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# Levee reliability analyses for various flood return periods – a case study in Southern Taiwan

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## Abstract

In recent years, heavy rainfall conditions have caused damages around the world. To prevent damages by floods, levees have often been constructed in prone-to-inundation areas. This study performed reliability analyses for the Chiuliao 1st Levee located in southern Taiwan. The failure-related parameters were the water level, the scouring depth, and the in-situ friction angle. Three major failure mechanisms were considered, including the slope sliding failure of the levee, and the sliding and overturning failures of the retaining wall. When the variabilities of the in-situ friction angle and the scouring depth are considered for various flood return periods, the variations of the factor of safety (FS) for the different failure mechanisms show that the retaining wall sliding and overturning failures are more sensitive to the variability of the friction angle. When the flood return period is greater than 2 years, the levee can undergo slope sliding failure for all values of the water level difference. The results for levee stability analysis considering the variability of different parameters could assist engineers in designing the levee cross sections, especially with potential failure mechanisms in mind.

## 1 Introduction

Taiwan is located in a subtropical area, so disastrous weather conditions due to typhoons are inevitable during the summer season. Precipitation in the range 2500 to 3000 mm year$^{-1}$ has been recorded in the mountainous areas of Southern Taiwan and this enormous rainfall can cause floods. If levees are not designed and constructed properly, the outcome can be disastrous. In general, there are several possible failure mechanisms of a levee system during floods: (1) overtopping, (2) scouring of the foundation, (3) seepage/piping of the levee body, and (4) sliding of the foundation (Ojha et al., 2001; Vrijling et al., 2011; Dos Santos et al., 2012; Zhang et al., 2013). These mechanisms are influenced by the levee's geometrical configuration, the hydraulic conditions (e.g. water level and seepage conditions), and the properties of the levee material (e.g. the physical and mechanical properties of the in-situ soils).

Overtopping occurs when the flood water level exceeds the design capacity of the levee and flows over the structure, and is a common failure mechanism (Dou et al., 2014). During Hurricane Katrina, the levee system surrounding New Orleans experienced catastrophic overtopping, which was possibly due to shoaling and resulted in the inundation of approximately 80 % of the city. Many researchers have studied the stability of levees under overtopping flows (Seed et al., 2008a, b; Xu et al., 2012). The consequence of overtopping for the floodwalls in suburban areas of New Orleans, USA was the gap formed between the floodwall and the canal-side backfills. The built-up water pressure against the floodwall pushed over the floodwall and thus caused inundation around the navigation canal (Brandon et al., 2008; Duncan et al., 2008). Besides, overtopping for the levee can also erode the backfill at the protected side of the levee, leading to a loss of support from the backfill material at the protected side of the levee (Briaud et al., 2008).

Piping and inside levee erosion are also common failure mechanisms for levees (El Shamy and Aydin, 2008; Riegger et al., 2009). During Hurricane Katrina, some part of the city canal flood wall did not experience overtopping, but the surrounding areas were still inundated. Site investigation and analysis results have shown that seepage induced piping or heaving is also one of the possible failure mechanisms. The major reason for the piping and heaving to occur was insufficient subsurface exploration (IPET, 2007). For seepage and piping inside the levee or embankment body, Polemio and Lollino (2011) also employed a case study in Italy to define the factors affecting seepage-induced failure due to flood.

For levee slope sliding failure or foundation failure, Zhang et al. (2013) analyzed the levee located in Pearl River Delta under the above failure mechanisms, however, based on historical records, the local scouring of the flood side backfill was not serious and thus was not taken into consideration in the study. Levee foundation stability with respect to sliding and overturning was also examined by Huang et al. (2014) in a case study in Taiwan and found that the sliding of the levee foundation might be a possible failure mechanism under certain water level conditions.

In this study, a more in-depth levee stability analysis was performed, considering possible failure mechanisms and variability of parameters. The considered failure mechanisms are slope sliding stability, and foundation stability under different conditions. The rest of the possible failure mechanisms as mentioned above were also discussed based on interviewing reports from local residents and relevant analysis. Further, based on the experience and lessons learned from Hurricane Katrina in New Orleans, USA, 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; van Gelder et al., 2008). Therefore, the analyses in this study will take into consideration the responses of the case levee to the variation in the flood return period or the parameter variability. By considering the variability in parameters such as the in-situ friction angle, the responses of levees to various situations can be considered and incorporated into the engineering design of future levees. In this paper, we demonstrate this approach to parameter variability by performing a reliability analysis for Chiuliao 1st Levee. The goal of this study was thus to assess the stability of Chiuliao 1st Levee for various return periods, with the aim of providing insights into the design of levees, particularly with respect to ensuring their stability related to different return periods and guidelines for reliability analyses for levees under different scenarios.

## 2 Descritions of Chiuliao 1st Levee

On 8 August 2009 Typhoon Morakot invaded Southern Taiwan and caused significant loss of life and property (Lin et al., 2011; Wu et al., 2011; Weng et al., 2011; Huang et al., 2014). Many levees and revetments in Southern Taiwan were damaged during this event, and the river basin suffered severe flood disasters. In particular, the levees along Laonong River have been investigated thoroughly due to the large population that resides along this river. Of the levee breaches along Laonong River, the most serious occurred at the Chiuliao 1st Levee, which is located in Kaoshu village in Pintung County, as shown in Fig. 1. This levee was built on the left river bank near the confluence of Laonong River and its branch, Chokuo River. During Typhoon Morakot, Chiuliao 1st Levee broke apart, providing an opening for water to invade the protected side of the structure. This event drew significant public attention to the issue of levee safety, especially for levees in the suburban areas.

### 2.1 Levees along Laonong River and the site conditions

Laonong River Basin is located in the southern part of Taiwan. Laonong River is a tributary of Gaoping River. The length of Laonong River is approximately 133 km. During Typhoon Morakot, the levees along Laonong River experienced catastrophic breaches. Of the eight levees (Gueishan Levee, Chiuliao 1st and 2nd Levees, Leegang Levee, Dongjengshin Levee, Tsailiao Levee, Toocool Levee, and Shinshin Levee. The total length of the above levees is approximately 23 km) along Laonong River, four experienced catastrophic breaches, as shown in Table 1. The total breached length was approximately 1.5 km. Of these failed levees, Chiuliao 1st Levee and Shinshin Levee were washed away completely by the floods during Typhoon Morakot.

To analyze the stability of these levees, the site conditions along Laonong River, especially near the failed levees, must be obtained. In this study, site conditions were characterized by performing borehole measurements at bridges near the studied levees. Along Laonong River, the soil layers consist mostly of gravel to a depth of approximately 20 m.

The bridge near Chiuliao 1st Levee is Dajin Bridge. Huang et al. (2014) analyzed borehole information from Dajin Bridge to determine the in-situ subsurface profile. It was found that the friction angles of the gravel layer are in the range of approximately 37 to 45°. Chiuliao 1st Levee is located on Laonong River in section no. 14. The average particle size of the river bed material in this section is approximately 60.55 mm. The particle size analysis results for the river section along Laonong River between its confluences with Chokuo River and Kaoping River indicate that the in-situ river bed material is GW (well graded gravel) according to the United Soil Classification System (USCS).

### 2.2 Design of the levee

In addition to the site conditions close to the levee, we also examined the design cross-section of Chiuliao 1st Levee before Typhoon Morakot, as shown in Fig. 2. This levee was a gravity-type earthen levee with a height of 10.7 m. The foundation of the levee was laid on the surface of the in-situ gravel layer, with 1.5 m thick backfill on the flood side of the levee. In addition, another layer of rockfill (tetrapods) was placed on top of the backfill layer to prevent scouring of the backfill

## 3 Research approach

### 3.1 Levee failure mechanisms

As mentioned above, possible levee failure mechanisms include (1) overtopping, (2) scouring of the foundation, (3) seepage/piping of the levee body, and (4) sliding of the foundation. However, overtopping was not the main failure mechanism in the case of the breach of Chiuliao 1st Levee during Typhoon Morakot. According to the field investigation and the reports of eyewitnesses (Li et al., 2009; Chang, 2012), no evidence of overflow, such as flow traces or inundation, was found on the protected side of the levee. For levee foundation failure mechanisms, it has been shown that the Chiuliao 1st Levee could fail due to slope sliding and retaining wall sliding failure when the flood started to recede from the top of levee (Huang et al., 2014). The timing of the levee failure is consistent with the eyewitness' reports. Preliminary analyses of the seepage inside the levee also showed that the exit hydraulic gradient is much less than the critical hydraulic gradient. Therefore we focused on the three major failure mecha-





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nisms discussed above (slope failure and retaining wall sliding and overturning failure), as related to the three parameters discussed in the next section.

In summary, the following failure mechanisms were considered in this study:

1. Loss of slope stability of the levee under steady state seepage conditions;

2. Loss of retaining wall stability (due to sliding and overturning failures) under steady state seepage conditions. The bearing capacity failure of the retaining wall foundation is unlikely given that the in-situ friction angle is greater than 35°, so was not analyzed in this study.

### 3.2 Research method

Based on the analyses performed in Huang et al. (2014), a limited number of scenarios were analyzed to understand possible levee failure mechanisms, such as scouring depths of 0.5 and 1.5 m, as well as discrete combination of flood side and protected side water levels. For the purpose of risk assessment (as discussed later in the text), a more in-depth analysis of levee stability with respect to variations of the parameters is required. First, we analyzed the stabilities of the slope and retaining wall of the Chiuliao 1st Levee with respect to wide parameter ranges. The drainage and clog conditions on the protected and flood sides of the levee determine whether their water levels are the same. A difference between these two water levels results in seepage conditions in the levee. The distributions of the pore water pressure inside the levee and along the impervious boundary at the bottom of the retaining wall are required for the analysis of retaining wall stability. To perform slope stability analysis coupled with seepage analysis, the software products Slope/W and Seep/W in the GeoStudio suite were employed. Further, the slope safety factor was determined by using Spencer's method.

An illustration of the retaining wall is shown in Fig. 3 (Huang et al., 2014). The forces acting on the retaining wall include the active force from the levee backfill and the passive force from the backfill material on the flood side of the levee. It was assumed that the passive force from the backfill still remain unchanged at the flood side for less conservative analysis. However, this passive force might decrease when the water level starts to rise with increasing scouring depths. There are also pore water pressures acting on the retaining wall from both sides. As mentioned in the previous paragraph, the uplift force due to the pore water pressure at the bottom of the retaining wall could also reduce the stability of the retaining wall and thus result in the failure of the levee, so in the sliding and overturning failure analyses, these uplift forces were also included.

### 3.3 The variability of the parameters

Three principal parameters were investigated in the stability analyses of the levee: the water levels on the protected and flood sides of the levee, the local scouring depth (SD) of the backfill material on the flood side of the levee, and the in-situ friction angle along Laonong River. There is some degree of variability in all of these parameters. We now discuss these parameters in more detail.

#### 3.3.1 Water level

The water level (WL) is defined as the height of the water on the flood side from the in-situ ground surface, as shown in Fig. 4. There could 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 are shown in Table 2. The design water levels were estimated from the design flow rates in different river sections along the river. Comparing the design water levels for various flood return periods in Fig. 2 for Laonong River section no. 14 (where Chiuliao 1st Levee is located), it can be seen that a return period of 200 years results in a water level (8.5 m) that is approximately 80 % of the height of the levee (10.7 m). In this study, the water levels corresponding to the various return periods were employed directly in the analysis, with WLD coefficients of 0, 0.1, 0.2, 0.3, 0.4, and 0.5. Note that these design flow rates for various return periods were obtained before Typhoon Morakot. A newer data set that takes into account the rainfall record of Typhoon Morakot indicates larger flow rates for the same return period. However, it has been suggested by the Water Resources Planning Institute that the information listed in Table 2 remains valid because there are insufficient flood data to support the newer data set.

### 3.3.2 Local scouring depth

The scouring depth is defined as the depth from the surface of the original backfill on the flood side, as shown in Fig. 4. Huang et al. (2014) demonstrated that the scouring depth is a crucial factor in the stability of levees. However, their results were obtained by assuming particular values for the scouring depth. In this study, the scouring depth was estimated by using some common empirical equations. As mentioned above, design flow rates and particle sizes are available for the Chiuliao 1st Levee, and it was found that the empirical equation proposed by Lacey (1930) can be employed to obtain the scouring depth:

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

In this 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:

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

Lacey's equation can be used to estimate the scouring depths for natural river erosion (classified as Type A) and manmade structures along a bank line (classified as Type B) (USBR, 1984). For a Type B situation, the multiplying factor $Z$ in Lacey's equation is dependent on the river bending condition. For Chiuliao 1st Levee, the factor $Z$ was assumed to be 0.25 because its length and location correspond to a straight reach 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 can be obtained directly from the information in Table 2, whereas the average particle size varies with location along the river. Chiuliao 1st Levee is located along Laonong River between its confluences with Chokuo and Kaoping 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 %. 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 %. The averages of the generated randomized local scouring depths for the various flood return periods are shown in Table 2.

#### 3.3.3 In-situ friction angle

As mentioned above, the in-situ friction angle is in the range 37 to 45°. This friction angle seems reasonable for gravel material, but it exhibits some degree of variability and therefore was treated as a variable in this study for reliability analysis. According to Phoon et al. (2008), the coefficient of variation of the friction angle is between 10 and 15 %. In this study, the mean friction angle was assumed to be 40°, with a coefficient of variation of 10 %. In addition, the data distribution type was assumed to be log normal.





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## 4 Analysis results – stability of Chiuliao 1st Levee

We examined the slope stability and retaining wall stability under steady state seepage conditions with a wide combination of parameters. The related parameters employed in this study are the water level (and the WLD coefficient), the scouring depth, and the in-situ friction angle. As shown in Fig. 5, the water level on the protected side is denoted $h_1$, and the water level on the flood side is denoted $h_2$. For Chiuliao 1st Levee, the design backfill thickness on the flood side is 1.5 m, so we analyzed three distinct scouring depths, 0.5, 1.0, and 1.5 m. These stabilities were analyzed in the absence of scouring by Huang et al. (2014). It was found that the safety factor becomes most critical if the water level on the protected side is close to the top of the levee, when a water level difference can cause slope failure. As shown in Fig. 5 for scouring depths of 0.5 and 1.5 m, it was found that for scouring of only approximately 1/3 of the backfill material on the flood side (i.e. SD = 0.5 m), the water level has to be close to the top of the levee (which is approximately 10.7 m) for the safety factor to decrease, although its values remain greater than 1.0. However, when the scouring depth is 1.5 m (which indicates that the backfill material has eroded completely), the safety factor becomes less than 1.0 when the water levels on both sides of the levee are approximately 6.0 m. This water level is approximately 3/5 of the design levee height, and is lower than the water level for a flood return period of 200 years.

As shown in Figs. 6 and 7, the retaining wall stability was also analyzed with respect to the sliding and overturning failure modes for various scouring depths. According to their results for retaining wall stability in the absence of scouring, Huang et al. (2014) found that the corresponding water level has to be close to the top of the levee on the protected side and that a significant water level difference is required for the sliding and overturning safety factor to be less than 1.0. However, as shown in Fig. 6, the retaining wall sliding safety factor decreases as the water level inside the levee increases for scouring depths of 0.5 and 1.5 m, and when the water is close to the top of the levee on the protected side (i.e. $h_1$ is large), sliding failure becomes critical: for a scouring depth





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of 0.5 m, when the water level on the flood side recedes to approximately 6.5 m, sliding failure occurs. When the backfill material on the protected side has eroded completely (i.e. SD = 1.5 m), the water level on the protected side at which sliding failure occurs is as low as 6 m when the flood side water level is slightly lower than the water level on the other side.

As shown in Fig. 7, the retaining wall overturning safety factor also decreases as the water level increases for scouring depths of 0.5 and 1.5 m, but most of the safety factors are greater than 1.0; only when the water level on the protected side is at the top of the levee with a significant water level difference does the retaining wall stability became critical (safety factors between 1.0 and 1.2). In short, overturning failure of the retaining wall of the Chiuliao 1st Levee is unlikely, even when the scouring depth is 1.5 m (i.e. when the backfill material has eroded completely).

Based on the above results, we conclude that the failure mechanism of the Chiuliao 1st Levee could be a combination of slope failure and retaining wall sliding failure. These failure modes could arise in the following scenarios: (1) when there is no local scouring of the flood side backfill material, and the water level on the protected side is close to the top of the levee, the sliding failure of the retaining wall can occur once the water has started to recede from the flood side. This result is consistent with the findings of Huang et al. (2014). (2) When there is a small amount of local scouring (such as 1/3 of the thickness of the backfill material), sliding failure of the retaining wall can occur when the water level difference is approximately 4 m. (3) When the backfill layer has eroded completely (a total thickness of 1.5 m), slope failure and retaining wall sliding failure can occur only when the water level is approximately half the levee height. Overturning of the retaining wall is unlikely because the critical condition for this type of failure only arises after the other two failure conditions have occurred. Although Figs. 5 and 6, and 7 illustrate these possible failure scenarios, some of the required conditions could be unrealistic. For example: (1) a zero scouring depth might not be possible, especially for a long flood return period and the resulting large flow rate, i.e. a large scouring depth; (2) a certain amount of scouring is possible for a given WLD





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coefficient, but it is better to treat these parameters as exhibiting significant variability. If the above situations can be considered in the analysis, the results can be closer to actual possible outcomes. With the above considerations in mind, a reliability analysis considering parameter variability was performed and is discussed in the next section.

## 5 Reliability analysis for Chiuliao 1st Levee in Southern Taiwan

### 5.1 Reliability analysis method

In the above analyses, the parameters that could influence the stability of the levee were varied across a range of scenarios and analyzed, but in reality these parameters vary with time and location in a single scenario. For example, there are several levees located in different sections of Laonong River, and the corresponding river profiles in these locations are likely to be different. Further, the particle sizes (which are related to the scouring depth) and the water levels (which are related to the flood return periods and the WLD coefficient) could also vary from location to location along the river, so it is necessary to consider the effects of this variability.

In this study, the levee's stability with respect to the above-mentioned failure mechanisms was analyzed in terms of wide ranges of the water levels on the protected and flood sides and of the scouring depth, in that the water levels of various flood return periods, and variation in the water level difference coefficient and scouring depth were used to determine the corresponding factor of safety for a given failure mechanism. Monte Carlo simulation (MCS) was employed in this study to obtain the distributions of the factor of safety for the various failure mechanisms. MCS was performed by generating a number of random variables (mean particle sizes and friction angles in this study) that satisfy the required distribution (a log-normal distribution in the current study), from which the corresponding factors of safety could be obtained. In this study, MCS was performed 5000 times in order to capture the entire distribution of the corresponding safety factors. The distributions of the safety factor, mean value, SD, and reliability in-





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dex could be evaluated for each failure mechanism from the analysis results and compared for various flood return periods and WLD coefficients. The reliability index was calculated by using the definition of the safety margin as $M = \mathrm{FS} - 1$ and the following equation

$$\beta = \frac{E[\mathrm{FS}] - 1}{\sqrt{\mathrm{Var}[\mathrm{FS}]}}, \tag{3}$$

where $\beta$ is the reliability index, $E[\mathrm{FS}]$ is the mean value of the corresponding factor of safety, and Var[FS] is its variance. Note that Eq. (3) is valid for a normally-distributed factory of safety.

### 5.2 Reliability analysis results for Chiuliao 1st Levee – constant friction angle

For the results discussed in this section, the friction angle was chosen as 40°, without consideration of its variability. The major purpose was to explore the sensitivity of the various failure mechanisms to variations in the other parameters.

The distributions of the safety factor are plotted in Fig. 8 for a flood return period of 100 years and a WLD coefficient of 0.3. The FS distributions of the different failure mechanisms are very distinct. Under these conditions, the Chiuliao 1st Levee experiences slope failure with 100 % probability, whereas the probability of retaining wall sliding failure is approximately 75 % and retaining wall overturning failure (0 % probability) is not possible. It can also be seen in Fig. 8 that the distribution of the slope failure safety factor is more sensitive to changes in the scouring depth (or the mean particle size because of Lacey's equation) than those of the retaining wall sliding or overturning failures. Slope failure was found to be more sensitive to changes in the scouring depth in all other analyzed cases, that is, for all return periods and water level difference coefficients.

When the reliability index is less than zero, the probability of failure must be greater than 50 %. When the distribution of the safety factor is similar to a normal distribution, the reliability index can be employed to estimate the corresponding probability of





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failure (although with a Monte Carlo simulation, the probability of failure related to the analyzed sample numbers can also be obtained). For a normal distribution of the safety factor, a reliability index of 4 represents a probability of failure of approximately $10^{-5}$, which is a commonly accepted probability of failure for most geotechnical facilities. The reliability indices were calculated for Chiuliao 1st Levee for various flood return periods and water level difference coefficients, as shown in Figs. 9 and 10. The variation in the reliability index for retaining wall overturning failure is not shown because it is not possible for Chiuliao 1st Levee to experience this type of failure when the factors of safety are greater than 1.2. (The minimum reliability index for retaining wall overturning failure is approximately 38, which is high.)

Figure 9 shows the variations in the slope reliability index for various WLD coefficients and return periods. First of all, the reliability indices increase as the flood return period decreases from 200 to 2 years. This increase is due to the corresponding decreases in the water level and the scouring depth: when the flood return period is reduced from 200 to 2 years, the average scouring depth decreases from 1.25 to 0.86 m. However, it was also found that there are only two situations in which the reliability index is greater than 4 (average FS greater than 1.20): for a flood return period of 2 years and for WLD coefficients of 0.4 and 0.5. It was found that Chiuliao 1st Levee could undergo slope stability failure even for a design flood return period of only 2 years. In fact, repair and maintenance records for Chiuliao 1st Levee show that this levee has been repaired several times, definitely in 2000 and 2005, and possibly on other occasions.

The variations in the reliability index for retaining wall sliding failure are shown in Fig. 10. It is evident that there are two different trends in the reliability index. The first trend arises when the WLD coefficient less than approximately 0.25: the longer the flood return period, the larger the reliability index. These reliability indices are greater than 4.0, which correspond to acceptable probabilities of failure. The other trend arises when the WLD coefficient is larger than 0.25: the longer the flood return period, the smaller the reliability index. Some of the reliability indices are even less than 0, which is definitely not acceptable for this type of failure. If a reliability index of 4 is deemed





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acceptable, then Chiuliao 1st Levee is unstable for flood return periods greater than 5 years and WLD coefficients less than 0.25. For a flood return period of 2 years, the maximum WLD coefficient that the levee can sustain is approximately 0.3. Note also in Fig. 10 that the longer the flood return period, the more sensitive the retaining wall sliding reliability index becomes to variations in the WLD coefficient. The reliability analysis results show that when the water level is relatively high, only small reductions in the water level result in more substantial decreases in the reliability index than is the case at lower water levels.

### 5.3 Reliability analysis results for Chiuliao 1st Levee – various friction angles

In the following analysis results, the friction angles and the average particle sizes (or the corresponding scouring depths) were treated as variables with the abovementioned averages and coefficients of variation. Log normal distributions were assumed for both variables.

Figure 11 shows the distributions of the safety factor for slope stability, retaining wall sliding, and overturning. The distributions in Fig. 11 are very different to those in Fig. 8. In Fig. 8, when a constant friction angle was employed in the analysis, the variation in the friction angle affects the shape and location of the distribution of the slope stability FS only weakly, and the distributions of the retaining wall sliding FS and the overturning FS are close to constant values. When the friction angle is treated as a variable, as shown in Fig. 11, the distribution of the retaining wall FS becomes broader. These results indicate that the slope stability FS is not sensitive to changes in the friction angle, because with the consideration of friction angle variations, the slope stability FS distribution is similar. The variation in the slope FS is due mainly to the variation in the scouring depth. The reason for the above results may be the location of the slip circle with respect to the in-situ soil layer. On the other hand, the stability of the retaining wall is not sensitive to changes in the scouring depth, as shown in Fig. 8; however, with the change of friction angles, the distributions of retaining wall FS become different when compared to Fig. 8. Note that these results are for a flood return period of 100 years





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and a WLD coefficient of 0.3. Other return periods and WLD coefficients also produced similar results.

As mentioned in the previous section, when the variability in the friction angle is taken into account, the slope FS does not change significantly. Figure 12 shows the variations in the slope FS reliability indices and WLD coefficients for various flood return periods; these results are not significantly different from those in Fig. 9. However, the results in Fig. 13 for the retaining wall sliding reliability index and WLD coefficient for various flood return periods are quite different. First of all, the trend in the results for a return period of 2 years is different to that of the other return periods. The reliability index is more sensitive to changes in the WLD coefficient for return periods less than 2 years. For the other flood return periods, there are similar relationships between the reliability index and the WLD coefficient. Although it was shown that the reliability indices are higher for shorter return periods, the reliability index decreases more rapidly with changes in the WLD coefficient for shorter return periods. By considering the variability in the friction angle, it was found that the retaining wall sliding FS of Chiuliao 1st Levee is less sensitive to changes in the return period. For flood return periods longer than 5 years, the results are similar. The retaining wall overturning FS is not shown because of its high reliability index.

### 5.4 Discussion about reliability analysis results for Chiuliao 1st Levee

Based on the above reliability analysis about Chiuliao 1st levee, quite interesting results can be concluded about the effect of variation of in-situ friction angles and local scouring depths, as discussed below:

1. If the in-situ friction angle (or other mechanical properties of the in-situ soils) is relatively uniform along the levee, the safety factors of levee foundation stability (sliding and overturning) do not vary significantly. The levee foundation sliding stability is more sensitive to the change of water level difference as the flood return period increases.





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2. If the in-situ friction angle (or other mechanical properties of the in-situ soils) is variable along the levee, the safety factor of levee foundation becomes variable. On some occasions, the levee foundation may fail with sliding failure. The levee foundation sliding failure is most sensitive to the water level difference when the flood has a short return period. For flood return periods larger than 5 years, the levee foundation sliding stability may not be a function of WLD coefficient, since the reliability results are similar.

3. The safety factor for slope stability analysis is more affected by the flood return period (i.e. water level heights and scouring depths) than the in-situ friction angle. The reliability indices increase with the increase of WLD coefficient, which means that the combination of various local scouring depths, water levels and the seepage direction may yield this kind of variation trend.

With the above discussion, for a design cross-section similar to Chiuliao 1st levee, the slope sliding failure is the most possible type to occur under all water level heights. However, if the levee is constructed on a relatively uniform (in terms of strength parameters) soil layers, the water level difference between protected and flood side of levee (WLD coefficient between 0.25 and 0.3) should be paid more attention when a long return period flood occurs, under which circumstance the levee foundation may undergo sliding failure. On the other hand, if the levee is constructed on a relatively various (in terms of strength parameters) soil layer, the water level difference may have more influence on the change of reliability indices for levee foundation sliding stability with a short flood return period. The reliability indices are similar (and low) with flood return periods greater than 5 years. Under this circumstance, WLD coefficient between 0.2 and 0.3 may result in levee foundation sliding failure.





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## 6 Conclusions

In recent years, heavy rainfall conditions have caused the loss of numerous human lives and properties around the world. To limit the damage produced by the floods resulting from such rainfall events, levees were constructed in low-rise or prone-to-inundation areas. However, if the design of these levees did not consider the effects of extreme flow rate (say more than 200 year flood return period) or of seepage through the levee or various failure mechanisms, levee failure can occur. For example, levee failures occurred during the rainfall events of Hurricane Katrina in the US in 2005 and Typhoon Morakot in Southern Taiwan in 2009. The rainfall record in Southern Taiwan during Typhoon Morakot was close to the world record. This study performed a reliability analysis of Chiuliao 1st Levee in Southern Taiwan. The reliability of the Chiuliao 1st Levee on Laonong River with respect to various possible failure mechanisms was analyzed. The parameters employed in this study were the water level and the scouring depth, which are related to the flood return period, and the in-situ friction angle. Three major failure mechanisms were considered, including slope failure of the levee, and sliding and overturning failures of the retaining wall. The possible difference between the water levels on the two sides of the levee was accounted for by including water level difference (WLD) coefficients in the above analysis and a steady state seepage condition inside the levee.

Our results show that retaining wall sliding and overturning failures are less sensitive to variation in the scouring depth than slope sliding failure when a constant value of the friction angle is considered. In addition, we found that the longer the flood return period, the more sensitive the retaining wall sliding reliability index becomes to variation in the WLD coefficient. On the other hand, when the variability of the in-situ friction angle and scouring depth were included in the analysis for various flood return periods, it was found that retaining wall sliding and overturning failures are more sensitive to variability in the friction angle. The results for the distribution of the slope sliding failure FS obtained when accounting for the variability in the in-situ friction angle are similar



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to those obtained with constant in-situ friction angles, which shows that this failure mechanism is less sensitive to variability in the friction angle. When the variability of the in-situ friction angle was considered, the reliability index is less sensitive to the return period when it is greater than 2 years.

Our comprehensive stability and reliability analysis of Chiuliao 1st Levee, which takes into account parameter variability, has shown that the levee could fail through slope sliding (for all WLD coefficients) and retaining wall sliding failure (for high WLD coefficients) for a flood return period of 200 years, which corresponds to a flow rate lower than that arising during Typhoon Morakot. The stability of Chiuliao 1st Levee can be divided into two regimes depending on the flood return period. When the flood return period is less than or equal to 2 years, Chiuliao 1st Levee is not stable with respect to retaining wall sliding failure when there is a large water level difference (WLD coefficients greater than 0.4). When the flood return period is greater than 2 years, slope sliding failure of the levee can occur for all values of the water level difference. These failures arise because of the large scouring depths (greater than 1.0 m) of longer flood return periods. Retaining wall sliding failures occur for only moderate values of the WLD coefficient (greater than 0.25). Based on the above failure mechanisms for Chiuliao 1st levee, the corresponding countermeasures can thus be taken during repair or maintenance of the levees. For example, in the renovation report of Chiuliao 1st levee, rows of piles and thickened backfill material were added into the design cross section without increasing the design height of the levee. The above engineering treatment methods can indeed increase the stability against slope sliding and retaining wall sliding, which are the two major failure mechanisms under different flood return periods concluded in this study. For general levee analyses, it is suggested to consider the stability of the levees from different flood return periods, because the levee failure mechanisms might be different.

In the past, it has been more common to adopt a general design cross-section for the whole length of a levee, especially local levees in suburban areas (mainly because of relatively low cost for construction and maintenance). However, the water level during rainfall events might vary at different locations on the river, indicating that an identical





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levee design cross section along the length of the levee may not satisfy various water heights when flood occurs. Furthermore, if the design or analysis does not consider the effects of heavy rainfall events and various failure mechanisms, unexpected failures of the levee could occur, as in the case discussed in this study. Although three major failure mechanisms were selected for analysis in this study because of previous site investigations and interviews with local residents, it is crucial for the design of other levees to consider possible failure mechanisms, especially under heavy rainfall conditions, and local scouring effects. In addition, the uncertainties of the parameters were also taken into account with reliability analysis in this study, as a response to the recommendations proposed by Sills et al. (2008) under extreme weather conditions, such as Hurricane Katrina. The sensitivity of the levee stability with respect to the relevant parameters can thus be examined with the variations of reliability indices.

Based on the reliability analysis for Chiuliao 1st levee, if one needs to re-examine the current levee stability due to floods caused under extreme rainfall, it is suggested to take the following approaches to understand possible failure mechanisms. (1) Collect levee repair or maintenance reports. If there are eyewitness reports when the levee failed, it is very crucial for the following analysis: (2) collect levee design cross sections and any nearby soil boring information. (3) Obtain hydrology analysis and design flow rate reports for the river on which the analyzed levee is located, and find out the corresponding water levels at that specific river section under different design flood return periods. (4) Select possible failure mechanisms. As mentioned previously, any repair, maintenance reports or eyewitness reports are crucial in properly determining the failure mechanisms. (5) Choose proper parameters for parametric study. Based on the analysis results in this study, the local scouring depths, water levels (at both sides of the levee) and in-situ friction angles are deemed crucial factors in different failure mechanisms. (6) Assume proper distributions for the above parameters. For geotechnical properties, it is common to assume a log-normal distribution for reliability analysis. (7) Perform comprehensive stability analysis for different failure mechanisms. (8) Perform Monte Carlo Simulation for reliability analysis. The results can thus be analyzed and examined to see the possible failure mechanisms. Although the above analysis approaches that have taken into consideration of the variability of parameters might increase the cost and time, however, to reduce the levee failures during the extreme rainfall condition (which is becoming more and more frequent), the comprehensive analysis costs may be comparable with the repair and renovation costs after the disaster occurs. Failures of levees under the influence of extreme weather conditions may thus be prevented by designing with possible failure mechanisms in mind, and the loss of human lives and properties could be minimized.

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**Table 1.** Flood-induced levee failures along Laonong River during Typhoon Morakot in 2009 (modified from Liu et al., 2009; Huang et al., 2014).

| No. | Levee/Total length (m) | Failure Condition |
|---|---|---|
| 1 | Gueishan Levee/1328 | Breached for about 200 m |
| 2 | Chiuliao 2nd Levee/815 | Breached for about 270 m |
| 3 | Chiuliao 1st Levee/648 | Total Collapse |
| 4 | Shinshin Levee/440 | Total Collapse |



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**Table 2.** Design flow rates and water levels of Chiuliao 1st Levee for various return periods.

| Flood Return Period (Years) | Chiuliao 1st Levee (River Section no. 14) | | |
|---|---|---|---|
| | Flow rate (cms) | Water level (m) | Average SD (m) |
| 200 | 15 500 | 8.5 | 1.26 |
| 100 | 14 200 | 8.24 | 1.23 |
| 50 | 12 800 | 7.92 | 1.19 |
| 20 | 10 900 | 7.13 | 1.13 |
| 10 | 9370 | 6.72 | 1.07 |
| 5 | 7650 | 6.53 | 1.00 |
| 2 | 4910 | 4.97 | 0.87 |

SD = Scouring Depth; cms = cubic meters per second





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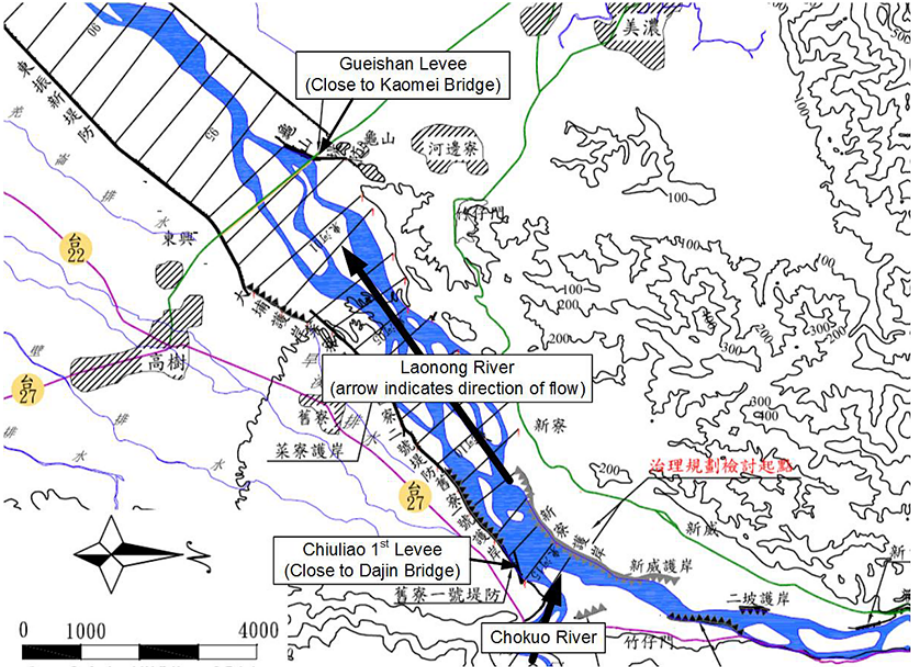


**Figure 1.** Locations of Chiuliao 1st Levee, Gueishan Levee, Laonong River and Chokuo River.





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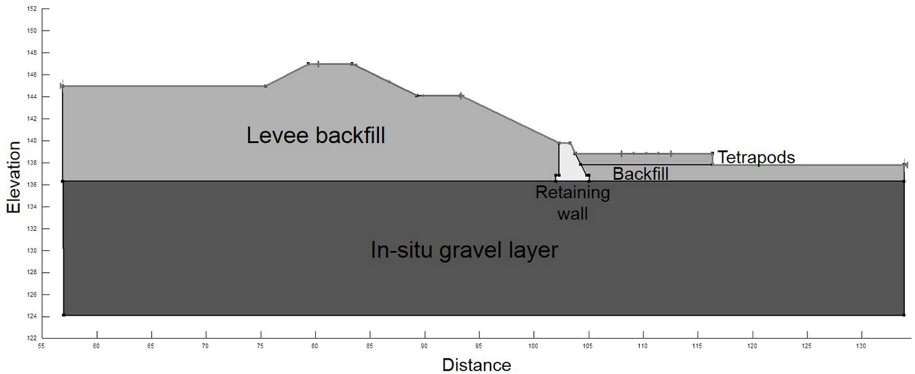


**Figure 2.** Simplified cross-section of Chiuliao 1st Levee before Typhoon Morakot (modified from Huang et al., 2014).

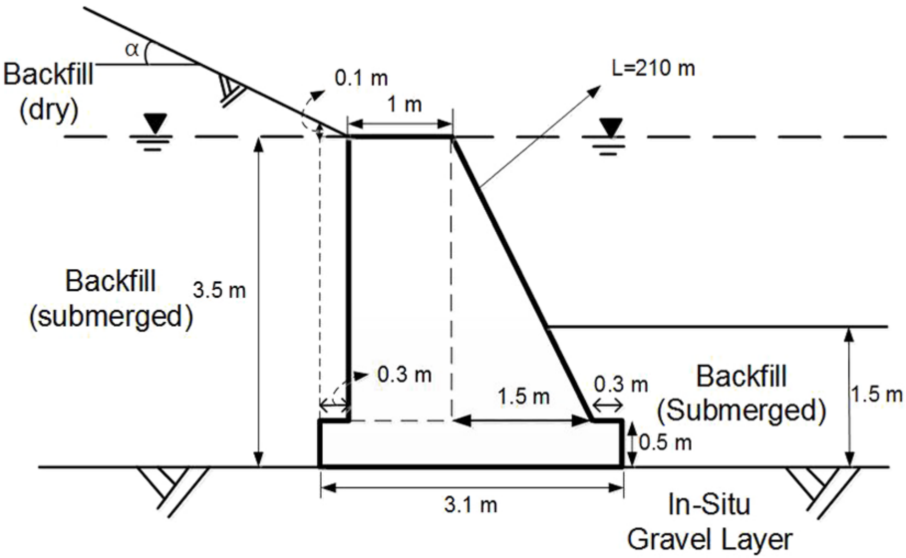


**Figure 3.** Cross-section of the retaining wall of Chiuliao 1st Levee (Huang et al., 2014).





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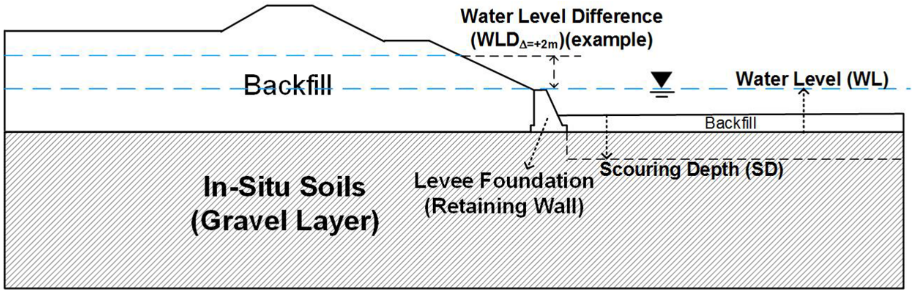


**Figure 4.** Definitions of the parameters (WLD, WL, and SD) used in levee stability analyses (Huang et al., 2014).

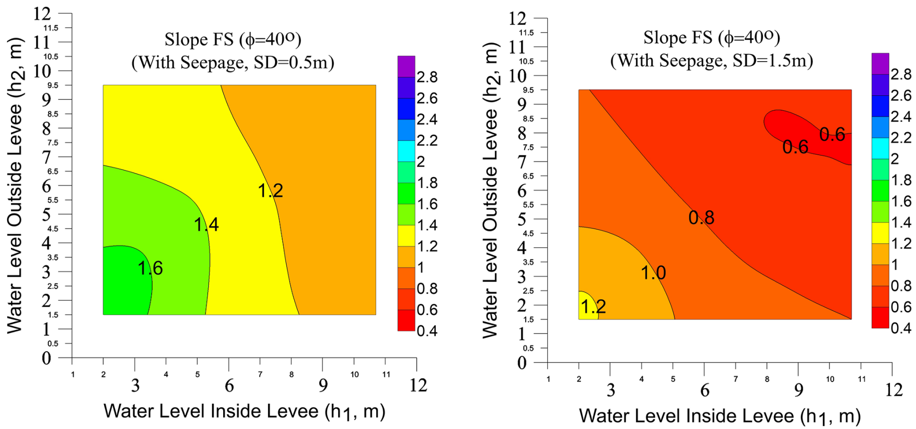


**Figure 5.** Slope stability of Chiuliao 1st Levee for SDs of 0.5 m (left panel) and 1.5 m (right panel).



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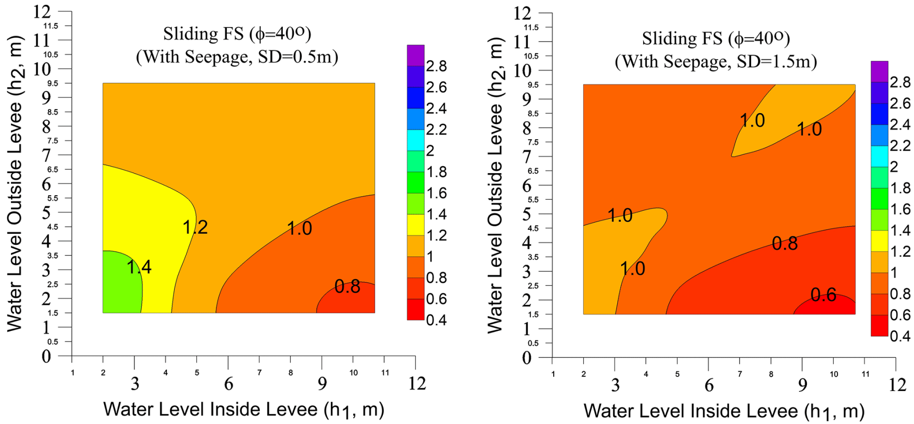


**Figure 6.** Retaining wall sliding safety factor of Chiuliao 1st Levee for SDs of 0.5 m (left panel) and 1.5 m (right panel).

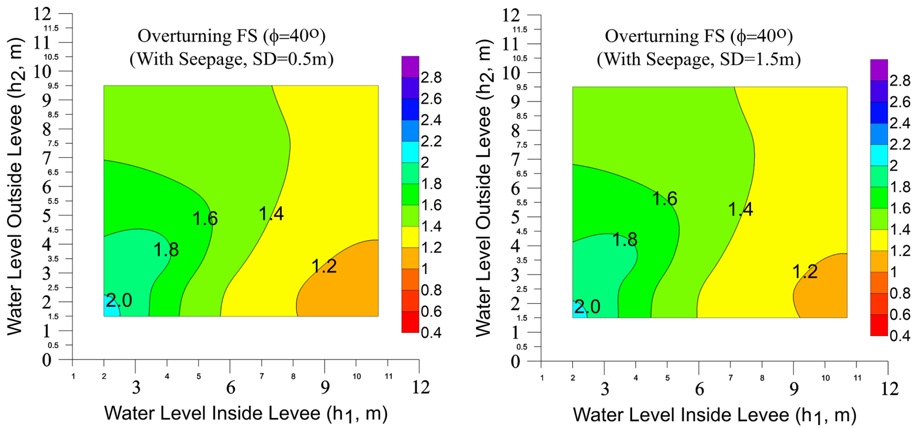


**Figure 7.** Retaining wall overturning safety factor of Chiuliao 1st Levee for SDs of 0.5 m (left panel) and 1.5 m (right panel).





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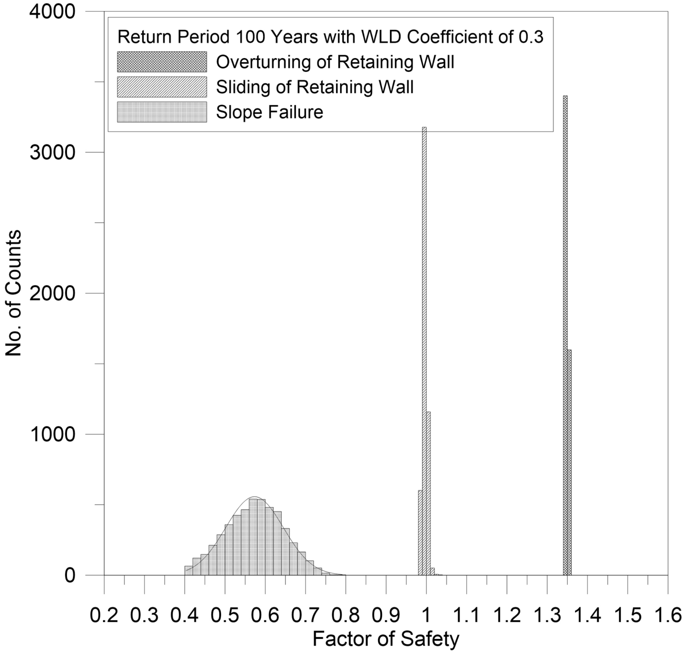


**Figure 8.** Distributions of safety factors for various failure mechanisms (results shown here are for a flood return period of 100 years and a WLD coefficient of 0.3).





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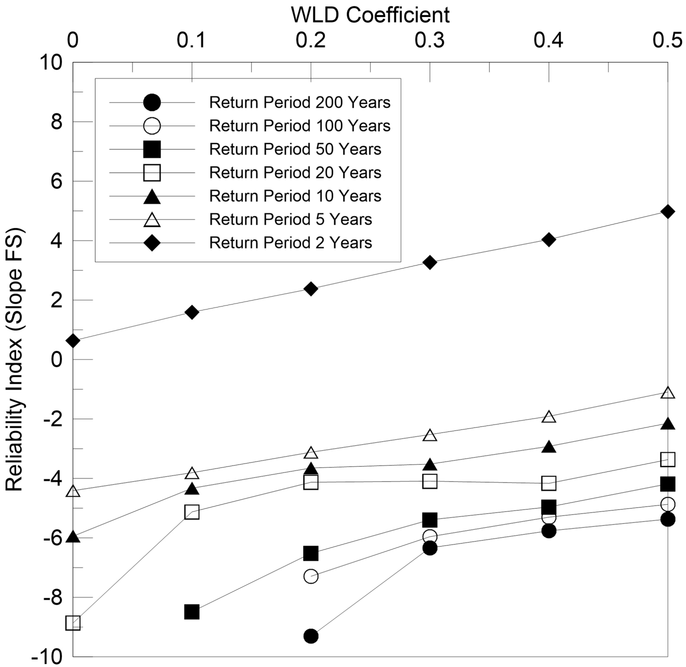


**Figure 9.** Variations in the slope FS reliability index with the WLD coefficient for various flood return periods.





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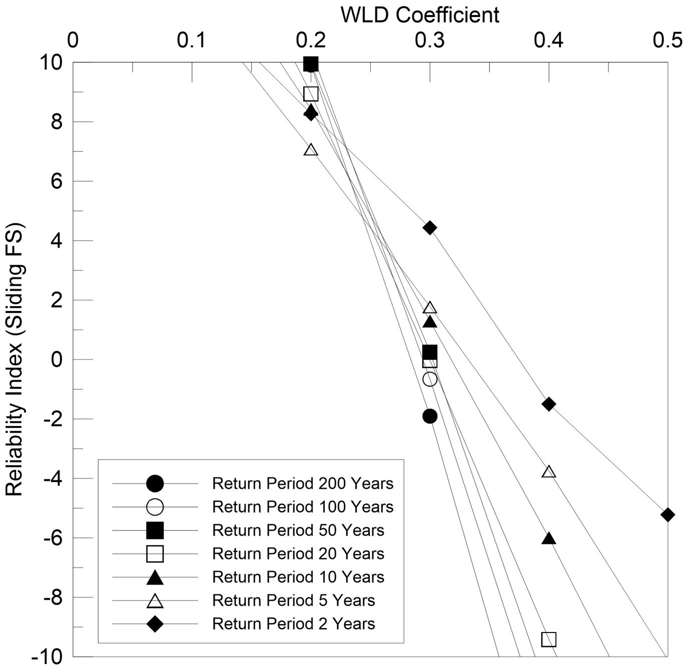


**Figure 10.** Variations in the retaining wall sliding FS reliability index with the WLD coefficient for various flood return periods.





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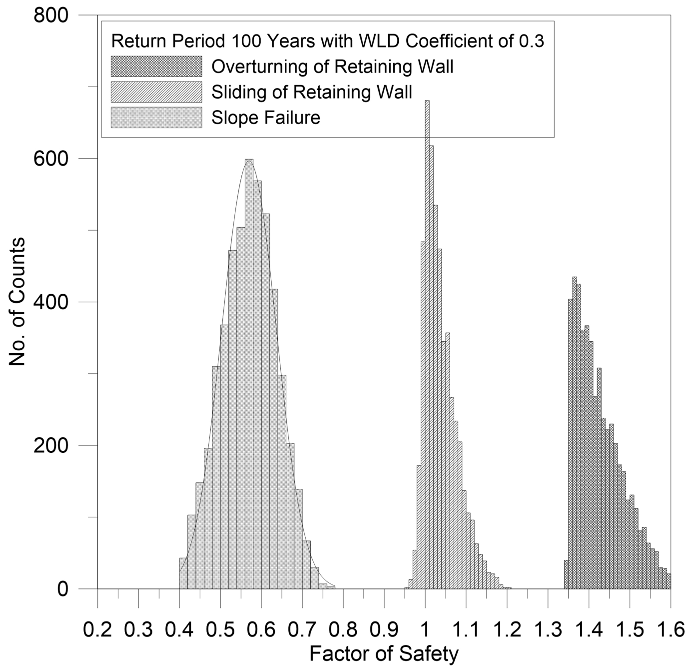


**Figure 11.** Distributions of the safety factor for various failure mechanisms, with accounting for the variability of the in-situ friction angle (results shown here are for a flood return period of 100 years and a WLD coefficient of 0.3).

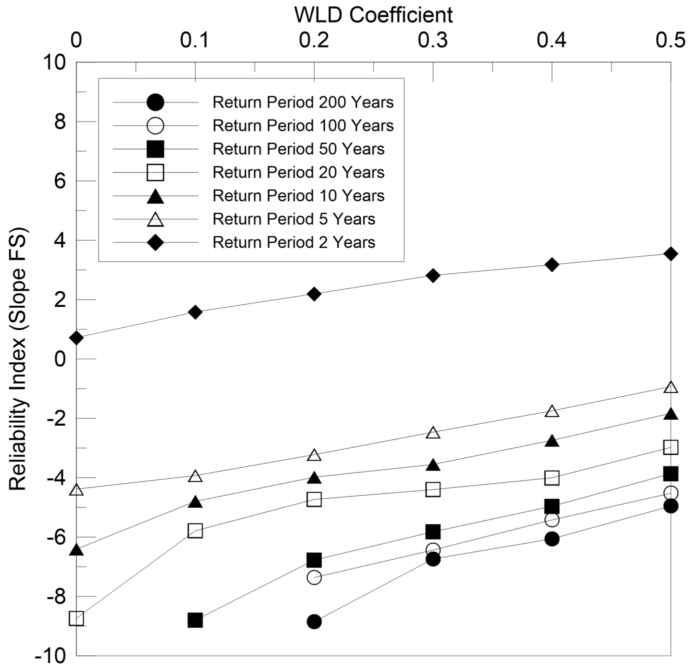


**Figure 12.** Variations in the slope FS reliability index with the WLD coefficient for various flood return periods, with accounting for the variability of the in-situ friction angle.





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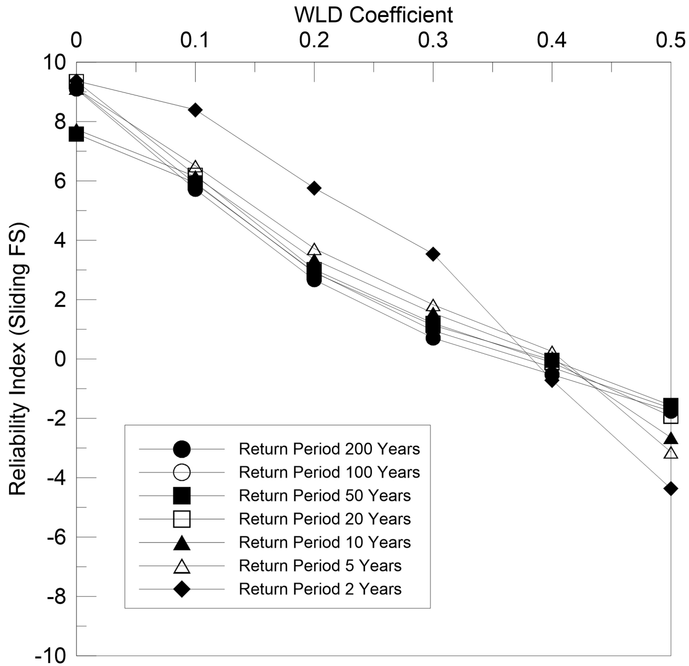


**Figure 13.** Variations in the retaining wall sliding FS reliability index with the WLD coefficient for various flood return periods, with accounting for the variability of the in-situ friction angle.





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