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Levee Reliability Analysis Considering Different Failure Mechanisms – A Case Study (Gueishan Levee) in Southern Taiwan

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ABSTRACT: Because Taiwan is located in a subtropical area, it is unavoidable to encounter severe disasters induced by typhoons during the summer season. On August 8, 2009, Typhoon Morakot invaded Southern Taiwan and many levees and revetments in southern Taiwan were damaged during this event. In this study, the uncertainty of the parameters was considered in stability analyses of one of the failed levees, the Gueishan Levee, under different flood return periods to examine the effect of the extreme weather conditions. Analysis results have shown that the slope sliding safety factor coefficient of variation (C.O.V.) is more influenced by the change of water level difference and less influenced by the change of flood return period. As the water level difference (WLD) coefficient increases, the safety factor is more concentrated and exhibit less uncertainty. The C.O.V. of sliding and overturning of retaining structure are both influenced by the variations of flood return periods and the WLD coefficient. As the flood return period increases, the two failure mechanisms associated with retaining structure exhibit less uncertainty under a long flood return period. On the other hand, as the WLD coefficient increases, the response of the two failure mechanisms related to retaining structure exhibit more uncertainty. It is therefore recommended to consider the water heights and possible scouring depths from hydrologic analysis of floods, and empirical equations in the levee stability analysis. If a specific levee is more important (more lives and properties are expected to be influenced), possible failure mechanisms may need to be considered under the effect of extreme weather condition, and thus the design can be reexamined and redesigned as a countermeasure to face the extreme weather conditions in the future.

1. INTRODUCTION

Because Taiwan is located in a subtropical area, it is unavoidable to encounter severe disasters induced by typhoons during the summer season. Possible disasters include slope sliding, debris flow, and flooding. On August 8, 2009, Typhoon Morakot invaded Southern Taiwan and many levees and revetments in southern Taiwan were damaged during this event, therefore, local inundation occurred and resulted in the loss of lives and properties. Among the levee breaches along Laonong River located in southern Taiwan, several levees were damaged partially or completely. As shown in Figure 1, the failed levees along Laonong River included Chiuliao 1st levee and revetment, Chiuliao 2nd levee, Tsailiao levee, Shinliao revetment and Gueishan levee. The levees were breached severely during Typhoon Morakot. Out of the breached levees along Laonong River, Chiuliao 1st levee and Gueishan Levee experienced total and partial failure during Typhoon Morakot. (Huang et al., 2014b) After this extreme weather event in Taiwan, a general concern about the stability of levees during the extreme weather event is raised across the country.

Generally, the failure mechanisms of a levee system during a flood include several aspects: (1) overtopping, (2) scouring of the foundation, (3) seepage/piping of levee body, and (4) sliding of the foundation. (Ojha et al., 2001, Vrijling, Schweckendiek, and Kanning, 2011, Dos Santos, Caldeira, and Serra, 2012, and Zhang et al. 2013).

Overtopping of levees occurs when the flood side water level exceeds the levee crest. During Hurricane Katrina, the levee system outside of downtown New Orleans experienced overtopping and severe erosion of the backfill material at the protected side of the levee occurred. The above conditions resulted in the push-over of the floodwall and caused inundation of the local areas. Seepage and piping of the levee body or foundation soils also occurred during Hurricane Katrina. The floodwall in downtown New Orleans experienced a loss of foundation soil due to seepage and piping of the in-situ soils. Although sheet pile walls were employed in the floodwall system, the depth of the sheet pile wall seemed to be not enough to cut off the seepage flow, and eventually seepage induced piping and heaving occurred during Hurricane Katrina. (Brandon, et al., 2008, Briaud et al., 2008, Duncan et al., 2008, Seed et al. (2008a, b)

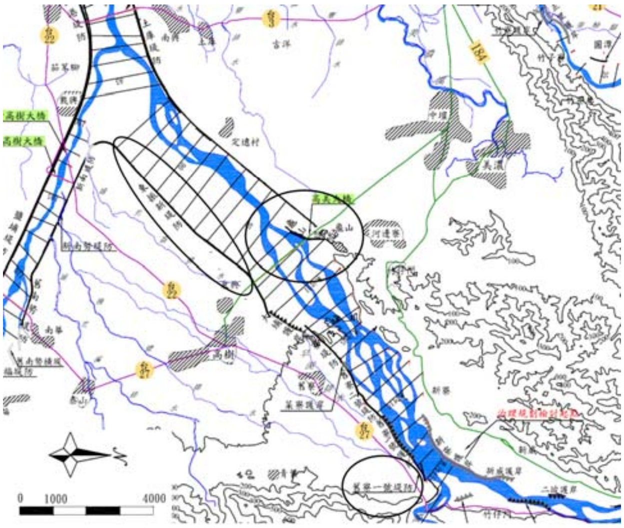


Figure 1: Locations of Chiuliao 1st Levee (lower right circle) and Gueishan Levee (middle circle). (Huang et al., 2014)

Huang et al. (2014a, b) have studied the levee stability based on the slope failure, sliding and overturning failure of the retaining structure considering seepage inside the levee after ruling out some of the less possible failure mechanisms, such as overtopping and seepage induced piping failure. The details of the failure mechanisms are discussed in the following paragraph.

Further, based on the experience and lessons learned from Hurricane Katrina in 2005, it was suggested that risk-based planning and designs are needed, in order to consider the variability of parameters in the analysis for the possible upcoming extreme weather conditions. (Sills et al., 2008 and van Gelder et al., 2008) In this study, the stability of Gueishan Levee is to be analyzed considering the uncertainty of design parameters, such as the local scouring depths, water heights (different at both sides of the levee), in-situ friction angle under a flood return period of 200 years (which represents an extreme weather condition) and 20 years (which represents a severe weather condition). The major purpose of this study is thus to provide insights to the design of levee cross-sections considering extreme weather conditions, which have become more and more frequent.

2. ABOUT GUEISHAN LEVEES

As shown in Figure 1, Gueishan Levee is located near Kaomei Bridge at the right bank of Laonong River between the confluences with Ailiao River and Chokuo River. The exact location of Gueishan Levee is at river section no. 98. The length of Gueishan Levee is about 1300m. The design cross-section of the levee before Typhoon Morakot is shown in Figure 2. As can be seen in Figure 2, there was a retaining structure at the toe of the levee. The backfill thickness at the flood side of the levee was 3.8m. In addition, the levee and the retaining structure were on top of a backfill material, with a thickness of 1.1m.

As mentioned previously, Gueishan Levee is located near Kaomei Bridge. In order to perform the analyses in this study, the in-situ soil properties were obtained from the boring logs during the construction of the bridge. It was found that the in-situ soil types are mostly gravel, with standard penetration test N values greater than 50. As mentioned by Huang et al. (2014), the empirical equations are mostly suitable for the estimation of friction angle of sands, the employment of common empirical equations by

Schmertmann (1975) or Hatanaka and Uchida (1996) might overestimate the friction angle of gravels, therefore in this analyses, we have assumed an average value of 40 degrees for the in-situ gravel material. The average particle size of the riverbed material in this section is approximately 60.55 mm, the same as Chiuliao 1st Levee. The particle size analysis results for the river section along Laonong River between its confluences with Chokuo River and Ailiao River indicate that the in-situ riverbed material is GW (well-graded gravel) according to the United Soil Classification System (USCS).

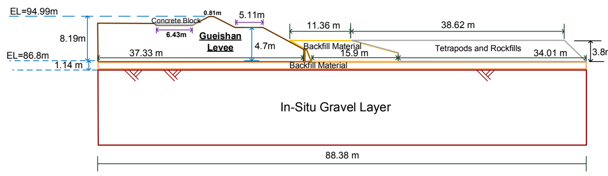
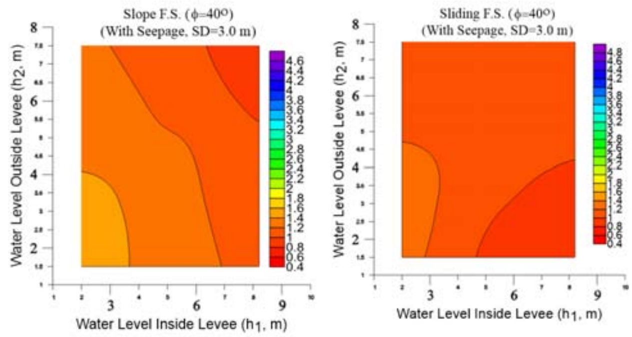


Figure 2: Design cross section of Gueishan Levee. (Huang et al., 2014)

Huang et al. (2014a, b) have analyzed the levee stability from various failure mechanisms, including the slope failure, sliding and overturning failure of the retaining structures. Based on the analysis results by Huang et al. (2014b), as shown in Figure 3, the possible failure mechanisms for the Gueishan Levee may be one of the following scenarios. As the scouring depth increases gradually, when the scouring depths are less than 2.0m, the failure of the levee may be less likely for the three failure mechanisms under any water level conditions. However, as the scouring depth reached 3.0m, based on the analysis results, the retaining wall might reach slope sliding failure first when the water level at the protected side is close to the top of levee without any water level difference. Overturning and sliding of the retaining structure might occur consequently with the receding of the water level at the flood side by about 3m. As the backfill material was eroded, the safety factor against slope failure, sliding and overturning failure of the retaining became critical for most of the water level heights.



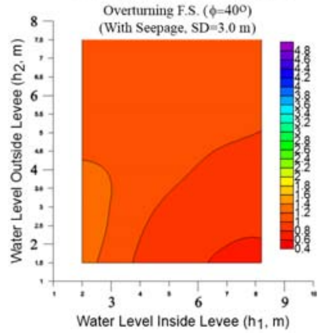


Figure 3: Stability analysis results of Gueishan Levee (Huang et al., 2014b)

3. RELIABILITY ANALYSES

As mentioned in the previous paragraph for the case in New Orleans, engineering design incorporated with reliability analysis has been recommended to avoid possible failures of the geotechnical facilities, especially under extreme weather conditions. In the analysis performed by Huang et al. (2014b), a comprehensive analyses of the stability of Gueishan Levee were performed. It was found that the levee might undergo slope sliding failure when large scouring depths and high water occurred, however, the scouring depths and water levels should also be considered from the hydrologic analyses, thus the scouring depths and water levels can be more realistic. The analysis results can therefore be more useful for engineering design. In this study, the water levels and scouring depths are considered under different flood returning periods, in order to examine the sensitivity of the levee stability from reliability analysis.

Based on the analysis results by Huang et al. (2014a, b), it was found that the following parameters are most critical when analyzing the levee stability, which are (1) the water levels on the protected and flood sides of the levee, (2) the local scouring depth (SD) of the backfill material on the flood side of the levee, and (3) the in-situ friction angle along Laonong River. Since the above parameters may have some degree of uncertainty, in the current reliability analysis for Gueishan Levee, these are considered as variables in the analysis.

3.1. Water level

The water level (WL) is defined as the height of the water on the flood side from the in-situ ground surface. There could also be a difference between the water levels on the protected and flood sides of the levee, i.e., the water level difference (WLD), due to clogging or drainage problems on either side of the levee. For ease of analysis, a WLD coefficient was defined as WLD divided by the water level on the flood side. In this study, the WLD coefficient was assumed to be greater than 0, which means that the seepage direction is from the protected side of the levee to the flood side. A preliminary analysis showed that this seepage direction is more likely and causes more stability issues for the levee. The design flood water levels for various flood return periods have been reported by the Water Resources Planning Institute of Taiwan and it can be found that flood return periods of 200 and 20 years result in water levels of 5.15m and 4.13m, respectively. The above water levels are approximately 64% and 50% of the levee design height (8.2 m). Finally, the WLD coefficients of 0, 0.1, 0.2, 0.3, 0.4, and 0.5 were employed in the analysis along with the flood water levels under 200 and 20 years of returning periods.

3.2. Local scouring depth

The scouring depth is defined as the depth from the surface of the original backfill on the flood side. Generally, it is very difficult to estimate the local scouring depths, due to its complexity and lack of site investigation information. In this study, based on available information in this research, the empirical equation proposed by Lacey (1930) was employed to obtain the scouring depth:

$$d_s = Z \cdot 0.47 \cdot (\frac{Q}{f})^{(1/3)} \tag{1}$$

In the above equation, d_s is the scouring depth, Z is a factor related to the river bending condition, Q is the design discharge in cms (cubic meters per second), and f is Lacey's silt factor, which is related to the mean particle size (D_m, in millimeters) of the scoured material as follows:

$$f = 1.76 \cdot (D_m)^{(1/2)} \tag{2}$$

Based on Pemberton and Lara (1984) for a Type B structure (river banks), the multiplying factor Z in Lacey's equation is dependent on the river bending condition. For Gueishan Levee, the factor Z was assumed to be 0.7 because its length and location correspond to a bending condition. Lacey's equation implies that the design flow rate and the average particle size are the two major parameters governing the scouring depth. The flow rates under flood return periods of 200 and 20 years are 15500 and 10900 cms, whereas the average particle size varies with location along the river. Gueishan Levee is located along Laonong River between its confluences with Chokuo and Ailiao Rivers, so soil boring information was collected between these river confluence points. The coefficient of variation (COV) of the average particle size in this river section is approximately 67%, as mentioned previously. It was assumed that the particle size distribution fits a log normal distribution with an average particle size of 60.55 mm and a COV of 67% for reliability analyses.

3.3. In-situ friction angle

As mentioned above, the average in-situ friction angle is assumed to be 40 degrees. To consider the variability of the friction angle, the coefficient of variation was assumed to be 10% with log normal distribution.

With the above-defined variables, the reliability analysis was performed through Monte Carlo Simulation (MCS, 5000 testing samples.) under flood return periods of 200 and 20 years. Another test of 20000 MCS runs showed similar results but it took much longer time. Therefore it was not reported here. The corresponding factors of safety under different failure mechanisms can be estimated from the database that has been developed under various possible conditions by Huang et al. (2014b). Thus the probability of failure can be calculated by summing the number of failed cases with all analyzed case numbers.

4. RELIABILITY ANALYSES FOR VARIOUS FAILURE MECHANISMS

The reliability analyses were performed under flood return periods of 200 and 20 years for various failure mechanisms. In addition, the effect of flood water receding and the induced water level difference was also considered through WLD coefficient. The following discussions are focused on the effects of water level difference and extreme weather conditions for different failure mechanisms.

4.1. The effect of water level differences

With the flood return period of 20 years under a WLD coefficient of 0 (water levels are the same at both sides of the levee), the histogram of the corresponding factor of safety of different failure mechanisms are shown in Figure 4. It can be found that under this situation, the probability of failure is the highest for the slope sliding failure, with a value of 4.9%. Overturning and sliding of the retaining structure is less likely since all of the analyzed safety factors are greater than 1.0.

If a WLD coefficient of 0.4 was considered under a flood return period of 20 years, the analysis results are completely different. First of all, the corresponding probability of failure under slope sliding, retaining wall sliding and overturning are 0%, 24.4% and 60.2%. The above results can also be seen in Figure 4. By comparing the results under different WLD coefficient, it was found that the water level difference can result in different failure mechanisms. When the water levels are the same at both sides of the levee, the levee might undergo slope sliding failure, however, the distribution of the safety factors are scattered (C.O.V. is higher), showing that this failure mechanism exhibit more uncertainty, higher than those of overturning and sliding failure of the retaining structure, as shown in Table 1.

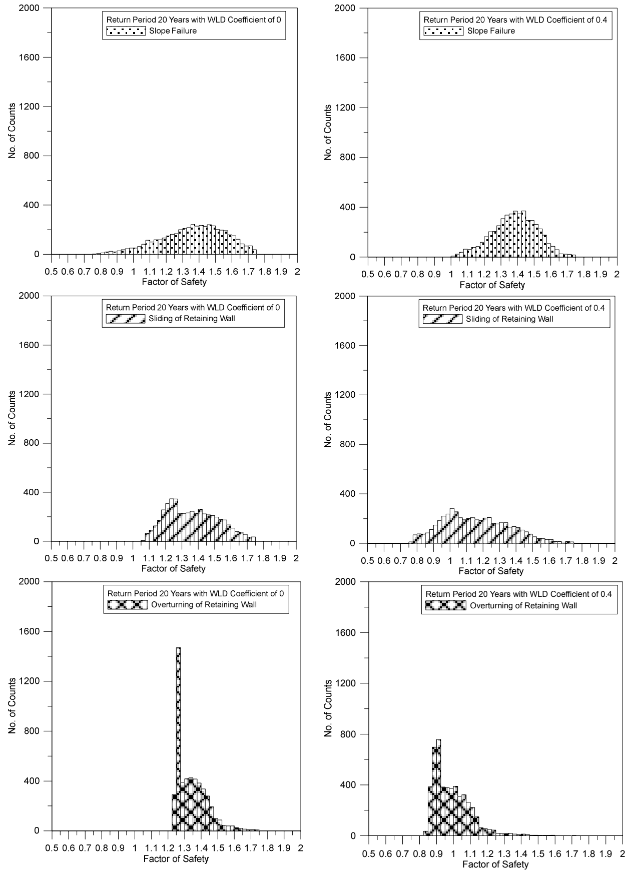


Figure 4: Monte Carlo Simulation histogram results of Gueishan Levee under flood return period of 20 years (left column: WLD coefficient of 0, right column: WLD coefficient of 0.4, first row: slope sliding, second row: sliding of retaining structure and third row: overturning of retaining structure)

As the water level difference coefficient becomes 0.4, indicating that the water at the flood side has receded, the probability of failure in slope sliding failure reduces from 4.9% to 0% in the 5000 MCS runs, while the probability of failure in sliding and overturning of the retaining structure has increased substantially. Under this situation, the retaining wall overturning and sliding failure is the major failure mechanisms. The trends under 200 year flood return period are similar as compared to the ones under a flood return period of 20 years. Please refer to Figure 5 for details.

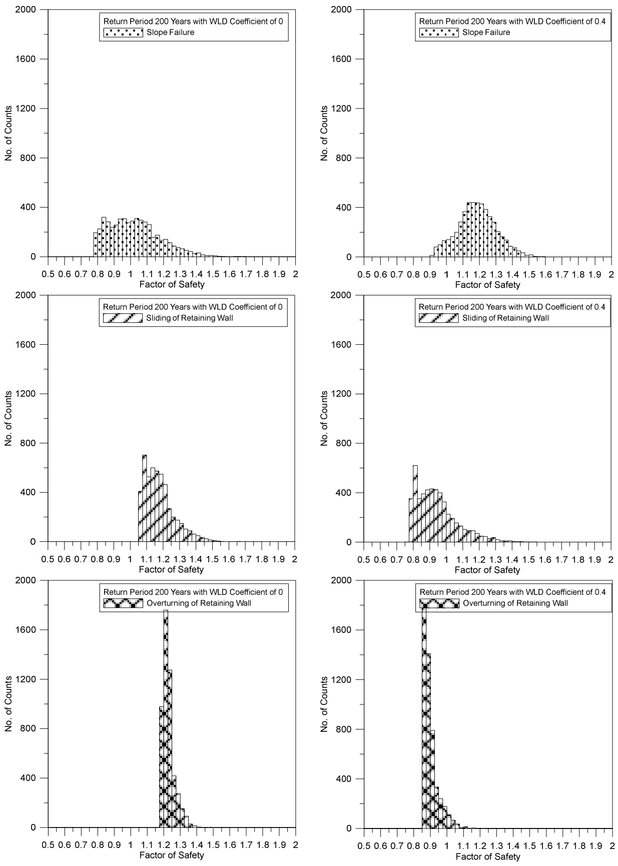


Figure 5: Monte Carlo Simulation histogram results of Gueishan Levee under flood return period of 200 years (left column: WLD coefficient of 0, right column: WLD coefficient of 0.4, first row: slope sliding, second row: sliding of retaining structure and third row: overturning of retaining structure)

4.2. *The effect of extreme weather condition*

It is of interest in this study to explore the stability of the levees under extreme weather conditions. Although the definition of extreme weather condition has been discussed and criticized most of the time, in the current study, the extreme weather condition is defined as the longest flood return period in the published hydrology reports, as it represents the most disastrous weather condition on record. As can be seen in Figure 5, it can be found that under a 200 years flood return period, Gueishan Levee may undergo slope sliding failure when the water levels are the same on both sides of the levee, the probability of failure is about 48%, however, the distribution of slope sliding safety factor is more scattered than these of the rest of the two failure mechanisms. Under this situation, it is also not likely to have retaining wall sliding and overturning failure. The distribution of these two safety factors is less scattered as compared to the slope sliding case. The probability of failure of slope sliding is apparently higher than the one under a flood return period of 20 years. The coefficient of variation of slope sliding safety factor is approximately the same, meaning that the C.O.V. may be less influenced by the change of flood return periods when the water levels are the same on both sides of the levee.

On the other hand, as the water level difference coefficient has changed to 0.4, indicating that the water level on the flood side has receded, the stability condition is changed significantly. As can be seen in Figure 5 and Table 1, the probability of failure of slope sliding, sliding and overturning of the retaining structure are 6.5%, 74% and 95%. As discussed in the previous paragraph, the sliding and overturning of the retaining structure is very sensitive to the water level differences at both sides of the levee, as this situation can increase the probability of failure significantly. The analysis results of flood return period of 20 years under a WLD coefficient of 0.4 showed that the probability of failure decreased and the distributions of the safety factors are more concentrated (or less uncertainty) in the analysis results of long flood return period.

Overall, considering from flood return periods of 200 and 20 years along with WLD coefficients of 0 and 0.4 under the failure mechanisms considered in this study, the following findings can be summarized as: (1) the slope sliding safety factor C.O.V. is more influenced by the change of water level difference and less influenced by the change of flood return period. As the WLD coefficient increases, the C.O.V. of slope sliding safety factor decreases. (2) the C.O.V. of sliding and overturning of retaining structure are both influenced by the variations of flood return periods and the WLD coefficient. As the flood return period increases, both of the C.O.V. decrease, meaning that the variation of safety factors are more concentrated under a long flood return period. On the contrary, as the WLD coefficient increases, both of the C.O.V. increase as well, indicating that the distribution of safety factors are more scattered. (3) On most situations, the overturning failure of the retaining structure shows less variation comparing to the rest of the failure mechanisms.

Table 1: Average safety factor, coefficient of variation and probability of failure

	Flood Return Period (Years) / WLD coefficient			
	200/ 0	200/ 0.4	20/ 0	20/ 0.4
Average Slope Sliding FS/C.O.V./P_f	1.02/ 15%/ 48.2%	1.19/ 10%/ 6.5%	1.38/ 16%/ 4.9%	1.39/ 10%/ 0%
Average R.S. Sliding FS/C.O.V/P_f	1.18/ 8%/ 0%	0.94/ 13%/ 74.4%	1.38/ 12%/ 0%	1.17/ 18%/ 24.4%
Average R.S. Overturning FS/C.O.V./P_f	1.23/ 3%/ 0%	0.9/ 5%/ 95.1%	1.34/ 7%/ 0%	0.99/ 11%/ 60.2%

* R.S.: retaining structure

5. CONCLUSIONS

Extreme weather conditions have occurred extensively around the world and caused numerous loss of lives and properties. In Taiwan, Typhoon Morakot made landfall in southern Taiwan in August 2009 and the accumulated rainfall caused landslides, debris flow and inundation of residential areas. The inundation of the residential areas resulted from the breach of the levees. In the analysis by Huang et al. (2014a, b), the levee failure scenarios were assumed and may not be realistic according to the hydrologic conditions of the Laonong River, therefore in this study, the water levels are considered from different flood return periods. In order to understand the effect of extreme weather condition, flood return periods of 200 and 20 years are analyzed. In addition, the uncertainty of the in-situ friction angle and the local scouring depths was also incorporated into the analyses, to explore the levee stability from a reliability analysis point of view under different flood return periods. First of all, the water level difference (WLD) coefficient was examined in the three failure mechanisms, including the slope sliding failure, retaining wall sliding and overturning failure. When the water levels are the same (WLD coefficient is 0), the most possible failure mechanism for Gueishan Levee might be the slope sliding failure. The probability of failure is 48% and 4.9% for flood return periods of 200 and 20 years. However, as the WLD coefficient is 0.4 (water level at the protected side is higher than that at the flood side), the probability of failure for retaining wall sliding is 74% and 24% for flood return periods of 200 and 20 years. The probability of failure for retaining wall overturning is 95% and 60% for flood return periods of 200 and 20 years. It can be found that the possible failure mechanisms might be different with different water level conditions.

Generally, the design cross section may be employed along the whole section of the levee, however, based on the results in this study, it can be found that the corresponding water levels and scouring depths might be different at different river sections. It is therefore recommended to consider the water level heights and possible scouring depths from hydrologic analysis of floods, and empirical equations in the levee stability analysis. If a specific levee is more important (more lives and properties are expected to be influenced for example), possible failure mechanisms may need to be considered under the effect of extreme weather condition, and thus the design can be reexamined and probably redesigned as a countermeasure to face the extreme weather conditions in the future.

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