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SCALING OF UNCERTAINTY IN VALIDATION OF FLOODING SIMULATIONS: AN ILLUSTRATIVE CASE STUDY

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INTRODUCTION

Nuclear industry has undertaken several studies to ensure safety against flooding in power plants after the tsunami induced flooding at Fukushima Daiichi power station in 2011. A large number of such studies rely on advanced flooding simulation tools. Simulation of catastrophic external or internal flooding events often suffers from a lack of confidence in the predictions due to inherent randomness, lack of knowledge about the physics of complex interactions and the associated uncertainties. Some recent studies have focused on the development of a consistent methodology for verification and validation of these advanced simulation tools. Yet, such validation studies are quite challenging due to a lack of real world data. In almost all cases, simulation tools are validated by comparison with data from laboratory experiments. Furthermore, the data from laboratory experiments is also used for uncertainty quantification. However, it must be noted that a certain degree of validation based on laboratory experiments does not necessarily mean the same degree of validation at real-world scale. This is so because of the scaling effect on uncertainty quantification. The premise used for the study presented in this paper is embedded in the belief that the degree of uncertainty in laboratory experiments does not translate into the same degree of uncertainty at the real-world scale. However, it is difficult to provide an explicit proof of this premise due to a lack of usable quantifiable data at real-world scale. Therefore, we present a case study that collects data from similar laboratory experiments at different scales and illustrates the concept of variation in uncertainty quantification based on the scale, i.e. the scaling effect.

An improved understanding of the scaling phenomenon would help to reduce the gap between a real application at the plant level and a test facility at smaller scale. When a simulation tool used for studying a real world application is validated through a smaller scale facility in laboratory, an implicit extrapolation of the data is considered when simulating a real-world scenario. This is due to application that is well beyond the domain of validation and in turn leads to scale distortion and greater uncertainty in predictions. While it is impractical to design a full-scale experiment model for each plant, it is important to understand the scaling phenomenon by considering the data at many different and yet smaller scales. This understanding can assist with relatively more logical extrapolation of the data.

Lack of available quantifiable data at full scale, and lack of understanding about the applicability of data obtained at reduced scale leads to a residual epistemic uncertainty in a simulation model. Presently, this inadequacy is addressed through expert opinion and professional judgment. If relevant data for a particular scenario exists at multiple though relatively smaller scales then it can facilitate an improved understanding of the complex extrapolation associated with the particular scenario. Such an improved understanding can reduce the reliance on heuristic approaches for expert opinion.

An increased awareness of the scaling phenomenon can help guide future experimental studies to focus on collection of data at multiple scales and in effect enhance the performance of simulation scaling. A reduction in scale distortion will enhance our ability to estimate flooding risks more effectively. In this study, we characterize the scaling pattern by collecting data from small to medium scale experiments and then extrapolate the uncertainties for larger scale applications.

DESCRIPTION OF APPLICATION CASE STUDY

The particular case study considered in this paper relates to an external flooding scenario wherein the flood water could enter a plant's building through a door or window opening. Ventilation openings have often been cited as the key locations of concern that are susceptible to failure during an external flood thereby creating an opening for flood waters to enter the building. When the opening is only partially covered with water, the scenario is representative of flow over a weir. The concept of flow over a weir has been studied extensively by the experts in the field of fluid mechanics. The flow of over a weir concept also applies to a scenario wherein a part of a floodwall collapses to create an opening for the flood waters to enter the plant landscape. Alternatively, overtopping of the floodwall can be considered as a similar scenario but with some limitations. For the particular case study in this paper, we consider a rectangular weir case. In real world application, the geometry of the opening may not necessarily be rectangular. However, there is a significant volume of literature and experimental studies available from the research on rectangular weir and hence the selection of particular case study in this paper.

EXPERIMENTAL SET-UP AND ANALYSIS

In this section, we describe the experimental setups used to conduct the scaling study as proposed earlier. Data is extracted from five different laboratory experiments for the rectangular channel with rectangular opening at the outlet. The parameter that can be subjected to scale change in a rectangular weir are as follows: Length of the channel (L), weir opening width (b), weir total width (B), fluid height (h), weir height (P) and maximum fluid height (H) (See Figure 1).

Evaluation for the discharge (volumetric flow rate per second) is important because it determines the flow rate of the incoming flood. We focus on the main parameters which affects the discharge prediction directly according to the fluid mechanics principles (here h and b for rectangular weir). The discharge equation is given in Eq. 1 for a simple rectangular channel. The parameters used in the equation are shown in the Figure 1.

$$\begin{gathered} Q_{th} = \frac{2}{3}\sqrt{2g}\, b\, h^{1.5} \\ Q_{act} = C_d Q_{th} \end{gathered} \qquad \text{Eq. (1)}$$

where, Q_{th} is the theoretical discharge, Q_{act} is the actual discharge and C_d is the coefficient of discharge

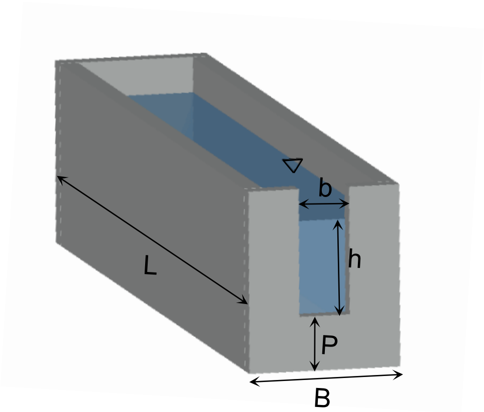


Figure 1. Geometry of rectangular weir at the outlet

Theoretical model of the rectangular weir considers water height h and opening width b for the evaluation of discharge. However, it ignores the contribution of various other weir parameters such as *P, B, H, L*, ratio *b/B*, ratio *h/H*, ratio *h/P*, shape of edges and corner geometry. The theoretical model remains inadequate due to lack of knowledge of the underlying physics of the weir discharge. However, the inadequacy in the model for calculating the theoretical discharge is addressed by the coefficient of discharge. It is also impractical to consider large set of parameters since most of the data is not recorded and unavailable at real scale. For example, appropriate weir length for the modelling of flood approaching the protection dikes at the power plant cannot be defined. Uncertainty associated with these other parameters is reflected into the coefficient of discharge. Henceforth our focus in this paper remains on the three main parameters; h, b and C_d.

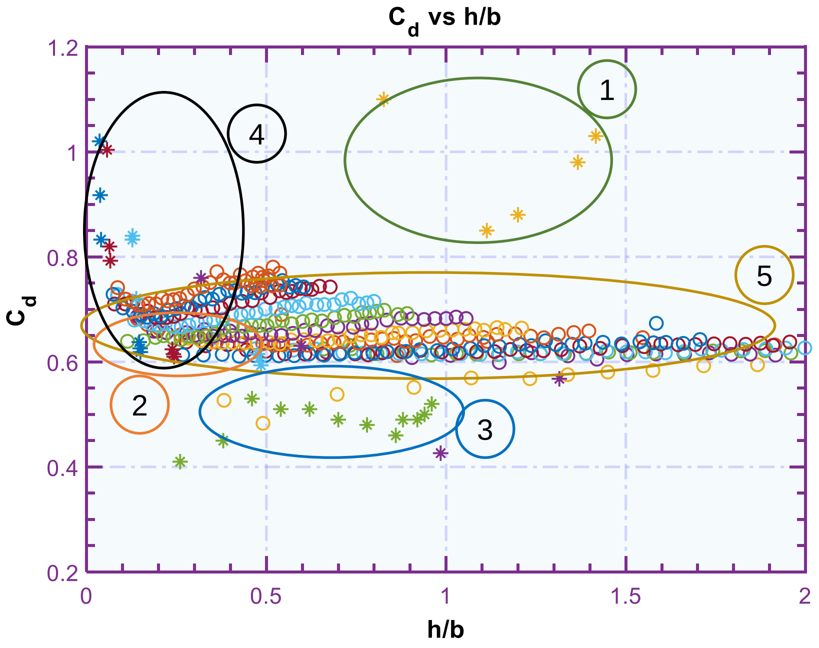
As the scale for the experiment changes, some parameters will have significant effects and others will have minor effects. Instead of quantifying the effect of each parameter separately, C_d allows to quantify the overall effect of the scale change. Opening width and water height used in these five experiments are listed in the Table 1.

Table 1. Dimension of weir outlet for all the experiments

Experiment No.	b vs H (m)	Width scaling compared to 0.03 m	Height scaling compared to 0.05 m
1	0.03 x 0.05	1	1
2	0.033 x 0.05	1.1	1
3	0.05 x 0.08	1.67	1.6
4	(0.2 – 0.4) x 0.1	13.3	0.2
5	(0.02 – 0.32) x 0.28	10.6	5.6

Experiment 4 and 5 are performed for a set of varying opening widths. Hence, only the maximum and minimum opening width are mentioned in the table. Even though experiment 4 has data for different opening widths, it only mentions the experimental results with respect to maximum and minimum height. Since the water height, h varies in all the experiments, only the maximum height of water is mentioned in the table. Increase in the scale with respect to the smallest experiment scale is also listed in the table. The effect of change in scale can be determined from small to medium scale in these experiments since height and width scale vary 5 to10 times from the smallest scale.

Relation between C_d and *h/b* for all the experiments is shown in Figure 2(a). Weir opening width varies in experiment 4 and 5, therefore the C_d vs *h/b* data for each b is shown in different color. Display of the data shows that each experimental data set spreads over its mean with a certain standard deviation. The degree of spread also depends on experimental uncertainty and observation errors. It is difficult to eliminate these errors or uncertainties during the uncertainty quantification analysis because the experimental data is obtained from published literature. An attempt is made to understand the scaling pattern within the data despite these unquantifiable uncertainties.



(a)

Exp. No.	Mean of C_d	Std. dev. of C_d
1	0.9680	0.1038
2	0.5961	0.1387
3	0.4867	0.0334
4	0.7403	0.1482
5	0.6563	0.0185

(b)

Figure 2. (a) Plot between C_d vs *h/b* for all the experiments & (b) Mean and standard deviation of C_d for each experiment

Figure 3 shows a plot between C_d and *h* from the experiments (1, 2 & 5) where the opening width scale varies from 1 to 2. The relatively small variation in the scale does not require the data to be plotted with respect to non-dimensional quantity such as *h/b*. Experiment 1 data lies completely outside the range of the data from other similar scale experiments in the plot. Hence the experiment 1 data is considered an outlier and not considered for further assessment.

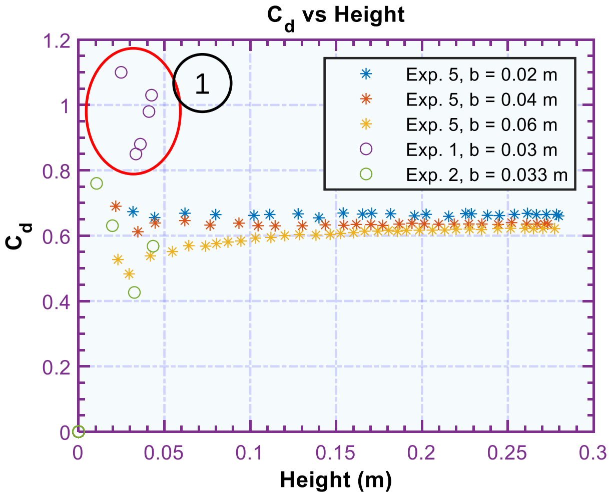
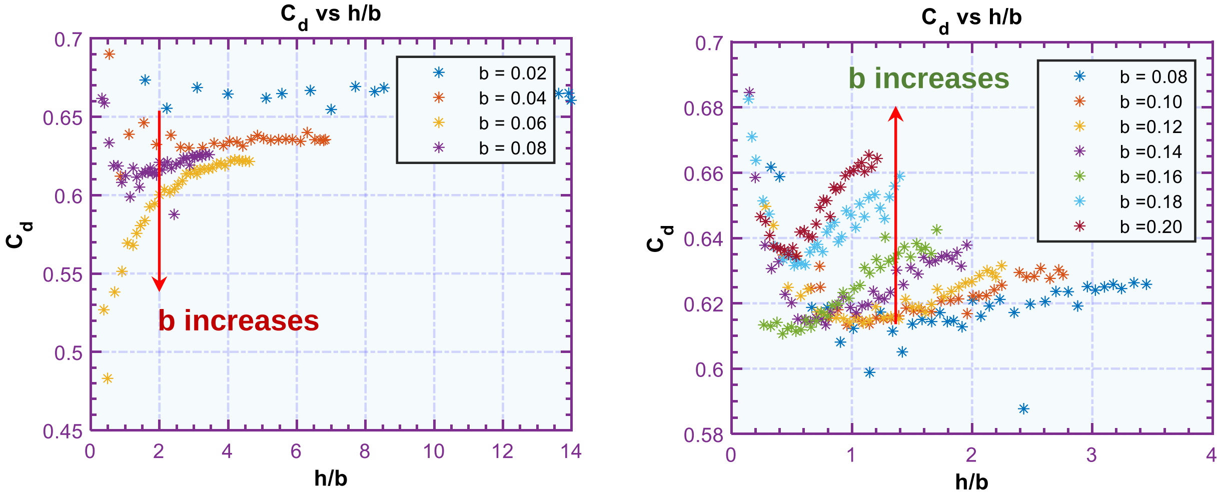


Figure 3. Biasness in the Experiment 1

Figure 4 compares C_d vs *h/b* plot for two different ranges of *b* in the experiment 5. For lower ranges of *b* (Figure 4(a)), C_d decreases as *b* increases for same *h/b* ratio whereas for higher ranges of *b* (Figure 4(b)), C_d increases as *b* increases for same *h/b*. It is intuitive that for each of the experiment such change in the pattern occurs at certain value of *b*. For example, this change occurs for experiment 5 at b ~ 0.08 m. However, it cannot be compared with data from other experiments as they do not provide C_d vs *h* data for different *b*. It should also be noted that *h/b* < 0.5 has a very different pattern. This is likely due to boundary effects on low water heights or extremely wide weir size.

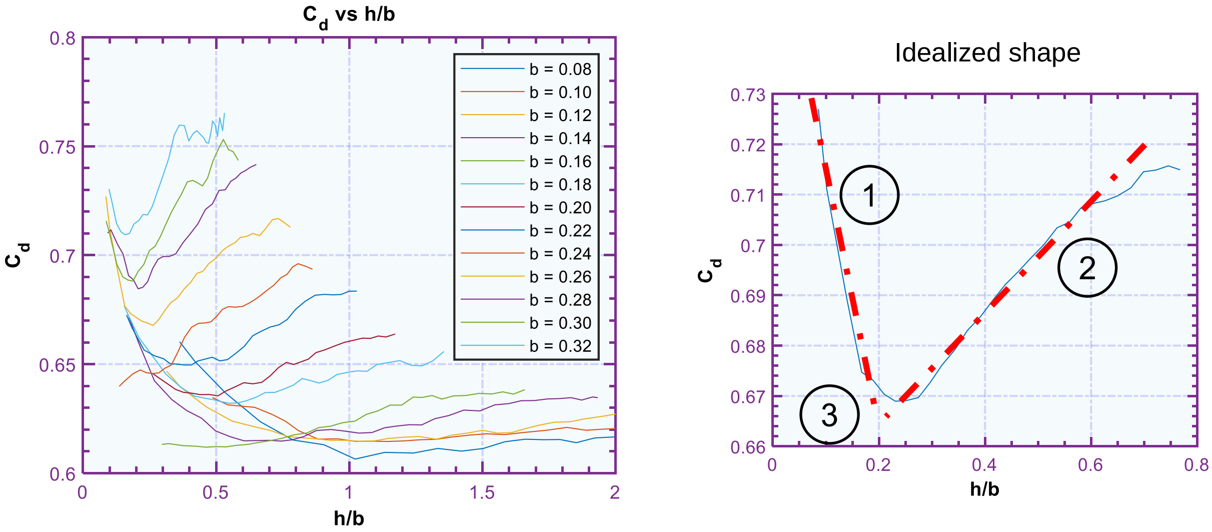
$b < 0.06$ m $b > 0.08$ m



(a) (b)

Figure 4. Plot for C_d vs *h/b* for experiment 5: (a) $b < 0.06$ & (b) $b > 0.06$

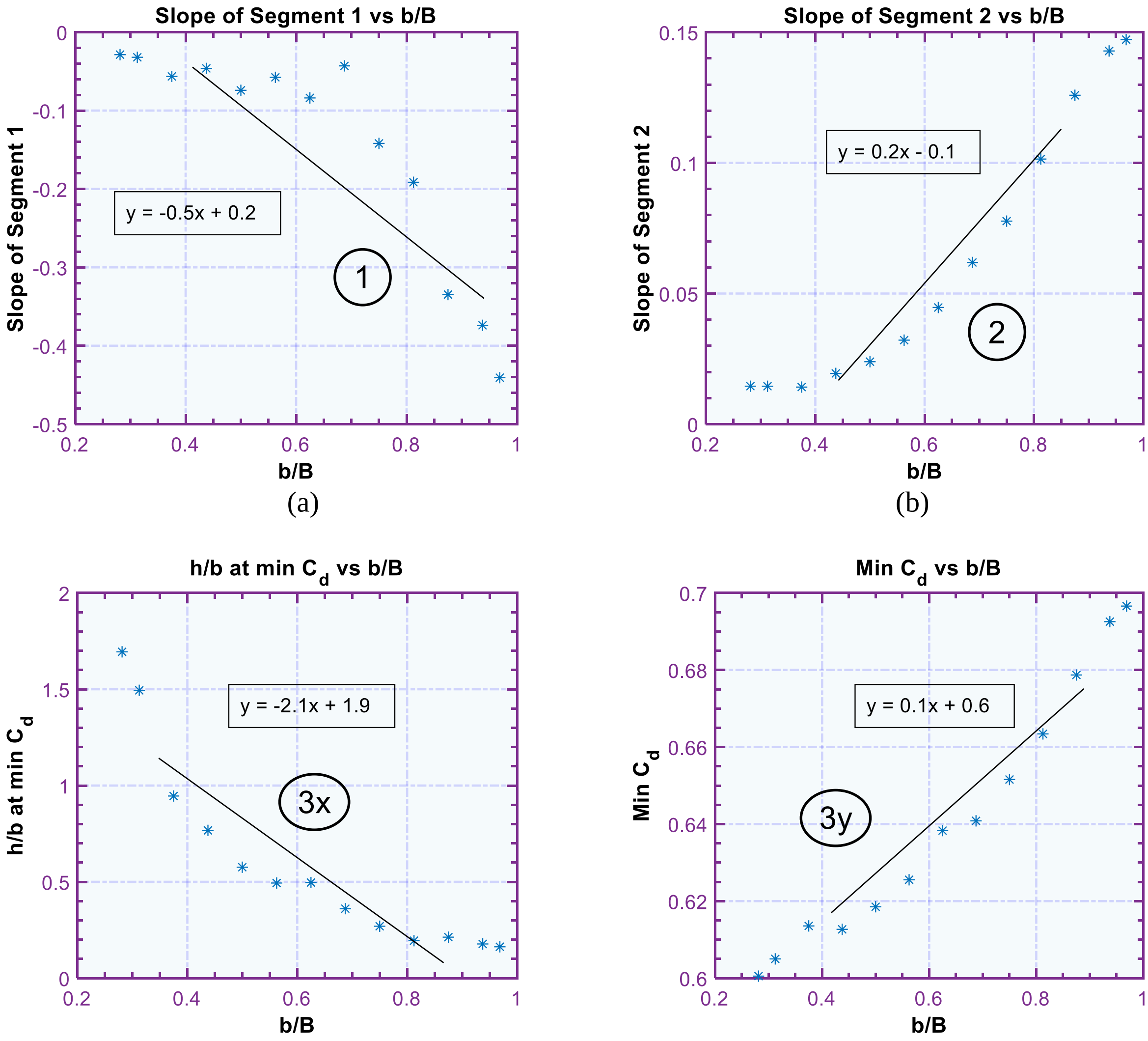
C_d vs *h/b* plot for all the opening widths more than 0.08 m (*b/B* > 0.25) shows a peculiar pattern between C_d and *h/b* in Figure 5(a). An idealized shape for C_d vs *h/b* curve for *h/b* > 0.1 can be plotted as Figure 5(b). The limit on *h/b* is applied because for a low *h* or large *b*, the boundary condition will change the flow characteristics. The idealized shape for C_d vs *h/b* plot has two segments intersecting at the lowest point of the graph (point 3). Slope of both the segments and the *x*, *y* coordinates of point 3 can define the complete shape of C_d vs *h/b* curve. Hence, relation of these four quantities with the weir width is found in Figure 6(a) to Figure 6(d). Use of weir width *b* is not appropriate when the scaling pattern is established. Hence, the parameters (slope and lowest coordinate) for idealized shape of C_d vs *h/b* curve are plotted with respect to dimensionless ratio *b/B*. Abscissa in these plots varies from 0 to 1 as weir opening width cannot exceed the overall width of the weir.



(a) (b)

Figure 5. (a) Plot for C_d vs *h/b* from all the experiments with *b/B* >0.25 & (b) Idealized shape for C_d vs *h/b*

Figure 6 shows that slopes of segment 1 & 2 and *x* & *y* coordinates of point 3 are linearly proportional to *b/B*. Slope of segment 2 and *y* coordinate of the lowest point in curve (3) decrease as *b/B* increases whereas slope of segment 1 and *x* coordinate of the lowest point increases. Linear correlation equations obtained from these 4 plots would define the C_d vs *h/b* curve completely. It should be noted that these relations are not valid when the ratio *b/B* < 0.25 and *h/b* < 0.1 as discussed earlier. Such rectangular weir with low *b/B* or *h/b* ratios would not show the same characteristics of flow as a normal rectangular weir (Figure 5(a)) due to boundary effects. A consideration of the effect of change in height and width scale significantly reduces the uncertainty associated with extrapolation.



(a) (b)

(c) (d)

Figure 6. Plot for parameters for C_d vs *h* plot: (a) Slope of segment 1 vs *b/B*, (b) Slope of segment 2 vs *b/B*, (c) *h/b* at the lowest point vs *b/B* & (d) Minimum values of C_d vs *b/B*

The actual flow rate of flood can be interpolated with the above correlations for a given opening width and the probable water height. Height of flood water, being an unknown at the stage of assessment, can be obtained from the probabilistic model developed for storm surge. The uncertainty within the coefficient of discharge is found by fitting the statistical distributions for Lognormal and Beta distributions to the histograms of C_d (Figure 7). Beta distribution is found to be a better representation for the uncertainty in the parameter C_d. The fitted distributions also show an increase in mean and standard deviation of C_d with the increase in width scale. The analysis presented in this paper not only quantifies the uncertainty in the evaluation of C_d, but also minimizes the scaling effects.

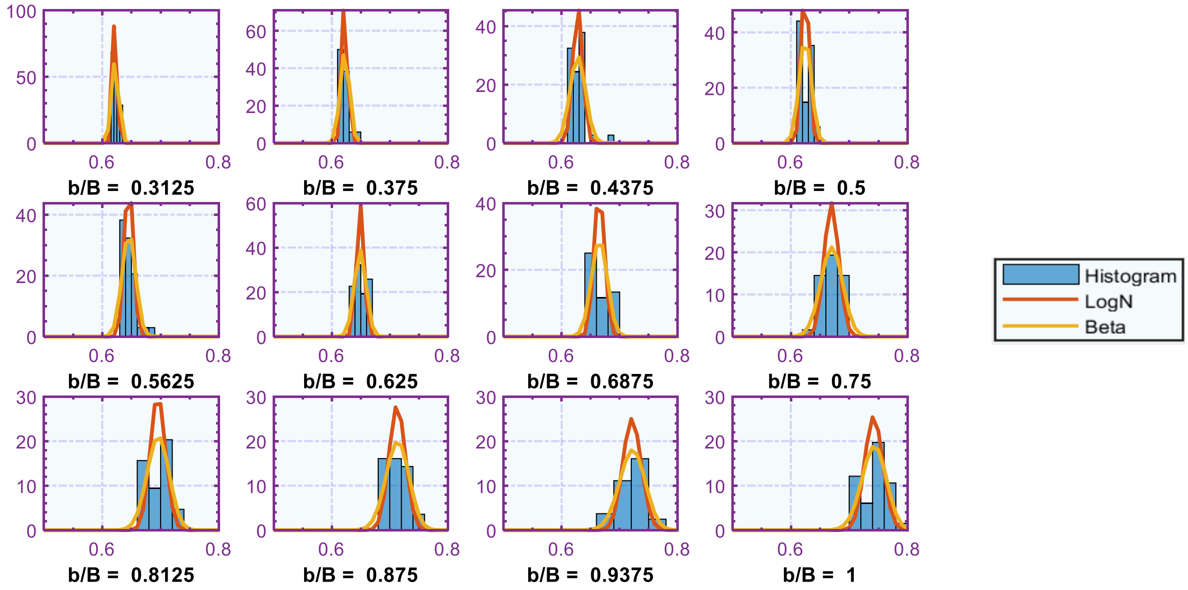


Figure 7. Fitting the Lognormal and Beta distribution for C_d

SUMMARY AND CONCLUSION

Several advanced simulation tools used for studying real world flooding scenarios are validated through smaller scale laboratory experiments. An implicit extrapolation is performed on the reduced scale data beyond the domain of validation when using these simulation tools for real-world applications. Issues related to such scale distortion and associated uncertainty in predictions are often resolved by profession expertise. Understanding of the scaling phenomenon is extremely important to enhance and support expert data analysis. This paper introduces a methodology which considers reduced scale experiments at different scales to illustrate the scaling effect.

Available literature on experiments for flow over a rectangular weir is used to illustrate the application of the proposed methodology. Width and height of rectangular weirs in the experiments have a scale that is at least 10 times larger than the smallest scale experiment. The main source of uncertainty in the mathematical model (coefficient of discharge, C_d) remains proportional to the scaling parameters, despite a relatively large difference in the scale. Uncertainty within C_d follows Beta distribution and it is proportional to the increase in scale. The discovered effect of scaling at the reduced scale can be extended for use at plant level flooding to minimize the uncertainties associated with scale distortion. The paper establishes a methodology to improve the validation of advanced simulation tools by illustrating the analysis on multiple reduced scale experiments.

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