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Sensitivity Analysis of Dam Breach Parameters for Variation Capacity Earthen Dams

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Abstract: Sensitivity analysis is an effective tool to determine the robustness of an assessment by examining the extent to which the results are affected by changes in input. In this study, the FAST method was applied to analyse the sensitivity to the earth dam failure process. Four (04) input variables were selected including breach development time, breach width, side slope, and initial breach position. The effects of these parameters on the two (02) outputs i.e., the maximum outflow, and rising time were assessed. The study was applied to 08 reservoirs with different capacities. The sensitivity analysis showed that the development time and initial breach location dominantly affect these outputs. Additionally, development time is the most important factor in rising time. The lateral slope has an insignificant effect on outputs. The effect of breach width can be neglected to rising time, however, its influence on maximum outflow is significant. The results of this study show the role of input variables in the flow hydrograph due to dam failure. Through this research, the workload of the breach parameter analysis process can be substantially reduced.

Key words: Dam breach, sensitivity analysis, FAST, breach development time, breach width, side slope, initial breach position.

Introduction

Dam breach is a type of disaster causing heavy casualties to the structure itself as well as the downstream area. Research on dam breach has been carried out for a long time ago (Froehlich, 1995a; MacDonald and Langridge-Monopolis, 1984; Xu and Zhang, 2009). The outflow by dam breach is essential for the implementation of flooding at the downstream areas. However, this is a complicated process. As the breach size develops over time, the outflow through the breach varies drastically. A common strategy used to study dam breach is using empirical equations to estimate breach parameters such as breach development time or breach width. Outflow hydrograph is then determined through hydraulic principles (e.g. flow over spillway). Several common equations have been used to estimate development time (Froehlich, 2008; MacDonald and Langridge-Monopolis, 1984; Xu and Zhang, 2009). Meanwhile, the study results obtained by Froehlich, (1995b) and Von Thun and Gillette (1990) are often used to predict the breach width. The advantage of these equations is that input data are easily collected. However, these equations are based on dam failure data from the past. So the almost collected data such as peak discharge and development time are often indirectly determined. This seems to be a common problem in this approach because the method gives different results when using different equations.

To fill this literature gap, previous studies have emphasised on uncertainty analysis. This means that they were limited to determine the accuracy of model outcomes depending on the uncertainty and variations of the inputs. For example, Shih et al. (2018) investigated a range of discharge and inundation extent that were based on breach development time and breach width. This research only showed that computed peak discharges, which were very sensitive to breach parameters. Seminal contributions have been made by Wahl (2004) and Froehlich (2008) who also concluded that the effect of breach parameters were the most important factors that affect outflow hydrograph. However, no previous research has investigated which parameter played the most important role, which parameter had insignificant contribution or the interaction between input parameters. Moreover, to our knowledge, no prior studies have examined that how the effects of the parameters changed under different capacity reservoir conditions. The study addresses the research question on the role of dam breach parameters as well as the effect of reservoir conditions on their roles.

An alternative approach to the problem is sensitivity analysis. Sensitivity analysis is an examination of the variation of the outputs due to the influence of the variability of the input variables (Saltelli, 2002). This analysis is conducted to assess the main driver for variation in the output(s) on the influence of input variables. The greater the influence of the variable, or the higher the importance of the input variable, the higher is the sensitivity index of that input variable. The classification of sensitivity analysis methods can be based on: Local and Global sensitivity analysis, Quantitative and Qualitative sensitivity analysis, or One-At-a-Time and All-At-a-Time (Pianosi et al., 2016). Currently, sensitivity analysis has been applied in many areas of life as well as in dam safety. There have been a number of studies on the problem of sensitivity analysis for earth dam failure, among which the study by Chen et al. (2019) is well-documented. It is also well-acknowledged that soil erodibility and initial piping position can significantly affect the earth dam breach process. However, these authors only considered the variation of maximum outflow corresponding to three levels of each of these input variables. This approach can be considered like uncertainty analysis. Ren et al. (2019) applied the Morris analysis method (Morris, 1991) for the parameters of the hydrothermal coupling model for the earthen dam. Research has shown that hydraulic conductivity has the greatest effect on the temperature of the earth dam, while other parameters such as porosity and saturated water content, are of less importance. Hall et al. (2009) evaluated the effects of variables in reservoir water level, breach development time, and roughness on downstream water level using the FAST method (Cukieret al., 1978). All the above research show the potential results. It leads us to examine sensitivity analysis of dam breach. The aim of this work is to rank dam breach input parameters uncertainties regarding their impact on the maximum outflow and the rising time of the hydrograph. The study was carried out under reservoir conditions with different capacities to evaluate the effect of reservoir storage on the sensitivity of these parameters. In this research, eight reservoirs are selected. They all have an earthen dam. Their capacity varies evenly from small to extremely big reservoirs. The smallest reservoir capacity is only more than half a million cubic meters, while the largest reservoir has a capacity of nearly 10 billion cubic metres. In addition, all the detailed information about reservoirs (dam crest elevation, upstream slope, downstream slope, Z ~ V ...) are available. The key information of the research reservoirs is listed in Table 1. The location of the reservoirs is shown in Figure 1

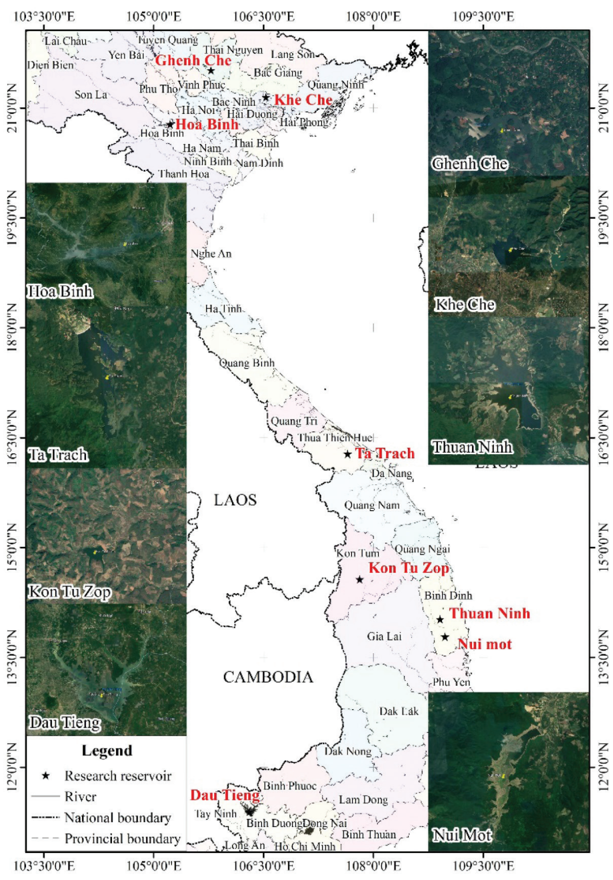

Figure 1: Research reservoir locations.

Materials and Method

The study was conducted following the approach proposed by Pianosi et al. (2016). In this approach, the

Table 1: The key information of research reservoir

Parameter	*Unit*	*Hoa Binh*	*Dau Tieng*	*Ta Trach*	*Nui Mot*	*Thuan Ninh*	*Khe Che*	*Ghenh Che*	*Kon Tu Zop*
Basin area	km^2	51700	2700	717	110	78.5	22.4	12.3	6.22
Normal water level	m	117	24.4	45	46.2	68	23.48	33.15	650
Dead water level	m	80	17	23	25	56	14.88	27.6	645
Normal volume	$10^6 m^3$	9862	1581	486	111	35.4	10.5	2.87	0.57
Dam type	-	Rock-earth fill	Earth fill	Rock-earth fill	Earth fill	Earth fill	Earth fill	Earth fill	Earth fill
Maximum dam height	m	128	28	39.5	32.5	28.7	20	15.1	13
Dam length	m	660	1100	313.7	670	492	600	234	197
Dam crest level	m	123	28	56	51.70	71.2	26.6	36.1	653

sensitivity analysis is usually determined in four steps: experimental setup, input sampling, model evaluation and post-processing (Figure 2).

The experiments started with an input or parameter selection process. According to Xu and Zhang (2009), there are two parameter groups in dam breach issues. They are shape group (breach with, breach side slope,..) and hydrological group (breach development time, maximum discharge,...). The numerous studies (Chen et al., 2019; Froehlich, 1995b; Xu and Zhang, 2009) and guidelines (ANCOLD, 2012; FEMA, 2013) indicate that, in general, the shape of breach usually has a trapezoidal shape and the breach develops to reach the bedrock layer. The same assumptions were applied in this study, so based on the breach width and side slopes, the breach shape will be determined. Based on the result of Chen et al. (2019), the initial breach position is also included as an input variable. In this study, the maximum discharge was defined as the output variable, so this variable was not selected as the input variable for the sensitivity analysis. Thus, the input variables identified in the study include breach width (B), side slope (S), initial breach position (Z), and breach development time (t). These input variables will be used to evaluate the robustness of maximum outflow discharge and the rising time of flood caused by the dam failure.

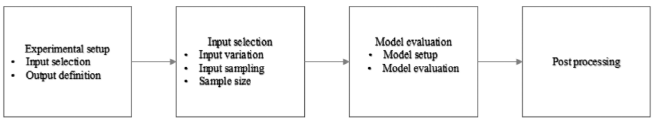

Figure 2: Sensitivity analysis process.

Based on the selected variables, in the next step, the study determines the variation range of the parameters. According to FEMA (2013), breach development time and breach width are the two parameters with the greatest uncertainty. Wahl (2010) indicated that the best empirical equation for breach development time (Froehlich, 1995b; Von Thun and Gillette, 1990) has an uncertainty, which is of ± 2/3 order of magnitude. While this value for breach is ± 1/3 order of magnitude corresponding with Froehlich (1995b).

In this study, the equation of Froehlich (Froehlich, 1995a) was used to determine the variation ranges of input parameters. These variable ranges covered all estimated values via common equations (Froehlich 2008; MacDonald and Langridge-Monopolis, 1984; Xu and Zhang, 2009). FEMA (2013) recommends a lateral slope from vertical ($S = 0$) to 45º($S = 1$). The initial breach position was assumed to vary from bedrock layer to normal water level. Since the number of reservoirs in this study is large (eight reservoirs), a huge number of simulations need to be run. According to Norton (2015), the FAST sampling technique is one way to greatly reduce the amount of computation. Based on the degree of variation, the FAST sampling technique (Cukieret et al., 1978) was used to create the samples. The number of samples was increased until it reached the convergence condition.

In phase 3, the model was used to determine the dam breach peak discharges and the rising time of flood hydrograph. For each set of samples created, a model needs to be performed. With a huge number of required simulations, the hydraulic model is not suitable because it is time-consuming. Model HEC HMS (Scharffenberg, 2016) was chosen to ensure the computation series of the model in a reasonable time. Each simulation took about only 2 seconds. This approach was also followed by Pa and Sin (2020) to calculate the dam breach hydrograph for North Yamar Lower Dam. The structure of the model is relatively simple, including only one reservoir component. The simulation process was performed. The maximum outflow results were then compared with observer data to ensure the reliability of the model. To eliminate disturbance effects outside the reservoir, for example, large floods on the basin will reduce the effects of input variables, our study took the assessment of dam failure under sunny day conditions. This means that the reservoirs will fail at normal water levels, while the upstream and downstream area of the reservoir has no rain.

The variance-based technique Fourier Amplitude Sensitivity Test (FAST) was selected for sensitivity analysis. In this case, the sensitivity analysis was based on estimating the fractional contribution of each input factor X_i with the variance of the model output Y. Based on the sequences of model result which was performed in the third step of the process, the first-order sensitivity indices S_j of X_j was estimated via Equation (1).

$$S_j = \frac{V_j}{V} \tag{1}$$

where V is total variance. It is the sum of all conditional variances, which can be estimated by Equation (2).

$$V = \sum_{j=1}^{n} V_j + \sum_{j=1}^{n-1} \sum_{k=j+1}^{n} V_{jk} + \ldots + V_{12..n} \tag{2}$$

where $V_j = V(E(X_j = x^*_j))$ and $V_{jk} = V(E(X_j = x^*_j, X_k = x^*_k)) - V_j - V_k$.

$E(X_j = x^*_j)$ denotes the expectation of Y conditional on Xi having a fixed value x^*_j

Results and Discussions

In order to explore the sensitivity analysis, the input factors were assigned to the uniform distribution. The ranges of parameters were estimated as the described method in the previous part. This range has been checked to cover values calculated by empirical formulas. In this study, all distribution of parameters was assumed to be uniform. We have described the results of a range of parameters, which is shown in Table 2.

Based on the range and distribution of parameters, the samplings were defined. The sampling size is increased to check the convergence conditions. According to Cukier et al. (1978), the value 329 is the minimum sampling size corresponding with four input parameters. Saltelli et al. (2008) suggest Equation (3) to estimate sample size.

$$N = r(M+2) \tag{3}$$

where N is the sample size; M is the number of the input variable.

In this case, the number of input variables M equals 4. The common value for r range from 500 to 1000. Applying this assumption into equation 3, N varies from 3000 to 6000. So the maximum size in our case is a 1.5-time maximum sample size suggested by Saltelli et al. (2008). Figure 3 shows the results of the sensitivity indexes of maximum discharges for different sample sizes. From the results, it is clear that the convergence condition was satisfied for all reservoirs with our sample size. The results lead to a similar conclusion for the rising time in Figure 4.

We describe the results of first-order sensitivity indices evaluated by the FAST sensitivity analysis for eight reservoirs, which are shown in Table 3. From these results, it is clear that the sum Si of all variables is close to 1 in all cases for both maximum outflow and rising time. It indicates that the presence of interaction between variables is low (Saltelli et al., 2008). It means that the selected variables in this study are independent.

This research used the historic dam failure database of Wahl (1998), Pierce (2010), Xu & Xhang (2009) for model evaluation. Figure 5 shows the comparison results between observer data and calculated results. In this figure, the vertical axis presents maximum outflow, the horizontal axis is a product of reservoir volume

Table 2: Range of parameters

Parameter	*Unit*	*Kon Tu Zop*	*Ghenh Che*	*Khe Che*	*Thuan Ninh*	*Nui Mot*	*Ta Trach*	*Dau Tieng*	*Hoa Binh*
		Min	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*
Btb	m	8.83	26.28	21.23	42.47	34.96	70.57	57.97	118.82
T	hr	0.11	1.10	0.24	1.99	0.44	3.04	1.14	2.80
S	-	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
Z	m	642.00	650.00	25.00	33.15	13.00	23.48	42.00	68.00

Table 3: First-order sensitivity indices for maximum outflow and rising time

Parameter	*Maximum outflow*					*Rising time*				
	B	*t*	*S*	*Z*	*Sum*	*B*	*t*	*S*	*Z*	*Sum*
Kon Tu Zop	0.438	0.270	0.072	0.063	0.844	0.032	0.700	0.017	0.122	0.870
Ghenh Che	0.318	0.357	0.048	0.168	0.890	0.003	0.704	0.001	0.192	0.901
Khe Che	0.234	0.438	0.019	0.214	0.906	0.002	0.659	0.000	0.229	0.890
Thuan Ninh	0.211	0.248	0.021	0.349	0.829	0.020	0.464	0.006	0.365	0.854
Nui Mot	0.280	0.224	0.017	0.342	0.863	0.010	0.447	0.002	0.400	0.859
Ta Trach	0.178	0.323	0.021	0.353	0.875	0.006	0.488	0.002	0.375	0.871
Dau Tieng	0.558	0.079	0.006	0.296	0.939	0.001	0.845	0.000	0.093	0.939
Hoa Binh	0.143	0.464	0.011	0.267	0.884	0.003	0.715	0.001	0.162	0.881

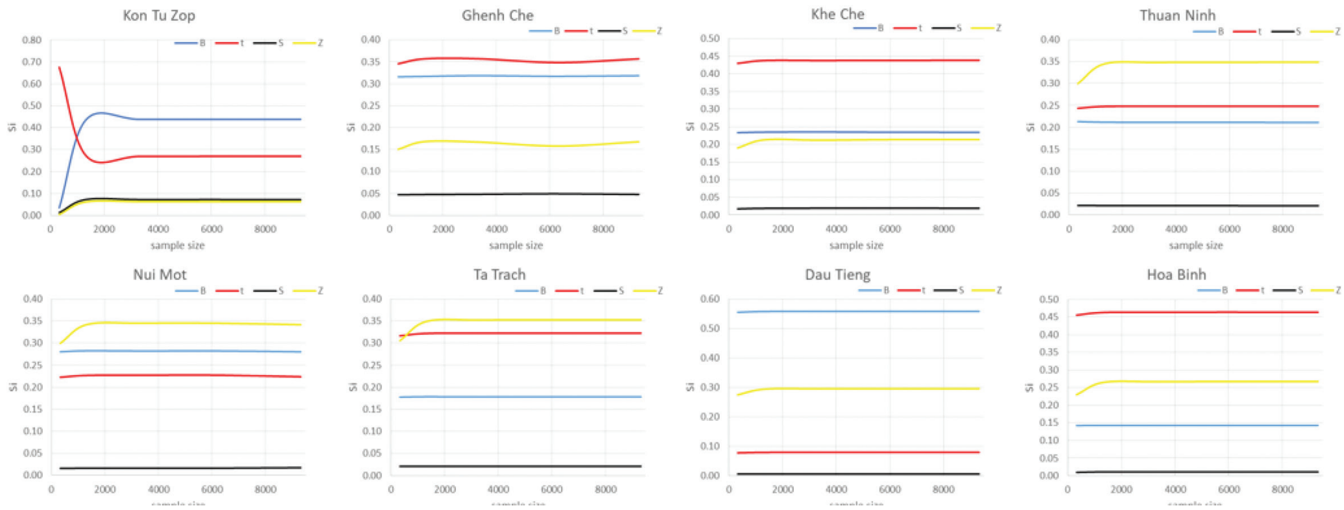

Figure 3: The convergence plots for maximum outflow.

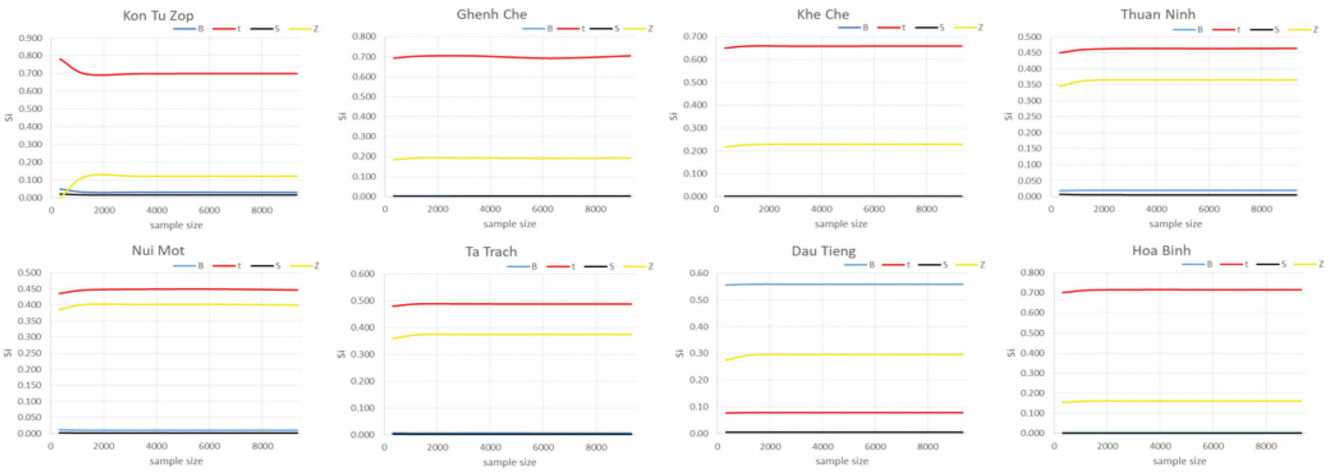

Figure 4: The convergence plots for rising time period.

and water height above breach invert level. Calculated results for each reservoir are shown in a range. From the results, it is clear that the calculated results are in the permissible range. This means that the model can reflect consistency with reality.

During the dam breach process, the water level decreased while the breach size increased. The value of maximum outflow depended on breach size and head of water above invert breach level at this moment. For maximum outflow, the lateral slope had the smallest value of *S*i. The influence of this variable can be neglected while the *S*i index was close to 0 for all reservoirs. A popular explanation for this case is that, for earth dams, the dam height was much smaller than the dam width. Therefore, the lateral slope does not change much of the breach size. This is why the lateral slope had little effect on the maximum outflow. The influence of the breach width on the maximum outflow varied with the reservoir capacity. In general, for a reservoir with a small capacity, the impact of the breach will be greater, as the volume increases, the role of this variable will decrease. However, there are also some special cases that do not follow this trend, such as the Dau Tieng reservoir, which is shown in Figure 6. Dau Tieng reservoir had a dam height relatively low compared to its capacity. Therefore, the water level did not change much during the dam failure process. It is clear that a major source of uncertainty was represented by the breach size. This explains why the Si of breach width, in this case, was so high (0.558). Also for the above reason, the *S*i value of the breach development time was very small in this case. Meanwhile, for all other cases, *S*i values of the breach development time are all high as compared to other factors. This proves

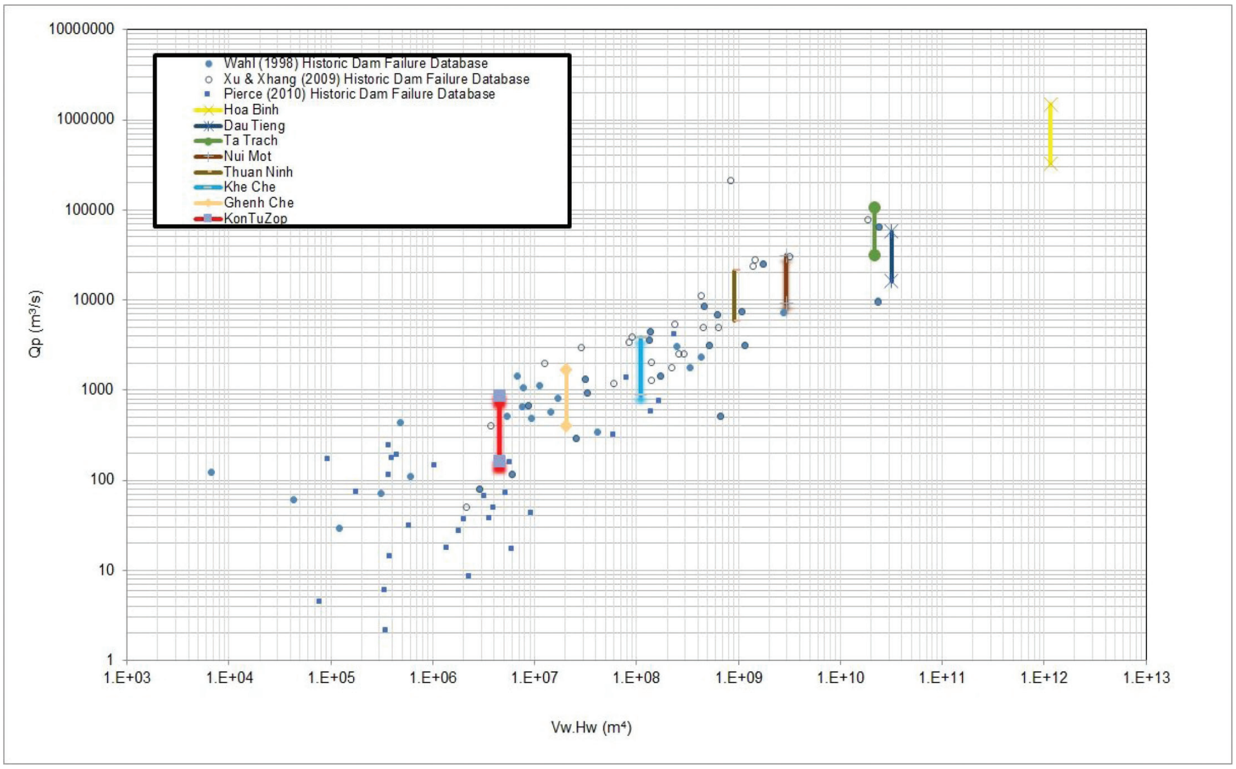

Figure 5: The comparison plots between observer data and calculated results.

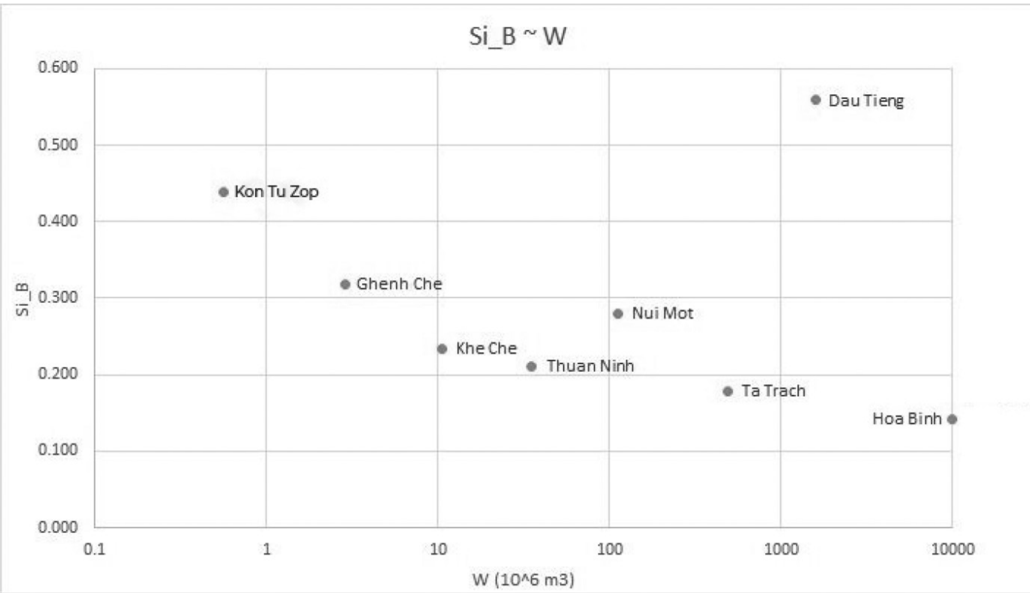

Figure 6: Scatter plots of the Si index and normal volume of research reservoirs.

that the time of breach development is of considerable importance to the maximum outflow. Except for the Kon Tu Zop reservoir, the result in Table 3 shows the important role of initial location when their *S*i values are always high as compared to other variables in most cases. A reason to doubt the explanation because in this case, the Kon Tu Zop reservoir has a small capacity. Consequently, the maximum outflow is not affected by the variation of the initial location.

The most important parameter affecting the rising time is development time. Table 4 presents the correlation coefficient between rising time and

Table 4: First-order sensitivity indices for maximum outflow and rising time

Parameter	*Kon Tu Zop*	*Ghenh Che*	*Khe Che*	*Thuan Ninh*	*Nui Mot*	*Ta Trach*	*Dau Tieng*	*Hoa Binh*
Correlation coefficient	0.85	0.93	0.70	0.67	0.69	0.82	0.85	0.84

development time. The results confirm the good correlation between them. This explains why for rising time, the Si indexes of development time are highest as compared to other variables for all reservoirs. The influence of the initial location on the rising time is also significant. This parameter affects the rising time slightly, in comparison with its effect on development time. Similar to maximum outflow, the lateral slope does not have a significant role in affecting the rising time. As described above, the change in lateral slope does not change the breach shape too much. Therefore, this factor also did not affect the rising time. This is shown in Table 3 when the *S*i values for all reservoirs are approximately 0. The influence of the breach width parameter on the rising time is also negligible. The results in Table 3 show that the *S*i values varied from 0.001 to 0.032. This is in contrast to the result of maximum flow.

Therefore, in the dam breach parameter study, breach development time and initial breach location are key parameters. It is worth discussing these interesting facts revealed by the results of the role of initial location. This result goes beyond previous reports while this problem is almost not mentioned by other studies. However, these impacts can provide valuable information to minimise the uncertainty of calculation results. As analysed above, the determination of breach development time still has many uncertainties. Meanwhile, the determination of the initial location can completely minimise the uncertainty through the field survey process. It is entirely possible based on the position of the seepage at the downstream dam face.

One concern about the findings of our result was that the hydraulic routing was not considered. During the dam breach process, the shape of the reservoir should be effective in the reservoir routing process. It leads to the reservoir water level and outflow discharge as after effects. These effects were neglected in our research due to the limitations of hydrological models.

Conclusion

In this paper, the study has provided a sensitivity analysis for the earthen dam breach. The study was applied for eight different capacity reservoirs. In the FAST technique, four independent factors have been selected that drive this uncertainty of maximum outflow and rising time outputs. The result shows that development time is the most important parameter with rising time and has a significant impact on maximum outflow. The effect of initial breach location on both outputs is reasonable. On the other hand, the side slope can be simplified considering proper assumptions because this parameter has little effect on both outputs. The effect of the breach width on the outputs is different. Although the breach width is important to maximum outflow, it has no significant effect on the rising time.

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