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Assessment of Levee Breaching Risks to the Pearl River Delta

L. Zhang
Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong, China

Y. Xu
China Institute of Water Resources and Hydropower Research, Beijing, China; Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong, China

Y. Liu
Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong, China

ABSTRACT: A levee system poses enormous risks to the safety of people protected by the system. Levee risk analysis is at the heart of levee risk mitigation and engineering decision making. An explicit methodology of levee risk analysis is desirable. In this paper, a case study on the risks of the North Pearl River Levee System (NPRLS) in Guangdong Province, China, is conducted to illustrate an explicit procedure of levee risk analysis. Data required for risk analysis is first collected and analyzed. The performance of the levee upon a 100-year flood at milestone 7+330 is evaluated. The failure probabilities are evaluated for three failure modes: overtopping, piping and slope sliding. The flood scenario resulted from a levee breach at water level 15.53m (100-year flood) is simulated. The loss of life is estimated following the risk analysis procedure and based on fatality rates suggested by the authors. Possible measures to mitigate the risks of the levee are also proposed in the paper.

Keywords: risk analysis, North Pearl River Levee System, levee breach

1 INTRODUCTION

Originating from the Damaokeng Mountain in Xinfeng County, Jiangxi Province, the North Pearl River is one of the main tributaries of the Pearl River. The North Pearl River enters the Pearl Delta after merging with the West Pearl River at Sixianjiao. The entire North Pearl River is 468 km long with a catchment area of 46,700 km^2.

The North Pearl River Levee System (NPRLS) starts from Shijiao Town and ends at Shishan Town. The location of the levee system is shown in Fig. 1(a). NPRLS is the main flood control system for the Pearl Delta, protecting three large cities with a population of over 10 million. One of them is Guangzhou, the capital city of Guangdong Province. Topographically the protected area is higher in the northwest and lower in the southeast. As shown in Fig. 1(b), there are essentially no natural barriers in the area so the consequence of any levee breach can be catastrophic. Although there are some dikes inside the flood plain, they are for controlling floods generated within the flood plain rather for guarding against possible levee-breaching floods.

Some levees along the North Pearl River were constructed 1600 years ago. In 1954, an embryo levee system was constructed. This system was heightened and strengthened from 1983 to 1987, which significantly raised the flood control standard. As of this time, the levee system is 63.34 km in length. It has been experiencing another comprehensive improvement since 2005. As the construction work is still going on, the data used in this paper refers to that before the improvement work.

The Pearl River Delta was threatened several times by floods from the North Pearl River. In 1915, the region bounded by the North Pearl River was subjected to an extraordinary flood of 200-year frequency as a result of levee breaches. During that disastrous event, most parts of Guangzhou, Qingyuan, and Foshan were inundated; over 100 thousand people lost their lives or were injured. Levee breaches also took place in 1931, 1949 and 1982. Dangerous situations caused by extreme river floods occurred from time to time: in 1968, 1976, 1994, 2005 and 2006. A well-known case was the June 1994 flood, which was slightly smaller than a 100-year flood. Although the NPRLS survived the flood, dangerous conditions occurred in over forty places.

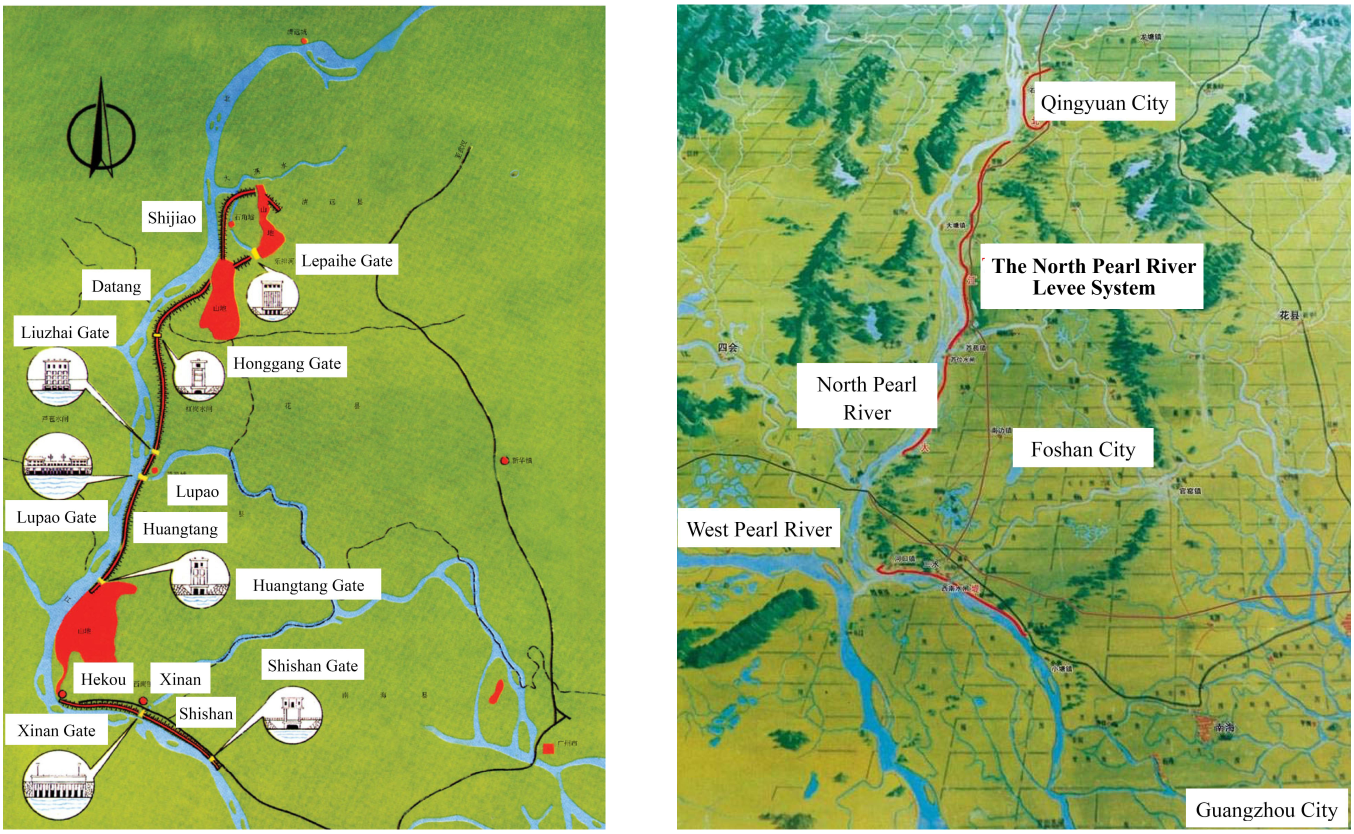

Figure 1. (a) Location of the North Pearl River Levee system; (b) Topographic condition of the flood plain.

Is the NPRLS safe enough to withstand a 100-year flood? What will be the consequence if the levee breaks? This paper attempts to answer these questions through an explicit risk analysis. In this paper, a detailed case study on the risks of the NPRLS upon a 100-year flood is conducted. Based on the risk analysis, possible measures to mitigate the risks of the levee are also proposed.

2 LEVEE FAILURE ANALYSIS

2.1 Hazards Identification and Failure Modes

Located at the beginning of the NPRLS, the Shijiao segment is investigated in this case study. Part of the segment is located on high permeability sand and is one of the most dangerous parts of the levee system. A typical cross section at Milestone 7+330 is chosen to represent this part, as shown in Fig. 2. Most part of the foundation is quaternary alluvium. The thickness of the pervious foundation, which is comprised of fine sand, coarse sand and gravel, is over 30 m.

The study area has very low seismicity. River floods are considered as the main source of natural hazard. In this study, the 100-year flood is chosen as the initiation event for risk analysis. Chou et al. (1999) conducted hydrological calculations. A flood hydrograph was obtained by referring to the 1915 flood and magnifying the 1994 flood to designated design peak discharge and flood volume. The corresponding relations between water elevation and time are shown in Fig. 3. Since the warning water level for the Shijiao segment is 10 m, the input hydrograph in the quantitative risk analysis begins at water level 10 m and assumed to stay at 10 m after the flood fades (Fig. 3(b)).

Based on the geologic conditions and historical performance, it is found that the NPRLS may have three possible failure modes: overtopping, piping in the foundation, slope instability, and bank erosion. The pervious foundation makes piping the main failure mechanism. Dangerous situations induced by this mechanism occurred many times in the past. Except for piping induced in the highly permeable foundation materials, slope instability due to the presence of clay layers is also a problem. The safety of the levee will be threatened if excessive settlement occurs as a result of the lack of bearing capacity or slope failures at sections where the clay layers have low shear strength. In addition, high velocity flows will erode the material at the toe of the levee and induce bank collapses. For the Shijiao segment studied in this case, bank erosion was not serious in the history. Therefore, only failures from overtopping, piping and slope instability are considered in the quantitative risk analysis.

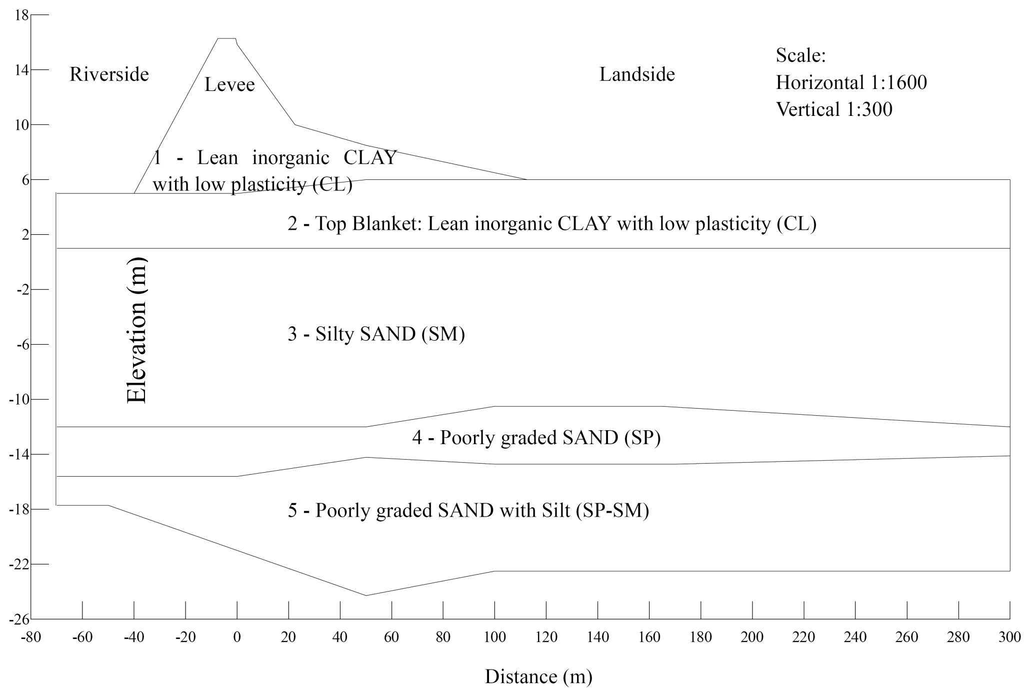

Figure 2. Typical cross section of the NPRLS at Shijiao.

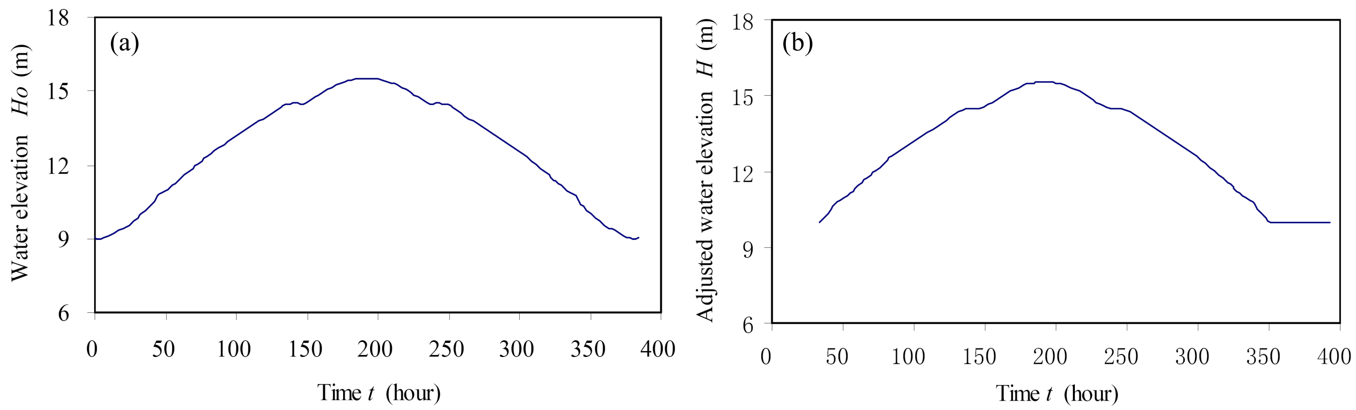

Figure 3. 100-year return flood for the North Pearl River: (a) Water level vs. time; (b) Adjusted water level vs. time.

2.2 Overtopping

Overtopping occurs when the water level exceeds the crest elevation of the levee. The elevation of the crest is 16.30 m and the peak water level of a 100-year flood is 15.53 m. The longitudinal flood wave and tide wave have already been taken into consideration. The 100-year return river flood level is lower than the elevation of the crest, hence overtopping is not a concern as long as the levee does not fail or settle excessively.

2.3 Piping in Foundation and Levee Body

Levee and subsoil profiles have been constructed based on borehole logs (Lin and Gu 2005). As shown in Fig. 2, the clayey levee is underlain by a layer of clay deposits, and these clay deposits sometimes contain sections of ancient levees. The top clay layer provides an impervious blanket at the top of the underlying sandy layers. The soil names in Fig. 2 are based on the soil classification system in ASTM D2488.

The soil properties are summarized in Table 1. Five random variables in Table 2 are defined for probabilistic analysis. The standard deviations of saturated permeability are given based on the original test data, with adjustments referring to reported data in the literature (e.g. Wolff 2008). In this study, the soils are assumed to be isotropic in terms of permeability.

Both steady-state and transient seepage analyses were conducted using SEEP/W. It is found that the maximum hydraulic gradient, i_{max}, from the transient analysis is larger than that from the steady-state analysis at the ending stage due to the slow dissipation of pore-water pressures in the levee. It also reveals that a steady state of seepage cannot be reached within a 15-day flood period. Therefore, a transient analysis is considered more reasonable for simulating a real flood effect. Typical results of transient seepage analysis are shown in Fig. 4.

Table 1. Expected values of soil properties

Soil layer	Natural density (g/cm^3)	Water content	Specific gravity	Dry density (g/cm^3)	Void ratio	Cohesion (kPa)	Friction angle / angle of repose (°)	Saturated permeability (m/s)
1	1.89	0.227	2.69	1.54	0.747	13.2	23.6	2.0×10^{-6}
2	1.90	0.319	2.67	1.44	0.854	15.2	10.5	2.3×10^{-7}
3	1.86	0.265	2.66	1.47	0.872	5.0	35.0	1.7×10^{-5}
4	1.91	0.326	2.70	1.43	0.875	-	/30.5	2.2×10^{-3}
5	1.95	0.283	2.65	1.51	0.743	-	/33.7	3.25×10^{-4}

Table 2. Five random variables for seepage analysis

Parameter	Expected value	Standard deviation	C.O.V.
Thickness of the top blanket (Soil 2), z	5 m	1 m	0.2
Saturated permeability of levee clay (Soil 1), K_l	2.0×10^{-6} m/s	1.6×10^{-6} m/s	0.8
Saturated permeability of the top blanket (Soil 2), K_b	2.3×10^{-7} m/s	1.8×10^{-7} m/s	0.78
Saturated permeability of silty sand (Soil 3), K_{SM}	1.7×10^{-5} m/s	1.0×10^{-5} m/s	0.59
Saturated permeability of sand (Soil 4), K_{SP}	2.2×10^{-3} m/s	1.0×10^{-3} m/s	0.45

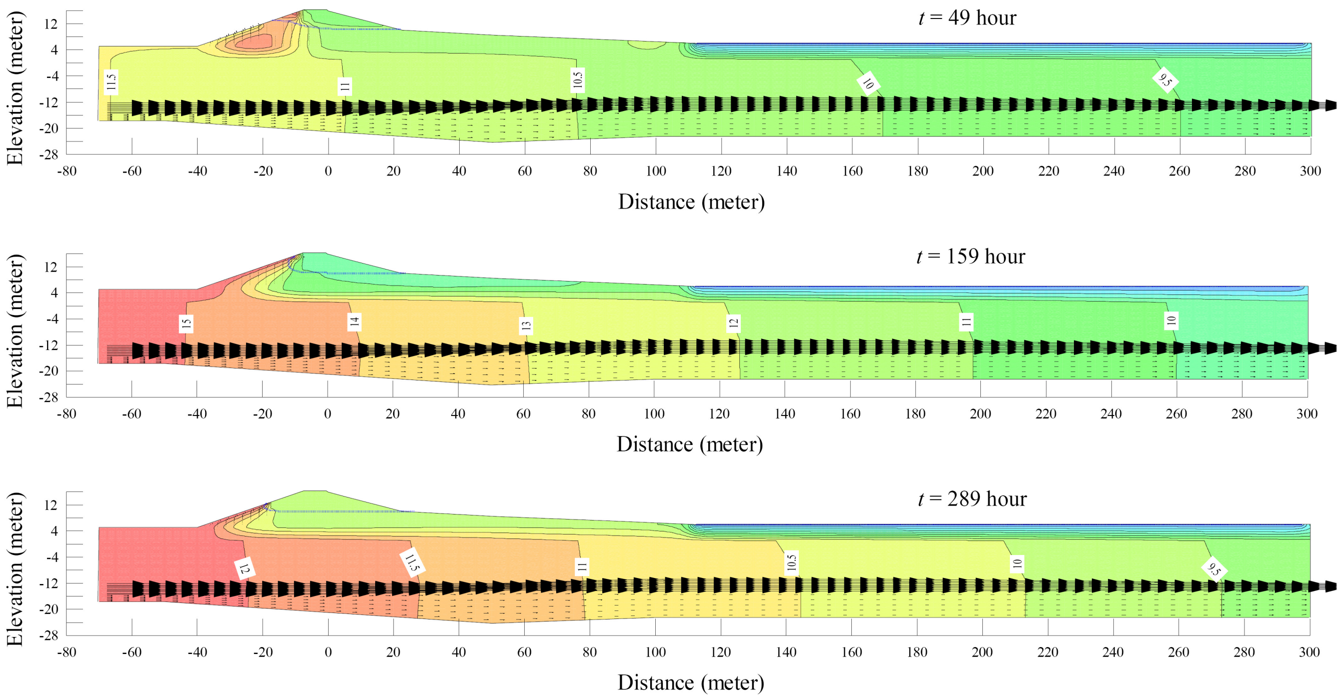

Figure 4. Typical results of transient seepage analysis.

Taylor's series finite-different method was used to calculate the probability of piping failure (Liu 2009). Eleven runs of SEEP/W were conducted. In addition to the first run using the expected values of the variables, ten more runs were conducted to determine the variance component of each random variable. For instance, the thickness of the top blanket is adjusted to the expected value plus or minus one standard deviation, while the other random variables remain at their expected values. A similar calculation is performed to determine the variance components contributed by the other four random variables. By comparing the magnitudes of the variance components (See Table 3), it is found that virtually most of the uncertainty is in the top blanket thickness. A similar result was found in under-seepage analysis of dikes along the Upper Mississippi River (Shannon Wilson Inc. 1994). This implies that when designing levees against under-seepage failure, effort must be made to obtain sufficient data to define the blanket.

When the variance components are summed, the total variance of the exit hydraulic gradient is obtained as 0.041. Taking the square root of the variance gives the standard deviation of 0.20. The exit gradient is assumed to be a lognormally distributed (Mean=1.19, Sta. Dev.=0.20). The critical exit gradient is also assumed to be a random variable following a lognormal distribution (Mean=0.9, Sta. Dev.=0.18). Therefore, the conditional probability of piping failure in the foundation at water level 15.53 m is P_p (H =15.53m) = P(lni - $\text{ln}i_c$ > 0) = 0.86. Repeating this procedure for a range of flood water levels, the conditional probability of piping failure in the foundation is plotted in Fig. 5. As expected, the maximum probability of failure is at the peak water level. It means the levee is in the most dangerous situation against piping failure when the flood water elevation is the highest.

Table 3. Variance components of five random variables

	z	K_1	K_b	K_{SM}	K_{SP}	Total
Variance component	0.04	0	0.0009	0.00016	0.00031	0.04137

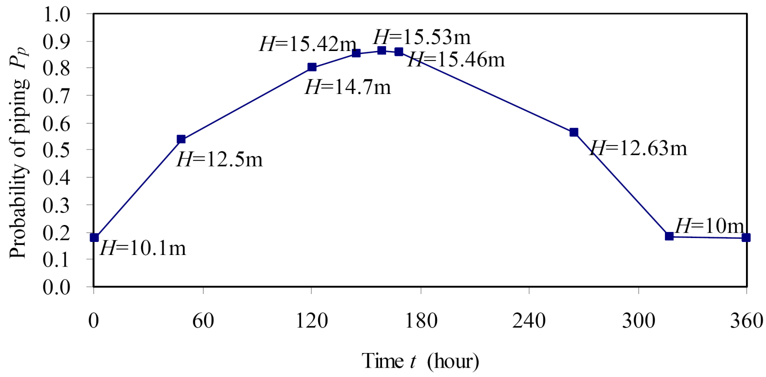

Figure 5. Conditional probability of piping failure in the foundation.

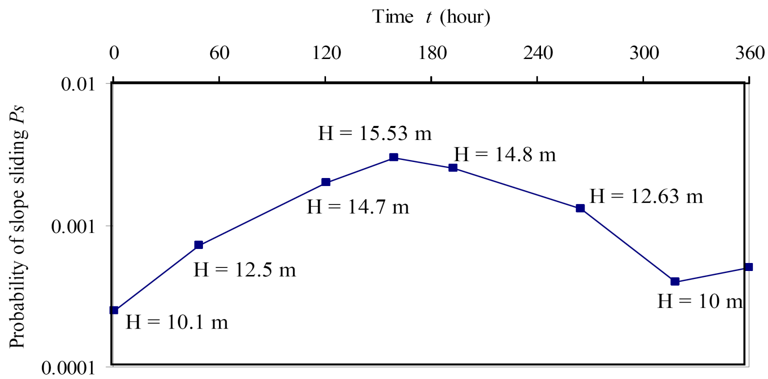

Figure 6. Conditional probability of slope failure.

2.4 Slope Instability

Slope stability analyses were conducted using SLOPE/W. The profile of the cross-section is shown in Fig. 2 and the shear strength properties are listed in Table 4. Besides the five random variables in seepage analysis, four additional random variables are involved in instability analysis, with their first and second moment values defined based on field exploration data. The coefficients of variation for the variables are comparable to those summarized by Wolff (2008). In preliminary analysis, the possible slope movement from right to left (Fig. 2) has been analyzed when the water level draws down. With the support of the static water pressure provided by the river water, the factor of safety (Fs) for the left-to-right movement is very high. Thus only the sliding failure mode from left to right is considered in detail.

Table 4. Four additional random variables for instability analysis

Parameter	Expected value	Standard deviation	C.O.V.
Cohesion of levee clay (Soil 1), C_1	13.2 kPa	8.5 kPa	0.640
Friction angle for levee clay (Soil 1), Φ_1	23.6°	2°	0.085
Cohesion of top blanket clay (Soil 2), C_b	15.2 kPa	6.5 kPa	0.428
Friction angle for top blanket clay (Soil 2), Φ_b	10.5°	3°	0.286

Again Taylor's series finite-difference method was adopted to calculate the probability of slope instability with the aid of SLOPE/W. It is found that most of the uncertainty is in the shear strength parameters; and the total variance of Fs is 0.128. The factor of safety is assumed to be a lognormally distributed random variable (Mean = 1.768, Sta. Dev.=0.357). Thus the conditional probability of slope failure at water level 15.53 m is P_s (H =15.53m) = P(lnFs < 0) = 0.003. The variation of probability of slope failure with river water level is shown in Fig. 6. The probability of slope failure is also the highest when the water level is at its maximum. The probability of slope failure is the lowest when the water level just retreats to the lowest level.

2.5 Summary of Failure Modes

Piping in the foundation is found to be the dominant failure mode (P_p=0.86), which agrees with the historical records. Compared with piping, slope sliding is less likely (P_s=0.003). It should be pointed out that the failure modes only represent the initiating event. How the failure process evolves from the initial event to the final breaching is not the focus of this study.

3 FLOOD ROUTING ANALYSIS

A levee breach is assumed to occur at Milestone 7+330. Levee overtopping and breaching is analyzed in HEC-RAS (USACE 2008) by modeling the levee as a lateral structure. Levees can be connected to storage areas or another river reach. If the water going over or through the levee will pond, then a storage area is appropriate for modeling the area behind the levee. Here flood routing in the area behind the levee is concerned, thus it is appropriate to model the area as a separate river reach. An integrated flood routing analysis of a levee breach consists of three steps: one-dimensional unsteady flow analysis in the main river (i.e., the North Pearl River), levee breaching analysis, and one-dimensional unsteady flow analysis in the flood plain that is also assumed to be a river.

The inundation map and flood severity caused by the levee breach at water level 15.53 m are illustrated in Fig. 7. Details of the flooding routing analysis are available in Liu (2009).

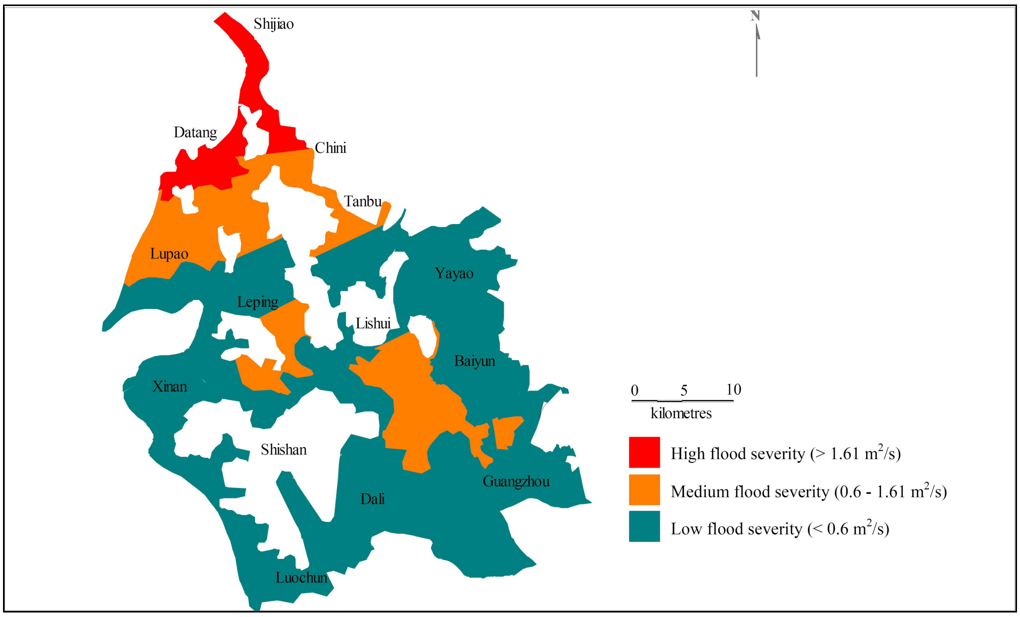

Figure 7. Flood severities of inundation, breach at water level 15.53 m.

4 ESTIMATION OF LOSS OF LIFE

The potential loss of life is often expressed as:

$$\text{Potential loss of life} = \text{Fatality rate} \times \text{Population at risk} \quad (1)$$

The population at risk (PAR) is estimated based on the inundation map generated by the flood routing analysis reported earlier and the statistics of registered population in 2006 (Yang et al. 2006). The administrative regions are divided into sub-regions, as small as possible whenever data is available. The population is assumed to be evenly distributed in each sub-region. The information of population distribution and inundation is well combined and displayed in MapInfo. Figure 8 shows a typical view of inundated population distribution resulted by a levee breach at water level 15.53 m. During this flood, 23 sub-regions are influenced. The PAR of each sub-region is equal to the product of the population density and the inundation area. Finally, the exposed population for each flood scenario is summed up. All the people in the inundation zone are taken as the population at risk.

To estimate the vulnerability, four influence factors are investigated: warning time, flood severity understanding, flood severity and evacuation efficiency. Graham's model (1999) is applied to each sub-region to estimate the potential loss of lives. The model is refined with flood severity degree defined by Abt et al. (1989) and an evacuation model by van Zuilekom et al. (2005). Recommended fatality rates are presented in Table 5.

Based on the PAR values and fatality rates, the total losses of life are estimated for the case when no warning is issued (Loss of life = 4267) and the case when warning is issued (Loss of life = 3029) before the levee breaks. It is found that 29% of loss can be avoided if a warning is issued before the breach so a warning system is essential for the zones near the breach.

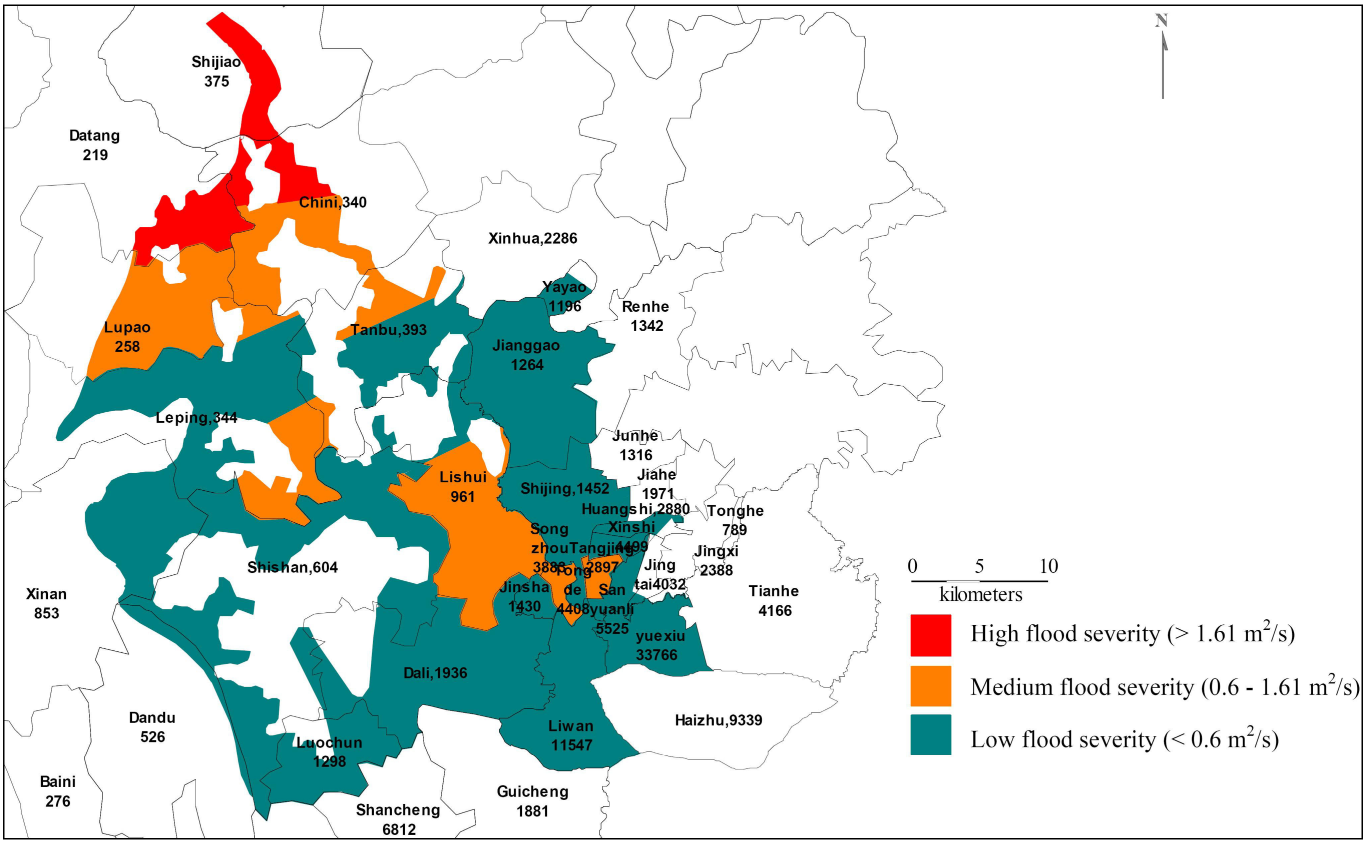

Figure 8. Population density in the inundation zone, breach at water level 15.53 m.

Table 5. Recommended fatality rates for levee failure in this study

Flood severity	Warning (minutes)	Flood severity understanding	Fatality rate
High	No warning	Not applicable	0.3
	15-60	Vague	0.27
		Precise	0.12
	>60	Vague	0.24
		Precise	0.06
Medium	No warning	Not applicable	0.03
	15-60	Vague	0.01
		Precise	0.005
	>60	Vague	0.005
		Precise	0.002
Low	No warning	Not applicable	0.005
	15-60	Vague	0.0007
		Precise	0.0004
	>60	Vague	0.0003
		Precise	0.0001

5 RISK EVALUATION

Risk is defined as

$$\text{Risk} = \text{hazard probability x fatality rate x population at risk} \quad (2)$$

Risk can be integrated into a systematic layout through a scenario tree. The effect of emergency actions and measures can be efficiently analyzed using the scenario tree. Figure 9 shows a flood scenario tree for the NPRLS at water level 15.53 m. Three failure mechanisms, i.e. overtopping, piping and slope sliding, are assumed to be mutually exclusive. The risk of the NPRLS against a 100-year flood is quantified in terms of total fatality, which is 270.

As indicated in the scenario tree, three aspects of measures can be taken to mitigate the risk: stabilizing the levee system, improving the emergency actions and decreasing the loss of life. In this case study, the levee is rather stable against sliding. Improving the slope stability will not effectively mitigate the risk. Instead, engineering measures should focus on decreasing the probability of foundation piping, such as installing relief wells and constructing a continuous concrete cutoff wall. Non-engineering measures such as developing an effective warning system is also highly recommended.

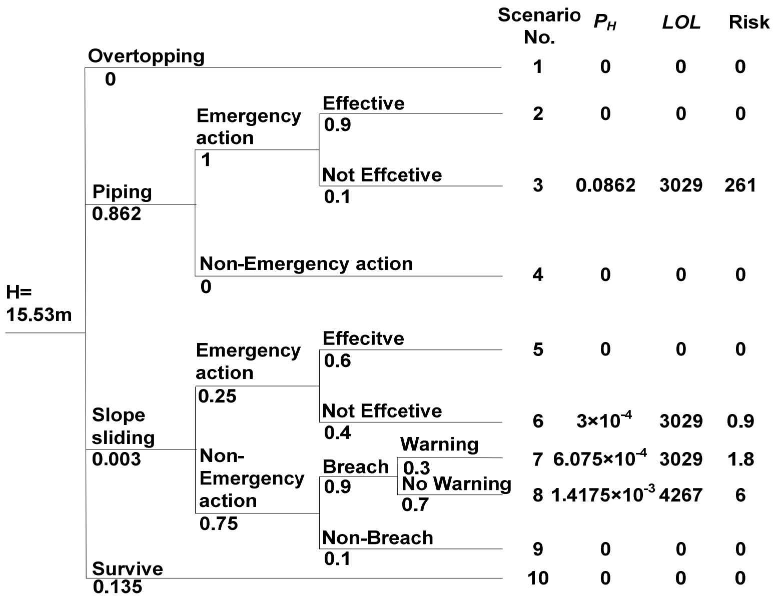

Figure 9. Scenario tree for risk assessment of the NPRLS upon water level 15.53 m.

6 SUMMARY

In this paper, a case study on the risk of the North Pearl River Levee System upon a 100-year flood is conducted following an explicit risk analysis procedure. In the Shijiao segment, piping in the foundation is found to be the dominant failure mode. Based on the estimates of probabilities of failure of piping and sliding, and loss of life, the risk of the levee is finally quantified in terms of fatality and presented in a scenario tree. Both engineering and non-engineering measures are suggested to mitigate the hazard and reduce the loss of life.

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