concrete when it comes into contact with discontinuities or abnormalities in the route of rapidly flowing water. The presence of a discontinuity or irregularity in the flow channel induces the water to separate from the flow surface, generating regions of negative pressure and subsequently forming vapor bubbles in the water. The aforementioned bubbles exhibit downstream movement and then undergo collapse. [6], Figure 2 damage in Oroville Dam spillway.

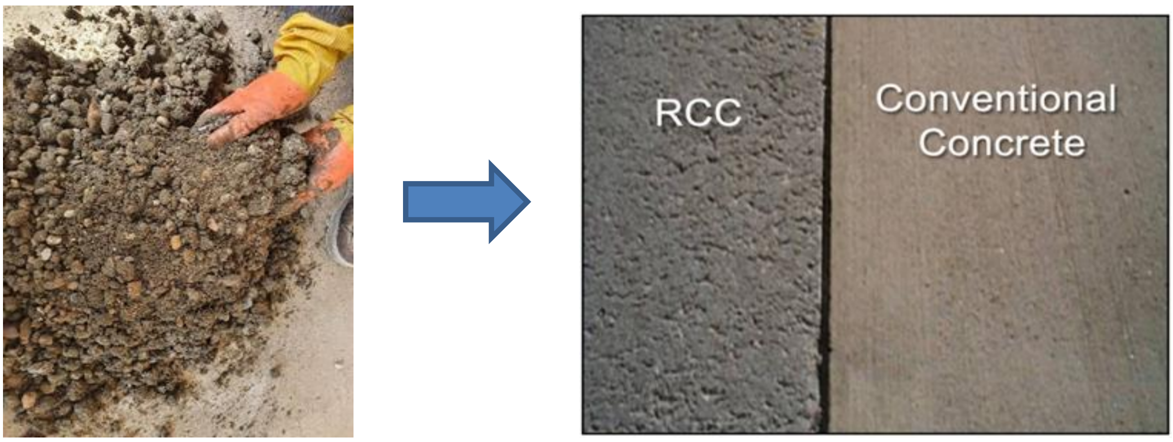

Fig. 1. RCC and Conventional Concrete (Surface Texture)

Fig. 2. Damage in Oroville dam spillway, causes by cavitation in California, USA [6]

2. References Mixes Zero Slump RCC

Benchmark mixes are evaluated as a reference standard concrete to determine the optimal combination proportions for RCC. Figure 3 depicts the process of preparing the concrete using the various w/c ratios (0.3, 0.35, 0.38, 0.4, 0.45) on which it was important to achieve zero slump in order to standardize the category of concrete, whereas Figure 4 depicts the process of test zero slump, which follows a very similar method but employs the design method recommended by ACI committee 207-5R-99 [7]. The following ingredients were found to be crucial in the final formulation of zero slump after much trial and error: Cement content = 325 kg/m^3, W/C ratio = 0.38 (water content = 123 kg/m^3), Fine aggregate =780 kg/m^3, Coarse aggregate = 1180 kg/m^3 that is considered a reference mix in this work.

Fig. 3. Process of preparing the concrete and mold of zero slump test

Fig. 4. Zero slump test

3. Flow Regime

3.1 General

Three distinct flow regimes may be seen over stepped spillways, including nappe flow, transitional flow, and skimming flow. According to Chanson [8], the spillway geometry determines the flow regime seen at different discharge levels. Specifically, nappe flow is observed at low discharges, transitional flow is observed at intermediate discharges, and skimming flow is observed at high discharges. The primary emphasis of this work is on the skimming flow regime. Several writers, such as Chamani, *et al.,* [9], Chanson, [10], Rajaratnam [11], and Sorensen [12], have provided descriptions of the properties of skimming flow. The skimming flow regime is often seen in scenarios characterized by high discharge rates or minor step changes in elevation Boes and Minor, [13]. The skimming regime may be classified into three distinct sub-regimes, which are determined by the slope of the spillway (ø) [14]. The following sub-regimes are enumerated below by Koen, J [1], and as seen in Figure 5.

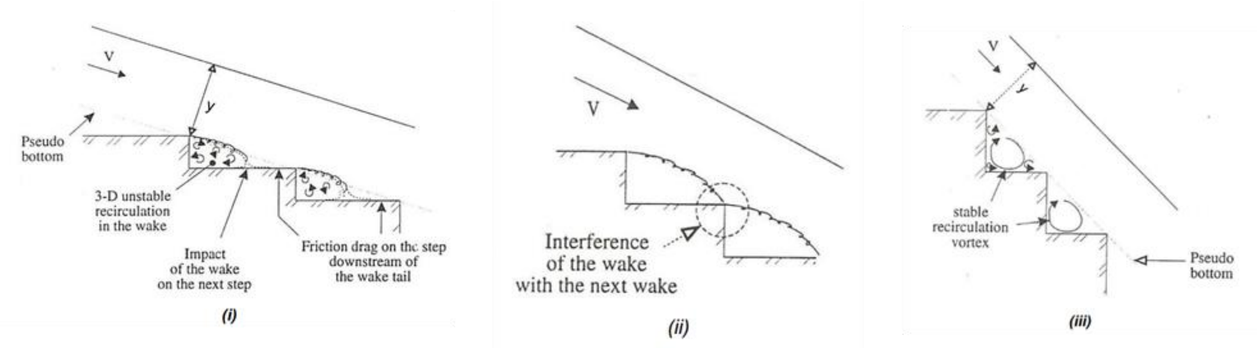

Fig. 5. Skimming flow regime (i) small slope less 27^o (ii) small slope equal to 27^o (iii) slope more than 27^o cavity condition [15]

3.2 Basic Parameters Described Flow

Figure 6 described the principles parameters that present the characteristics of skimming flow over stepped spillway. Chanson [15], explain that in experimental studies the air entrainment in skimming flow occurs when the turbulent boundary layer thickness coincides with the water depth. According to this concept the discharge and thickness of boundary layers developed play as primary players in selection the position of inception points.

At the point earlier of two-phase flow in upstream, the flow has a smooth and glassy appearance, whereas downstream of this point, the flow transitions to a more uniform state as the depth of the air-water combination increases. This location is defined by two factors, namely Li and di. There are two key factors to consider in relation to the boundary layer: the distance from the initial development of the boundary layer to the point of inception, and the depth at which the point of inception occurs. The initiation locations for aeration on stepped spillways are positioned farther upstream compared to smooth spillways. The location of the inception point on a smooth spillway is determined by both the discharge rate and the level of roughness exhibited by the spillway surface.

The parameters that describe this flow behavior, flow rate, step geometry and spacing, the surface tension of the water, and the angle of inclination of the spillway. Inception points refer to the locations where air is first entrained into the flow, typically at the step edges or corners. The location and number of inception points can affect the flow behavior and should be considered in the simulation setup.

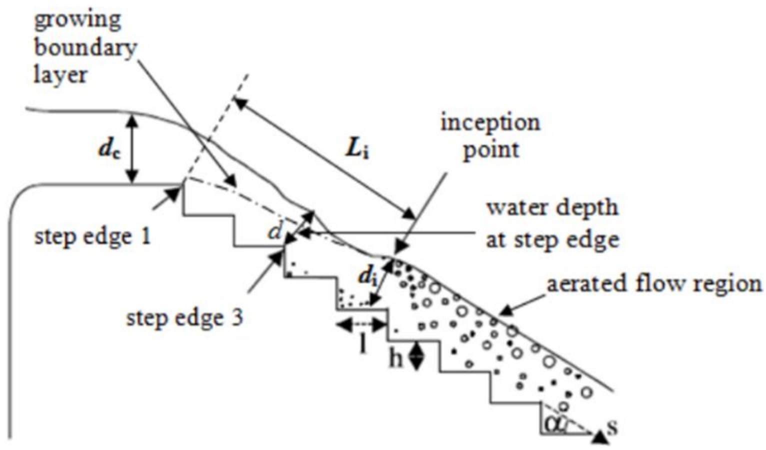

Fig. 6. Parameters of skimming flow over stepped spillway, Chanson [15]

Where: Li: present length of inception, di: depth at inception point (perpendicular to pseudo bottom), d: water depth at step edge, dc: critical depth that causes the skimming flow, h: step height, l: step length, α: slop of spillway, Ks: roughness of surface (h cos α)

3.3 Self-aeration and Inception Point

Self-aeration in stepped spillway refers to the process of incorporating air into the flowing water on steeped spillways. This phenomenon is of great importance in hydraulic engineering as it affects the flow characteristics and the performance of spillways. Understanding the self-aeration phenomenon on steeped spillways has been a topic of interest in both the computational fluid dynamics and experimental study communities. Numerous studies have been conducted to investigate the self-aeration of steeped spillways using both CFD simulations and experimental approaches. These studies have investigated various aspects of stepped spillways, including cavitation, air entrainment, energy dissipation, flow patterns, and hydraulic characteristics.

Chanson [14, 15], (conducted several studies on the hydraulics of stepped spillways, focusing on different aspects such as flow patterns, energy dissipation, and pressure distribution. His research involved experimental data and numerical simulations, using computational fluid dynamics models to compare with physical model tests. Chanson [14], work not only explored the interaction between air bubbles and turbulence in self-aerated flows, but also evaluated the efficacy of aerating weirs and the validation of CFD for modelling free surface flows past a broad-crested weir. This comprehensive research by Chanson on stepped spillways provides valuable insights into their hydraulic behavior and the impact of various design factors on flow patterns and energy diss. Chanson [14] proposed Eq. (1) to predicted the length of inception point

$$L_i = 9.719(sin\,\theta)^{0.08}(F^*)^{0.713}k_s \tag{1}$$

The Eq. (1) proposed by Chanson [14], modified to Eq. (2) by Hunt and Kadavy [15] for stepped slope spillways with flat stepped condition to estimate the length of inception point;

$$L_i = 6.1(sin\,\theta)^{0.08}(F^*)^{0.86}\mathrm{k_s} \tag{2}$$

The Eq. (1) and Eq. (2) proposed by chanson and Hunt are applicable for Froud number less than 100, so that Hunt and Kadavy [15], proposed another Eq. (3)

$$L_i = 7.48(F^*)^{0.78}k_s \tag{3}$$

Wan *et al.,* [16]. Conducted a Study on a smooth spillway. They found that the inception point is typically further downstream compared to a stepped spillway. It is reasonable to adopt this result because the roughness of stepped spillway makes the flow more dispersion and turbulence when compared with smooth spillway.

Wood *et al.,* [17], conducted a study on to determine the position of inception point, he present in empirical equation to calculated the distance from crest position to inception point for different discharge and roughness factors.

Pagliara, and Peruginelli, [18]. Conducted a laboratory study in hydraulic lab University of Pisa, Italy to investigated the hydraulic performance of different steppes configuration and martials. use the plastic grass in steps surface to modeling the roughness effect on the flow regime. The flowing figure shows some details of flume experimental, Figure 7.

Boes and Hager [13], adopted a mathematical formula to calculate the point of developing turbulent boundary layer and determination of the distance to the inception point.

3.4 Gab in Literature

Through the historical presentation of previous researchers in this field, we note that most researchers used a virtual surface flow (wood, plastic mold, or any other material that can be formed according to the requirements of the model), so did not find any researcher who actually used RCC material in an actual test model in order to investigate the behavior of the development of the boundary layer, as well as the effect of surface roughness on the location of the two phase flow development.

4. Methodology

4.1 Experimental setup and Physical Model

The Experimental work was carried out in the laboratory of the Faculty of Engineering, University of Kufa (central hydraulic laboratory). The Flume in which the experiments were conducted was 15 m long, 0.45 meters high and 0.3 meters wide. It contains a centrifugal pump (max flow rate 150 m3/h) for processing water with a capacity of up to 50 (l/sec), and a stilling tank, capacity 0.6 m3 to collecting water at the downstream and recirculation water. The flume has transparent glass clips on the side for clear reading of the levels and heights for examination. The following Figure 8 and Figure 9 shows the channel and some of its contents for conducting tests and experiments.

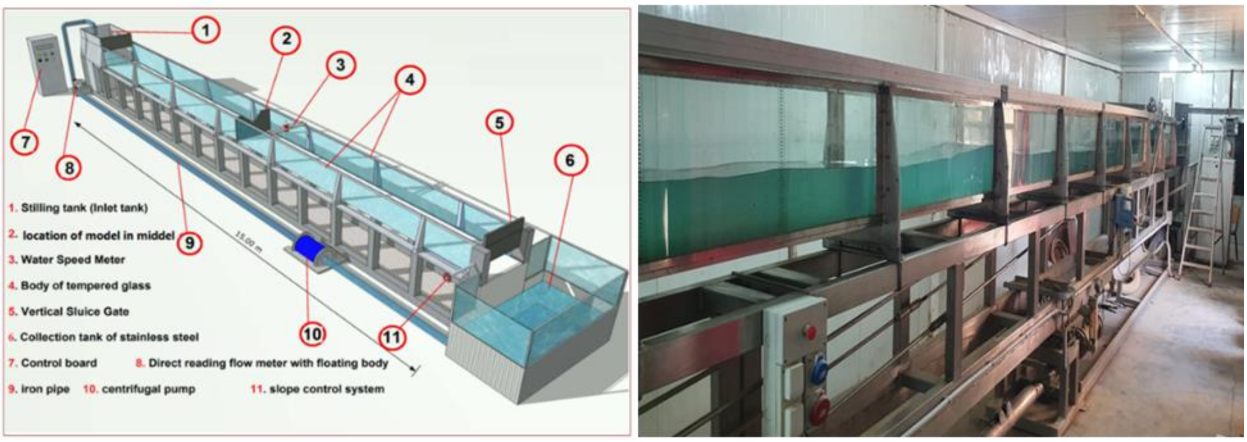

Fig. 7. Flume setup in hydraulic lab

Fig. 8. Physical model and Mold preparing for test

4.2 Physical Model

The Physical model was composite of two part: upper part made of roller compacted concrete using a hand sharpener and installed on lower part a moisture-resistant cork boards mold according to the required sizes of the model prepared for the experiment. the number of models chosen is five models that differ in terms of the number of Steppes and inclination. The preparation of the physical models was summarized in the following steps and the subsequent image, respectively.

i. The molds are configured according to the required size, which are made using moisture-resistant cork boards and cut according to the sizes using digital machines (CNC).
ii. Materials (sand: aggregates: cement and cementitious material) are processed and mixed according to the required percentages of the form (Zero Slump).
iii. These materials are compacted after mixing well in the form of layers not exceeding 1 cm. It is compacted using a concrete roller made for this purpose, weighing 15 kg and for at least 3 minutes per layer
iv. After the compaction process is completed, the form is left for 24 hours and the procedure is completed.

v. After that, this model is mounted on the template that was prepared earlier (first paragraph) and according to the required model size (the number of stepped and the required slope).
vi. These pieces are fixed to the mold using moisture-resistant adhesives to ensure that the profiled concrete pieces adhere to the mold
vii. The model is placed inside the channel by fixing it with metal hooks and screws that fix the bottom of the channel
viii. After installing the model, the required discharge value is controlled through a discharge measuring device (5 square meters per second to 50 square meters per second)

The following subsequent image in Table 1 present the several stages used to prepare the model of RCC and mixing proportion according to the steps size required.

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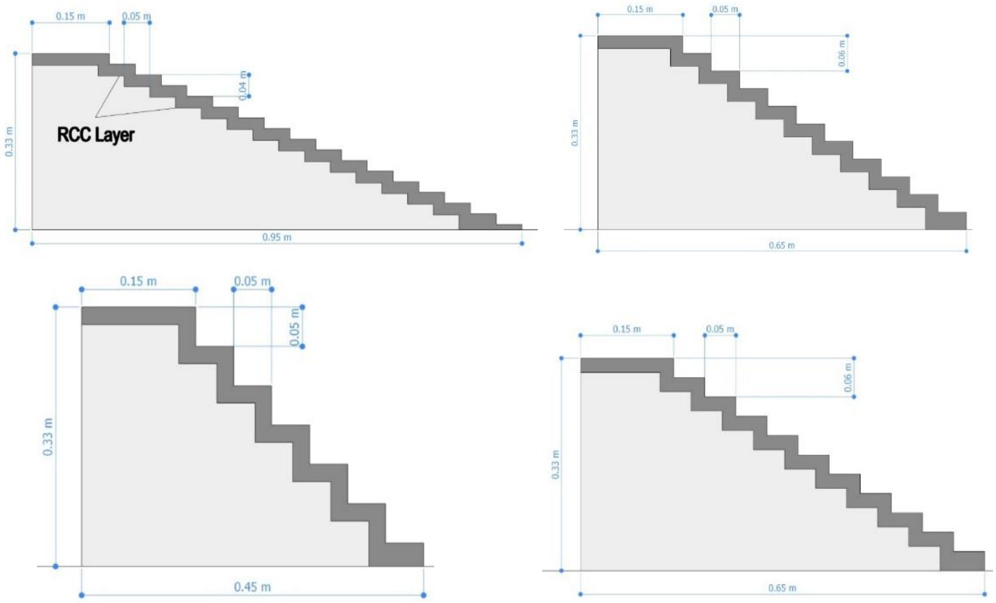


Fig. 9. Dimension of different physical model (slope variation 21°, 31°, 38°, 45°)

Table 1
Step by step to prepared the model of RCC and mixing proportion

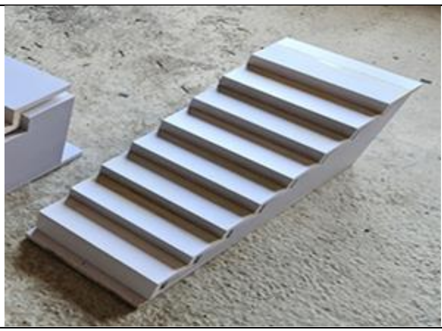
	
(1) Preparing the martials and mold	(2) mixing the martials

(3) Test the zero-slump requirement

(4) Compacting in layers (3 cm)

(5) Re-compacted layers to the level

(6) levelling the surface after each layer



(7) Mold moisture-resistant cork boards

(8) Setup the RCC layers in Mold

5. Computational fluid dynamic (CFD)

5.1 Review

CFD studies are of great importance in understanding and analyzing the behavior of two-phase flow in stepped spillways. These approaches allow engineers to predict the flow patterns, pressure fluctuations, and air entrainment in order to optimize the design and operation of stepped spillways for enhanced safety and performance. Additionally, CFD studies provide valuable insights into the hydrodynamic effects on overtopped structures, allowing for cost-effective and time-efficient analyses compared to traditional physical models [24]. By simulating the flow patterns and energy dissipation with different configurations, CFD studies help in evaluating the influence of step-edge designs and comparing hydraulic properties, [19].

5.2 VOF Model

VOF Model is commonly used to simulate the multi-phase flow in a stepped spillway. It allows for accurate prediction of the flow patterns and energy dissipation in different configurations of spillways and step-edge designs. Additionally, utilizing the VOF method in CFD models enables the simulation of air entrainment by aerators in stepped spillways [16]. Kurdistani, and Gianluca [20], combination of the VOF model with turbulence closures, such as the k-ε family, allows for a comprehensive understanding of the flow dynamics and the inception point of air entrainment, which is crucial for the design and evaluation of stepped spillways [21].

5.3 Mesh Discretization

The precision and stability of the numerical calculation are significantly influenced by the mesh quality [22]. Node point distribution, smoothness, and skewness are characteristics connected to mesh quality [19]. Incorrect mesh selection can have an impact on simulation accuracy, computational efficiency, and solution stability [23]. In the present work (0.8*0.8 mm) elements size are suitable to capture the air water interaction. Figure 10 present boundary condition and mesh discretization.

5.4 Boundary Conditions

This stage of preparing the model is very important because it determines the extent to which the physical phenomenon (air water interaction) can be represented phasic for flow of stepped spillway correctly. In present work, Figure 10 shown the all the boundary condition had been used, the maintains non-zero velocity (no slip wall) at the bed of spillway with roughness depth 2.5 mm and roughness constant 0.5. Also, the pressure condition for outlet boundary at the downstream set by default to zero gauge (or atmospheric). A symmetry boundary was designated for the model top surface.

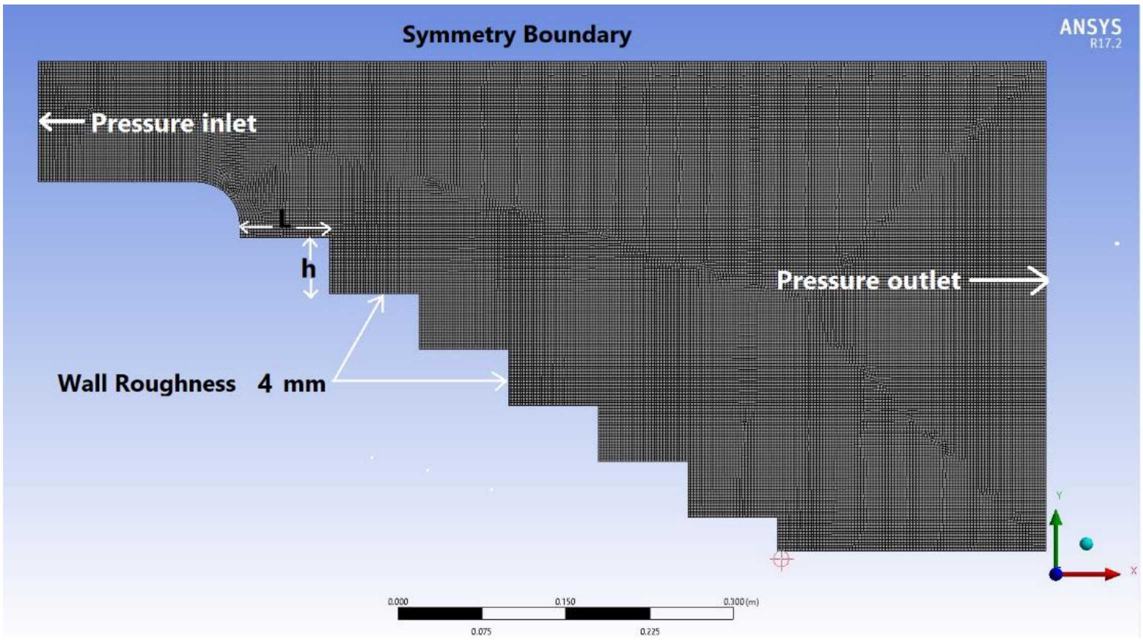


Fig. 10. domain discretization, mesh and boundary condition

6. Result of Experimental Study and CFD

The results and outputs obtained included a comparison between the laboratory results of four different inclinations and stepped height of RCC models for ten different discharges to clarify some characteristics of the two-phase flow. Three equations proposed by researchers were compared with the current results to clarify the extent to which the surface roughness and composition of the surface affects the flow characteristics and the development of the thickness of boundary layer. The following Table 2 to Table 6 present the results of experimental and numerical models for different conditions.

Table 2
Results of experimental and CFD model, h = 2 cm, L = 5 cm, Ks = 0.0185, ø = 21.8°

Test No.	q (m2/s.m)	(dc/h)	F*	Li Exp (m)	Li CFD (m)	Li Eq. (1)	Li Eq. (2)	Li Eq. (3)
1	0.018	0.90	3.75	0.27	0.25	0.426	0.325	0.388
2	0.024	1.20	4.99	0.36	0.33	0.522	0.416	0.485
3	0.03	1.50	6.25	0.42	0.40	0.613	0.504	0.577
4	0.036	1.80	7.49	0.50	0.45	0.698	0.589	0.666
5	0.042	2.10	8.75	0.61	0.58	0.779	0.673	0.751
6	0.048	2.40	9.99	0.73	0.68	0.856	0.755	0.833
7	0.054	2.55	10.62	0.79	0.75	0.895	0.795	0.874
8	0.06	3.00	12.25	0.89	0.84	1.005	0.914	0.992
9	0.066	3.30	13.75	0.95	0.91	1.075	0.993	1.068
10	0.072	3.60	14.99	0.97	0.94	1.144	1.070	1.143

Table 3
Results of experimental and CFD model h = 3 cm, L = 5 cm, Ks = 0.0257, ø = 30.9°

Test No.	q (m2/s.m)	(dc/h)	F*	Li Exp (m)	Li CFD (m)	Li Eq. (1)	Li Eq. (2)	Li Eq. (3)
1	0.018	0.60	1.947	0.21	0.22	0.38	0.266	0.323
2	0.024	0.8	2.50	0.27	0.24	0.455	0.325	0.392
3	0.03	1.00	3.24	0.36	0.36	0.547	0.406	0.480
4	0.036	1.20	3.894	0.40	0.42	0.624	0.476	0.554
5	0.042	1.40	4.54	0.49	0.51	0.696	0.543	0.625
6	0.048	1.60	5.193	0.58	0.61	0.766	0.610	0.694
7	0.054	1.80	5.517	0.62	0.64	0.80	0.642	0.778
8	0.06	2.00	6.491	0.69	0.74	0.898	0.739	0.826
9	0.066	2.20	7.14	0.79	0.81	0.981	0.802	0.890
10	0.072	2.40	7.789	0.83	0.86	1.023	0.864	0.953

Table 4
Results of experimental and CFD model: h = 4cm, L = 5cm, Ks = 0.0312, ø = 38.65°

Test No.	q (m2/s.m)	(dc/h)	F*	Li Exp (m)	Li CFD (m)	Li Eq. (1)	Li Eq. (2)	Li Eq. (3)
1	0.018	0.45	1.32	0.19	0.19	0.355	0.232	0.289
2	0.024	0.60	1.76	0.22	0.25	0.430	0.296	0.362
3	0.03	0.75	2.20	0.30	0.33	0.512	0.395	0.431
4	0.036	0.90	2.64	0.39	0.40	0.583	0.420	0.497
5	0.042	1.05	3.08	0.45	0.47	0.651	0.474	0.561
6	0.048	1.20	3.52	0.52	0.55	0.716	0.538	0.623
7	0.054	1.275	3.74	0.55	0.59	0.747	0.566	0.653
8	0.06	1.50	4.40	0.62	0.68	0.839	0.651	0.741
9	0.066	1.65	4.84	0.69	0.72	0.898	0.707	0.798
10	0.072	1.80	5.28	0.73	0.77	0.956	0.762	0.854

Figure 11 to Figure 16 demonstrated some physical outcome, stream flow, turbulence kinetic energy, velocity distributions, and air entrainment volume fraction. some of phasic definition are explanations below:

dc = critical flow depth, h = step height, q = flow rate, Li, LCFD = measured and computed longitudinal distance, di, d_{CFD} = measured and calculated water depth at the inception point.

Table 5
Results of experimental and CFD model h = 5 cm, L = 5 cm, Ks = 0.035, ø = 45°

Test No.	q (m2/s.m)	(dc/h)	F*	Li Exp (m)	Li CFD (m)	Li Eq. (1)	Li Eq. (2)	Li Eq. (3)
1	0.018	0.36	1.044	0.175	0.19	0.341	0.215	0.270
2	0.024	0.48	1.390	0.22	0.26	0.418	0.275	0.338
3	0.03	0.60	1.74	0.29	0.33	0.491	0.334	0.403
4	0.036	0.72	2.086	0.36	0.38	0.559	0.391	0.464
5	0.042	0.84	2.436	0.42	0.44	0.624	0.446	0.524
6	0.048	0.96	2.780	0.49	0.52	0.685	0.50	0.581
7	0.054	1.02	2.95	0.51	0.55	0.715	0.526	0.608
8	0.06	1.20	3.480	0.58	0.60	0.804	0.606	0.692
9	0.066	1.32	3.829	0.65	0.67	0.861	0.658	0.745
10	0.072	1.44	4.177	0.69	0.77	0.916	0.709	0.798

Table 6
Results of Experimental for modeling conventional concrete and RCC concrete surface texture (model h = 3 cm, L = 5 cm, Ks = 0.0257, ø = 30.9°

Test No.	q (m2/s.m)	(dc/h)	F*	Li RCC (m)	Li COV (m)	Li Eq. (1)	Li Eq. (2)	Li Eq. (3)
1	0.018	0.60	1.947	0.21	0.21	0.38	0.266	0.323
2	0.024	0.8	2.50	0.27	0.28	0.455	0.325	0.392
3	0.03	1.00	3.24	0.36	0.36	0.547	0.406	0.480
4	0.036	1.20	3.894	0.40	0.41	0.624	0.476	0.554
5	0.042	1.40	4.54	0.49	0.50	0.696	0.543	0.625
6	0.048	1.60	5.193	0.58	0.60	0.766	0.610	0.694
7	0.054	1.80	5.517	0.62	0.64	0.80	0.642	0.778
8	0.06	2.00	6.491	0.69	0.72	0.898	0.739	0.826
9	0.066	2.20	7.14	0.79	0.81	0.981	0.802	0.890
10	0.072	2.40	7.789	0.83	0.86	1.023	0.864	0.953

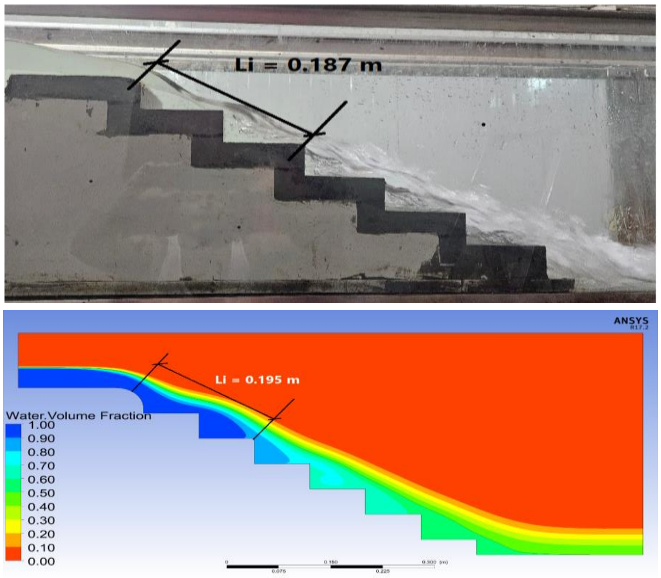
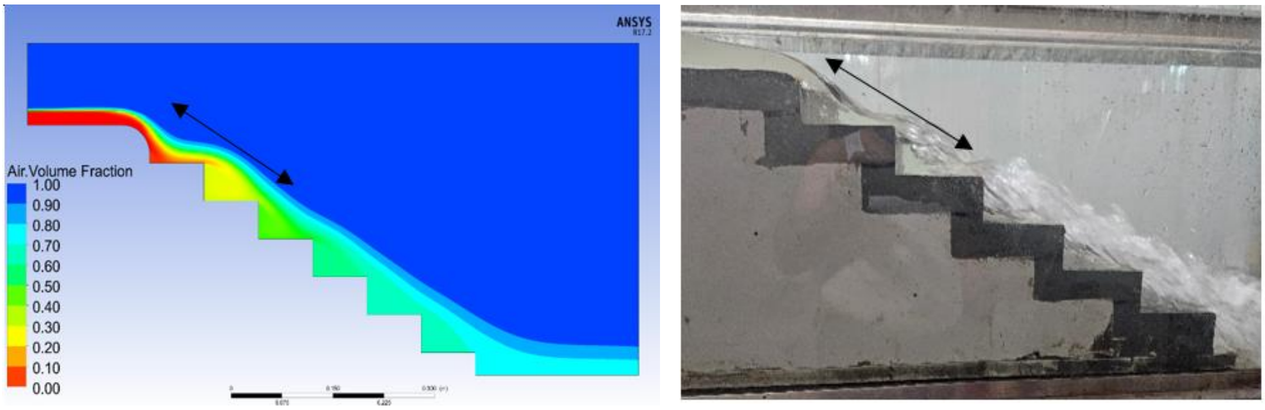
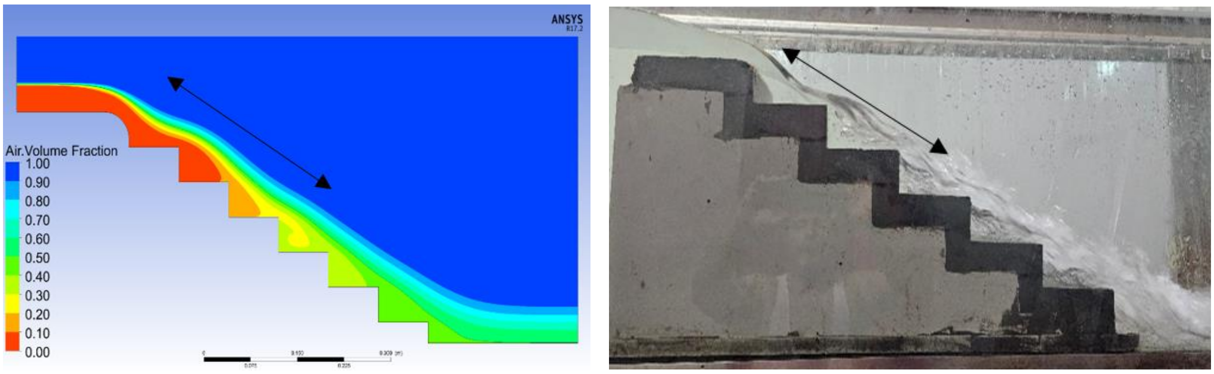


Fig. 11. Length to inception point for experimental and CFD modeling (q= 35 kg/sec)



(a)



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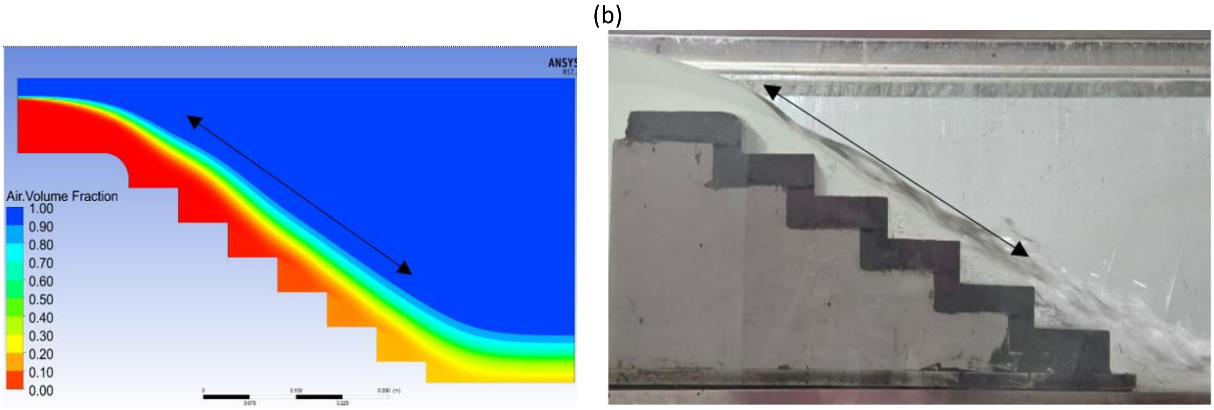
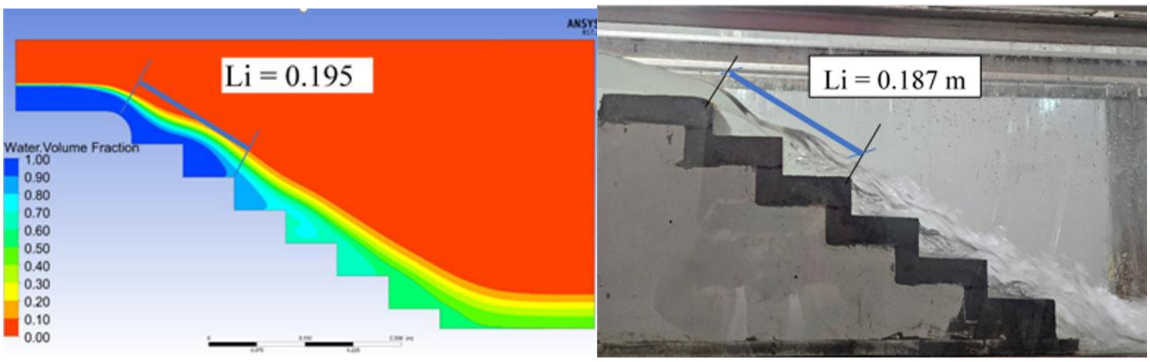


(c)

Fig. 12. Inception point location for experimental and CFD model for different unit discharge (a) Flow rate 19 (l/s), (b) Flow rate 39 (l/s), (c) Flow rate 72 (l/s)



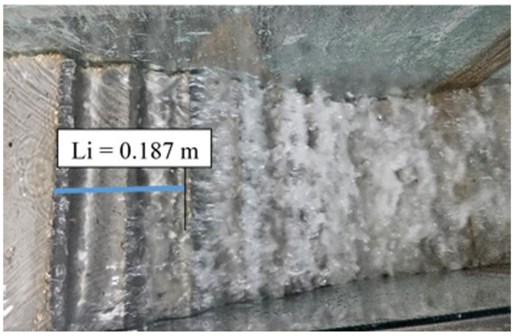


Fig. 13. Inception point location (white color represents air interment in water)

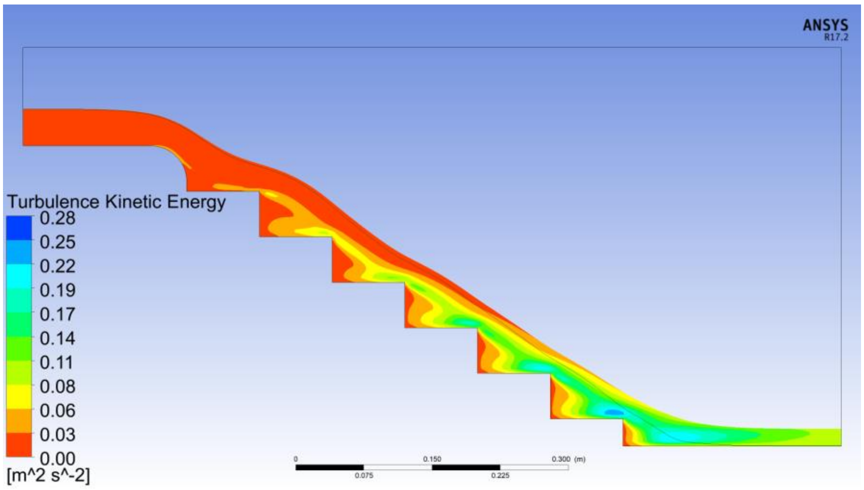


Fig. 14. Turbulences kinetic energy distribution along stepped spillway

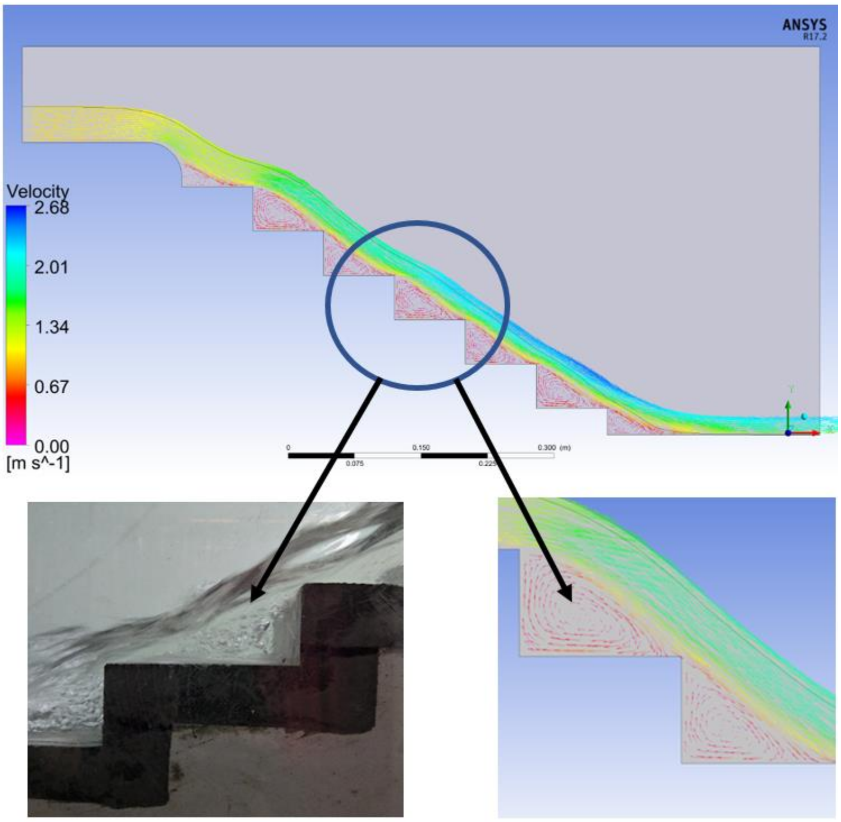


Fig. 15. Vortices and air entrainment in stepped for experimental and CFD model colored by velocity along stepped spillway

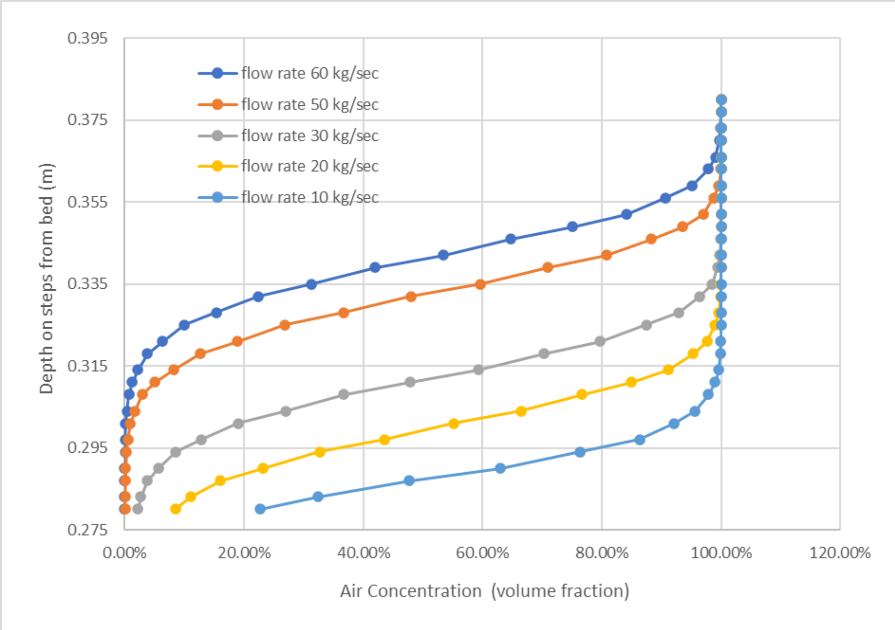


Fig. 16. Air volume fraction verse depth along steps 2 for different flow rate

6. Conclusion

One of the important conclusions obtained through the laboratory results and the CFD model is that the location of inception points of the two-phase flow in the rough surface model RCC starts with locations closer to the top of the crest than in the usual models when compared with models that do not use the actual RCC rough surface. The increase in discharge pushes the mixing point by moving it down the spillway. It was also noted that the values of the surface roughness coefficient are clearly affected by the velocity and low discharge, since the values of the surface roughness coefficient have a clear effect at low speeds.

The experimental results showed a clear agreement with the CFD results by comparing the outcomes of the location of inceptions.

The results were compared with previous outputs of other researchers (Eq. (1) - Eq. (3)), we note that the values of the location of the two-phase flow of the current study are in range (10% -20%) lower than the values obtained from another researcher result of traditional or typical stepped spillway. We also note that the surface roughness coefficient accelerates the developing of the boundary layer thickness in the few discharges and price, and we also note that the values of the surface roughness coefficient decreases its effect in high discharges.

Acknowledgement
This research was not funded by any grant.

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