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ARTICLE

Probabilistic risk analysis of dyke failure modes using FTA

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ABSTRACT
The mechanism of dyke instability was studied in this paper. First, based on a simplified fault tree (FT) for dyke failure, its instability was modelled. Second, dyke failure mode could be derived by solving FT, and then the limit state equations were formulated. Further, after analysing the distribution pattern of random variables and the parameters of each limit state equation, the probability of dyke failure in each failure mode was calculated using the Monte-Carlo simulation, and finally the total probability of dyke instability was obtained. In case studies, for the selected river, results showed that the probabilities of piping (No.2) and dyke landslide (No.3) were 0.9904×10^{-2} yr^{-1} and 1.3904×10^{-2} yr^{-1} respectively. The results have certain guiding significance on dyke design and safety evaluation.

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KEYWORDS Reliability; dyke failure; modelling and simulation; fault tree; infrastructure management

1. Introduction

1.1. Background

The research on the reliability of dyke came up with the development of structural reliability theory in the early 20th century. In 1919, *Kakinqi,* from Budapest of Hungary, introduced the statistical mathematics in this area (Glen, Luc, & Stuart, 1999). In 1926, *Meyer*, one of the earliest scholars, deemed that the structure safety analysis can be conducted by the probability theory (Krystian, 1998). In 1935, *Sitelielvciji* published some important papers in this area. Besides, in 1947, some scholars such as *Erranniqin* and *Sula* published successive results. From that time, researches in the scope of structural safety have gradually evolved into the new era of application of probability theory and mathematical statistics. It was worthy to point out that *Freudenthal* studied the basic problem about structural safety degree

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under the random load presented by him that has been accepted in engineering field. In 1947, *Freudenthal* published his research named *Structural Safety Degree* (Freudenthal, 1947), in which he provided a theoretical basis for structural reliability.

From 1970 to 1980s, the structural reliability theory has been improved and successively applied in national or professional standards in various countries. Since *C. A. Cornell* presented the first-order second-moment method, *N. C. Lind* deduced a whole set of safety coefficients for load and resistance based on the reliability indexes, which built the relationship between the reliability degree analysis and the design method. Subsequently, for the problem of basic variable with abnormal distribution, *R. Rackwitz* and *B. Fiessler* presented an equivalent calculation method for normal variable, which was improved systemically and recommended to civil engineering field by the Joint Committee of Structural Safety (Ahmed & Thomas, 1999). Meanwhile, this method also was adopted by various countries, such as the China *United Standard for Design of Building Structures* (GBJ 68-84) (Jinxin & Guofan, 2005).

1.2. Problem statement

Due to multiple factors such as section form and fill properties of dyke body, geological, hydrographic, topographic and construction conditions of dyke foundation, the dyke usually suffers from some dangers like overtopping, seepage failure of dyke body (foundation) and landslide of dyke body during the rainy season. The current safety factor method (or partial safety factor) based on limit equilibrium analysis cannot provide the evaluation indexes for engineering reliability, also doesn't give accurate prediction on flood risk due to human factors. In the design method based on probability theory, multiple parameters of the structure can be considered as the random variables, so that corresponding designs can be conducted for different dyke structures according to their degree of importance.

Current dykes in China are mostly constructed, damaged, restored and reinforced time to time in history. Due to the non-uniformity and complexity of soil materials, dykes usually suffer from different degrees of seepage damage, landslide, erosion etc. in the rainy season. After the serious flood in Yangtze River in 1998, large scale reinforcement constructions have been conducted for dykes. Meanwhile, the researches on engineering design, safety management and evaluation of dyke have been widely implemented too. But the research on the mechanism and prediction of dyke failure is so far remaining in the stage of naked-eye observation and monitoring data analysis. Consequently, the traditional empirical dyke safety evaluation and management method would be replaced by the risk management, which would help in understanding the dangerous points and accident scenarios using more rational calculation model and analysis method. Because the dyke foundation is usually a natural foundation, its dyke body cannot be normatively designed and constructed as the soil dam, besides that there is a large changeability in soil layer distribution and geotechnical parameter, which results in difficultly inconducting a safety evaluation on dyke. Due to that the variability of designed variable is not taken into consideration, the safety factor obtained by the conventional safety evaluation method of fixed value cannot demonstrate the safety degree of engineering, completely and accurately. However, the risk evaluation method based on reliability theory, in which multiple parameters of structure have been taken as random variables (DeKay & McClelland, 1993) and corresponding designs can be conducted according to the degree of importance of different dyke structures.

The flood risk is determined by combining dyke failure probability with flood losses, and the flood risk can be calculated only when the dyke failure probability is calculated before. When the resistance *R* of dyke is smaller than the pressure on it (Papoulis, 1965), the dyke will be damaged in different degrees. The dyke failure can be generally divided into two modes which include flood overtopping and dyke damage and instability, the dyke failure is caused by flood overtopping and can be simulated using the hydraulic model, while the dyke failure caused by the damage can be defined as dyke instability, the research focuses on analysing the dyke instability mechanism and the calculation of instability probability. The dyke instability probability can be calculated by directly analyzing the difference between instability modes and inputting the uncertainty of parameters, but the method above only can be applied for one or two simple instability modes. Besides, there are many factors such as spreading, soaking, fissure, piping, seepage and landslide that can influence the stability of dyke, the analysis and calculation on a simple instability mode is difficult to be considered for all the influencing factors, and it also does not follow the true condition (Cooke & van Noortwijk, 1998). Consequently, before the analysis and calculation of instability probability, it is necessary to understand the intrinsic physical essence of dyke failure more profoundly. The paper focuses on the research on the mechanism of dyke failure using FTA, and then the instability probability was obtained using the probability analysis.

Here, it analyzed and described the calculation of instability probability using the fault tree, associated with Monte-Carlo simulation, and finally total instability probability of typical inclined-wall-type dyke was calculated. The whole process was divided into five steps, in which a fault tree for dyke instability is established first, then all failure modes and limit state equations of corresponding failure modes were obtained, meanwhile the failure probability for each failure mode was calculated using the Monte-Carlo simulation and finally the total instability probability was obtained.

The advantages of the inclined-wall-type dyke is that the process of laying film is carried out after the completion of dyke reclamation, so that the construction disturbance is small and the quality of laying film is easier to ensure, so most new dyke works at home and abroad adopt sloping-wall structure. This paper chooses inclined-wall-type dykes as the object of study, considering a variety of probabilistic design methods of failure mechanisms it approaches the impacts of geotechnical statistical parameters and dyke geometry on overtopping, osmotic stability, dyke stability reliability index or risk of instability through changes in design parameters, which is conducive to the future development of a safety evaluation system based on conventional methods and theory of reliability. It also predicts the danger category existing in all sections of a dyke project, based on a variety of safety evaluation indexes. This will help to change the traditional and empirical-type dyke safety assessment and management methods to predictive risk management system.

2. Method

2.1. Dyke instability mechanism analysis

Dyke may suffer from various risks such as spreading, soaking, fissure, piping, seepage and landslide. There are numerous factors influencing its safety which includes section form, fill properties of dyke body, geological factors and water level and construction conditions. These factors include both internal and external factors, natural and human factors. Consequently, the profound analysis on the influence of each typical risk factor on the dyke safety provides a basis for risk analysis and calculation of dyke engineering.

According to the requirement of *1992 Formulation and Revision Plan of Project Construction Standards* (Annex II of JZH text [1992] 490) issued by the State Planning Commission, the *Dyke Project Design Specifications* was jointly developed by the Ministry of Water Resources in conjunction with other relevant departments and, undergoing the joint checkup by the departments, it was approved as a mandatory national standard document numbered GB 50286-98, and has come into force since October 15, 1998.

The *Dyke Project Design Specifications* require that the types of dyke projects should be integrally determined in accordance with the principle of 'local conditions, local materials', based on the factors of a dyke including the geographic location, degree of importance, geologic condition, dyke materials, water and storm characteristics, construction conditions, applying and management requirements, environmental landscape and project cost, through a technical and economic comparison. According to different dyke materials, earth dyke, stone dyke, concrete or reinforced concrete flood wall, partition-filled mixed materials dyke, etc., can be chosen; as for dyke section types, oblique dyke, straight-wall dyke, straight-or-oblique compound dyke can be chosen. According to the design of impervious barrier, homogeneous earth dyke, sloping-wall-type or core-wall-type earth dyke and so on can be chosen. As for the treatment of dyke foundation, economic and rational programs should be chosen based on the project levels, heights, dyke foundation conditions and seepage control requirements. Treatment of dyke foundation should meet the following requirements of seepage control, stability and deformation.

1. The seepage control should ensure the infiltration stability of the dyke foundation and the soil outside the landside toe;
2. The static stability calculation should be carried out to determine the stability of the dyke foundation. For a dyke designed according to seismic requirements, a dynamic stability calculation should be carried out for the dyke foundation;
3. After the completion of a dyke, the total settlement and differential settlement of dyke foundation and dyke body should not affect the safe use of the dyke.

The culverts, hidden rivers, collapse areas, animal nests, graves, caves, ponds, well pits, house foundations, miscellaneous fill and other hidden defects in a dyke foundation should be proven and handled.

According to the factors such as waves, currents, tides, ship waves, geologic and terrain conditions, construction conditions and use requirements, dyke protection works may choose the following types:

1. Slope revetment;
2. Dam revetment;
3. Wall revetment;
4. Other types of protection.

The structures and materials of dyke protection works shall be:

1. Durable, anti-erosion and anti-wear;
2. Able to adapt to bed deformation;
3. Easy to be build, repair and reinforce;
4. Built using local resources, economic and rational.

The dyke sections for eroding banks along narrow rivers, the sections without beach and vulnerable to water erosion, the sections with important protected objects, and the sections limited by terrain conditions or built buildings, wall revetments should be adopted. For the types of wall revetment structure, the outer side can be vertical or steep, the inner side can be vertical, sloping, broken-line-like, unloading step-like. The wall structural materials can be reinforced concrete, concrete, stone masonry, etc. The section size and the depth of wall base embedded in the dyke toe should be analyzed and determined according to specific conditions and the calculation of and the overall stability of the dyke. For the dyke sections undergoing serious water erosion, base-protecting measures should be strengthened. The space between the wall and bank slope should be filled with sand and gravel. Drainage holes should be set in the wall, and filters should be set at the drainage holes. For the top surfaces of the backfill bodies behind the walls in the dyke sections undergoing serious erosion of stormy waves, erosion-protecting measures should be taken. Deformation joints should be set along wall revetments, for reinforced concrete structure, concrete structure and masonry structure, the distances between the joints may be 20 m, 15 m and 10 m, respectively. At the places with change of dyke function conditions, deformation joints with treatment of seepage control should be added. For the wall bases of wall revetments, underground continuous walls, caissons and pile foundations can be chosen, the structures can be reinforced concrete or less reinforced concrete, and the cross-section sizes should be calculated and determined according to the structural stress analysis.

When the resistance R of dyke is smaller than the pressure S on it, the dyke will be damaged to different degrees and fail. The dyke failure can be generally divided into two modes including flood overtopping and dyke instability caused by damage. Among them, it is studied that there are three reasons for the dyke instability, which include dyke damage, dyke landslide and internal erosion. But for the typical inclined-wall-type dyke, the reasons for dyke erosion can be divided into three modes which include flood control slope instability, sand liquefaction and slope damage. Generally, the main reasons for dyke instability are as follows (Ahmed & Thomas, 1999; Freudenthal, 1947; Krystian, 1998):

1. During the low water season, the water level decreases, the pore water pressures in the slopes of bank form the seepage pressures triggering the landslide. Besides, the dyke is usually composed of silts, fine sands and soils formed by natural sedimentation on the bank of river, this type of soil formed by normal consolidation has low bulk density, large compressibility, small permeability coefficient and low undrained shear strength, so that once the water level of the river decreases, the water pressure outside the slope will disappear and soil bodies are more likely to become unstable.
2. River waters excavate and wash the slope toe, which results in the collapse of upper slope. From the current analysis on the typical inclined-wall-type dyke, the slope ratio around the bank slope ranges from 1:1

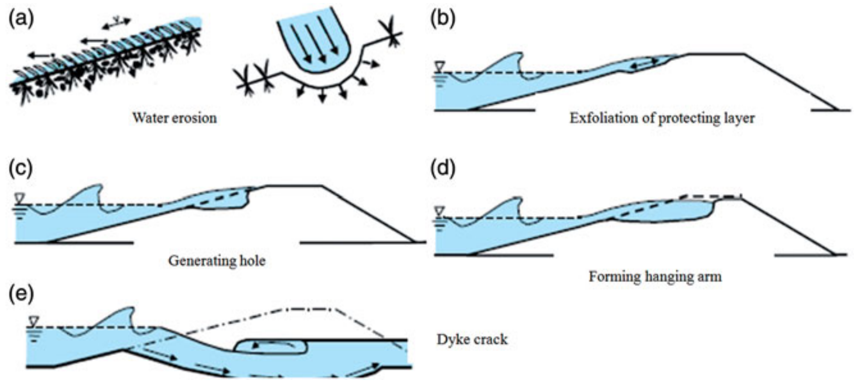


Figure 1. Schematic Diagram for Dyke Erosion and Damage.

to 1:4. Most of the slope toes are not steep but under water for a long time, and they are composed of silts and fine sands, which are the natural sediments with low-intensity index, negligible resistance and very low anti-sour capability. In the places where waters flow directly toward the slope and wash the slope from the top and the water level is variable, waters continuously wash, erode and empty the slope toe, which results in the slope instability and the collapse in upper part.

3. Rainstorms make the negative pore water pressures of parts of water bodies near the slope face disappear, which becomes a triggering factor for dyke landslide.
4. The dynamic water pressure of wave may be one of instability reasons. The bank has suffered for wave action for a long time, and some parts in the dyke are in tension.
5. Due to the long history of interaction between dyke and water, the dyke can be eroded and damaged by waters. Meanwhile, under the erosion of water flow, a number of holes will be formed in the dam body and the shear strength of dyke will decrease, and the hanging arm will be formed and the dyke will be damaged. The schematic diagram for dyke erosion and damage is shown in Figure 1 (De Mello, 1975).

According the analysis above, the internal mechanism for dyke instability is shown in Figure 2.

2.2. Establishment of fault tree

The fault tree can be used to analyze not only the systemic fault caused by single component, but also the systemic fault caused by several

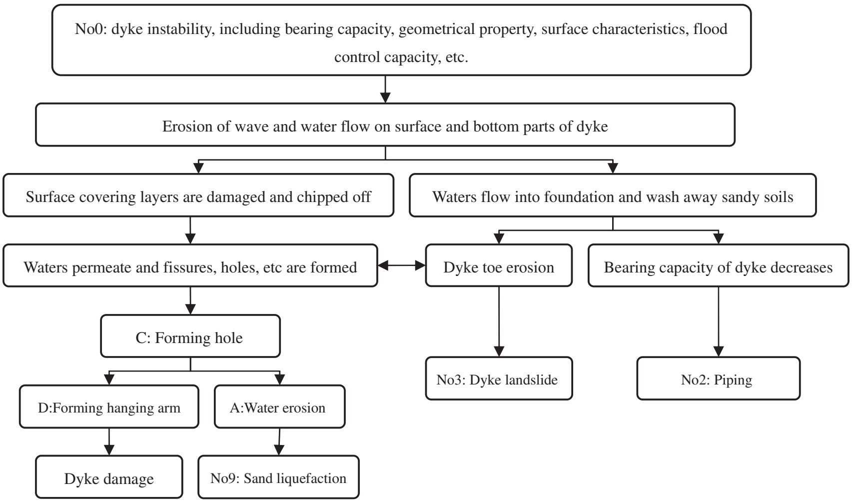


Figure 2. Analysis on Dyke Instability Mechanism.

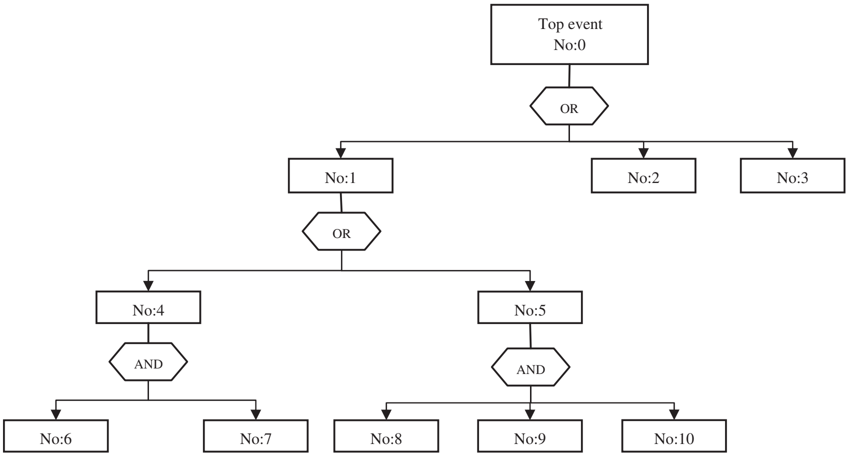
components in different modes. But for the dyke failure, a failure event due to complicated reasons, top importance measures of fault tree can ensure the integrity of problem solution process and rationally determine the priority sequence of each component.

The established fault tree is shown in Figure 3, from which it can be seen that the dyke failure is a top event, and the dyke erosion and failure are jointly caused by revetment failure and dyke dam erosion. It is finally indicated that the fault tree of dyke instability includes seven bottom events, including:

No:1- dyke erosion;
No:2- piping;
No:3- dyke landslide;
No:4- revetment failure;
No:5- dyke dam erosion;
No:6- revetment erosion;
No:7- revetment stripping;
No:8- coverging layer instability;
No:9- sand liquefaction;
No:10- the formation of the cantilever;

The top importance measures on fault tree were shown in Table 1.

One of the most important outputs of an FTA is the set of importance measures that are calculated for the top event resolved by Cut Sets or Path Sets. These top importance measures establish the significance for all the events in the fault tree in terms of their contributions to the top event probability. Both intermediate events (gate events) as well as basic events can be prioritised according to their importance. Top importance measures



Notes:
No0: dyke instability;
No1: dyke erosion;
No2: piping;
No3: dyke landslide;
No4: revetment failure;
No5: dyke dam erosion;
No6: revetment erosion;
No7: revetment stripping;
No8: covering layer instability;
No9: sand liquefaction;
No10: the formation of the cantilever;

Figure 3. Fault Tree for Dyke Instability.

Table 1. Importance Degree of Fault Tree.

Bottom event	No:6-revetment erosion	No:7-revetment stripping	No:8-coverging layer instability	No:9-sand liquefaction	No:10-the formation of the cantilever	No:2-piping	No:3-dyke landslide
Importance degree of mode	0.0211	0.0504	0.0231	0.0289	0.0252	**1.0000**	**1.0000**

Bold values indicate that if it occurs piping or dike landslide, the probability of dyke instability is 100 percent.

can also be calculated that give the sensitivity of the top event probability to an increase or decrease in the probability of any event in the fault tree. Both absolute and relative importance measures can be calculated.

In addition to providing the significance of the contributors, the top importance can be used to allocate resources. These resources might include testing and maintenance resources, inspection resources, upgrade resources, quality control requirements and a wide variety of other resource expenditures. By using the top importance, resources can be optimally adjusted to minimise total resource expenditures while maintaining the top event probability, thus providing a win-win situation. Alternatively, for a given resource expenditure such as for upgrades or for maintenance, the top importance can be used to allocate resources to minimise the top event probability. This aids decision makers in obtaining the 'biggest bang for the buck' by providing an objective assessment using systematic methodologies, with associated software if needed, to supplement and complement their subjective information.

A cut set is a set of basic events, which if they all occur, will result in the top event of the fault tree occurring. The minimum cut set of fault tree of the dyke failure is composed of:

1. {No.3}
2. {No.2}
3. {No.6, No.7, No.8, No.9, No.10}.

It can be seen that the importance degrees of {No.3-dyke landslide} and {No.2-piping} are at least ten times larger than other five bottom events covered {No.6-revetment erosion, No.7-revetment stripping, No.8-coverging layer instability, No.9-sand liquefaction, No.10- the formation of the cantilever}. So, piping and dyke landslide have greater influence to the top event than others and these two bottom events should be paid much attention to.

After obtaining the probability distributions of piping and dyke landslide using the Monte-Carlo simulation method, the total probability distribution can be analyzed and calculated. While for the Monte-Carlo simulation conducted for the probability distributions of piping and dyke landslide, it is only conducted for the typical inclined-wall-type dyke. Therefore, the total probability distribution of dyke instability is also aimed at the inclined-wall-type dyke (Kortenhaus et al., 2003; van Noortwijk et al., 1999; Wu, Ding, & Zhang, 2006).

3. Case studies

3.1. Selected river and dyke

The selected river lies in *Hebei* Province, that is located in the region from East longitude 112° to 120° and from North latitude 35° to 43°. The region is located in the northern part of North China, the river flows from west to east, and the basin has a temperate zone continental monsoon climate with four distinct seasons and sufficient sunlight as well as vast temperature difference between day and night. The annual average temperature is $5.4\sim9\,^{\circ}C$, annual precipitation is $330\sim550$ mm, frost-free period is $110\sim150$ days. In the region, winter is cold and long, it is dry and windy in spring, the rainfall is concentrated in summer, it is sunny and temperate

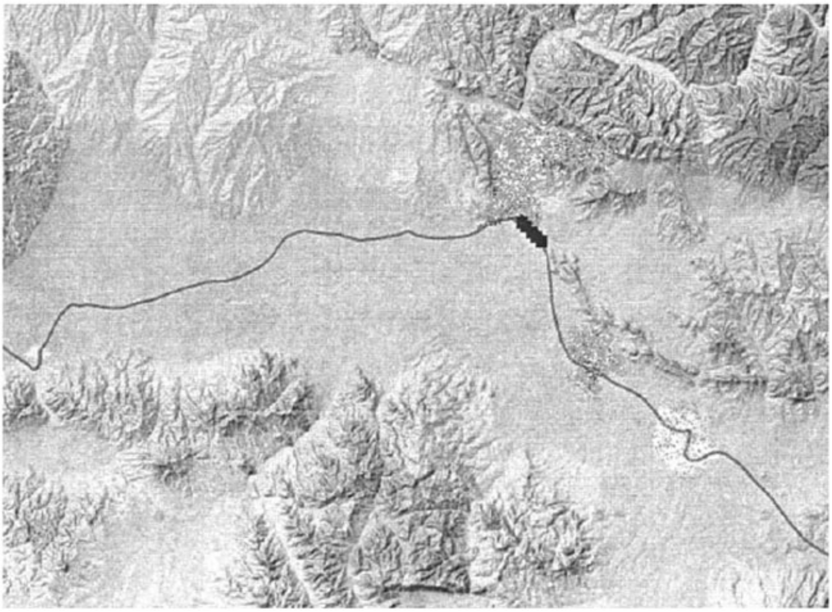


Figure 4. The studied river and its surrounding terrain.

in autumn. The area of the region is 36,873 km^2, of which arable land area accounts for 32.7%, forest land area accounts for 15. 5% and pasture area accounts for 12.4%. The maximum north-south distance is about 300 km; the maximum east-west distance is about 228 km. It has a population of 4.5 million. The lower reaches of the river is a flood-prone area in *Hebei*, in which there have been floods many times bringing serious losses to the vast region. The studied river and its surrounding terrain are shown in Figure 4.

A dyke section about 1km long was selected as the object of study (see Figure 4), the dyke section is a typical sloping wall dyke, with a main part of sandy soil covered by clay, and part of its design parameters are shown in Table 2 (Yikai, Liu, Guo, & Liu, 2007). Dyke cross-section diagram is shown in Figure 5.

In order to carry out the Monte Carlo simulation of dyke failure and the simulation of flooding range, a river water level curve better reflecting the real situation needs to be fitted with a limited number of river water level data. To seek a reasonable approximate expression to reflect the rule of the changes in river water level data, two problems need to be solved: first, what type of function should be selected as a fitting function (mathematical model)? and second, for the selected fitting function, how to determine the parameters in the fitting function? (Brown & Graham, 1988) Mathematical models should be established on the basis of reasonable assumptions, the

Table 2. Part of dyke design parameters.

Symbol	Parameter	Mean value/m	Source
h_o	Crest level	5.0	Design value
h_{bc}	Thickness of clay layer	1.5	Design value
L_k	Width of foreshore	10.0	Design value
M	Width of effective leakage path	68.75	Design value
W	Ratio of slope	2.5	Design value
t_{sb}	Width of dyke crest	5.0	Design value
h_{bc}	Thickness of permeable cover	0	Design value

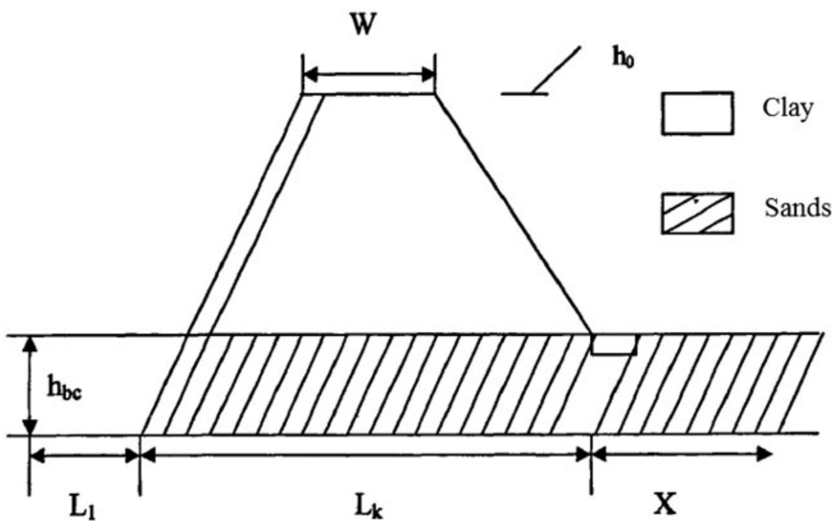


Figure 5. Cross-section of a dyke.

reasonableness of the assumptions is firstly reflected in choosing a certain type of fitting function which conforms to the trend of data change (overall changing rule) (Hawkes, Gouldby, Tawn, & Owen, 2002). The fitting functions can be chosen flexibly among linear functions, polynomial functions, exponential functions, trigonometric functions, normal functions and other functions, and this choice should be based on the trend of data distribution.

As shown in Table 3, the distribution trend of the data obtained from the water level detection station of the river reach is probably in line with the normal distribution rule, so a normal function is selected as the fitting function.

In the intervals where the water levels are measured, an uniform random sampling is carried out in accordance with the frequency ratio of water level within the flood season (May, June, July, August) (e.g., carrying out 125 times of samplings in the interval [2.50, 2.67]); the data samples randomly selected in each interval are combined to produce approximate data samples of river water level; the data samples of river water level undergo a

Table 3. Actual water levels measured by the monitoring station located at selected river.

Prob. density	0.125	0.429	0.200	0.100	0.050	0.040	0.020	0.013	0.010	0.007	0.004
Water level	2.50–2.67	2.67–2.96	2.96–3.15	3.15–3.30	3.30–3.34	3.34–3.46	3.46–3.52	3.52–3.57	3.57–3.62	3.62–3.69	3.69–3.84

Note: Water level is the an annual probability.

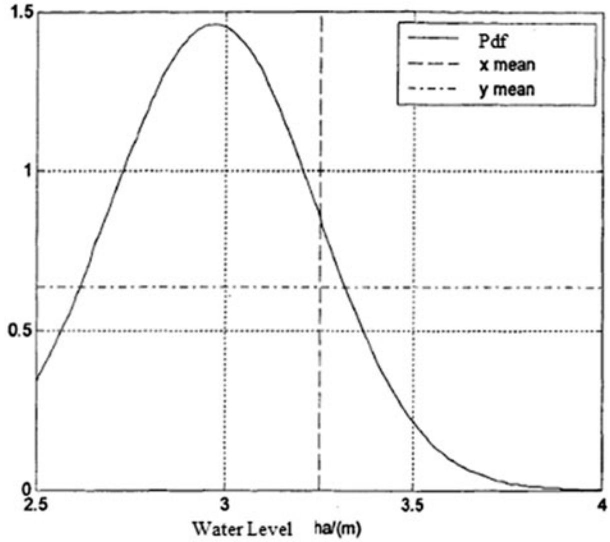


Figure 6. Probability density distribution curve for water lever.

normal fitting to get the parameters of the fitting function (means and variances), the data shown in Table 3 are the means and standard deviations of the normal fitting function obtained by fitting and simulating the data of 10 times of samplings. Then the fitting curve of the river water level (probability density distribution curve: as shown in Figure 6) is drawn in accordance with the obtained fitting function.

Table 4 shows the data of the normal distribution mean and standard deviation obtained by carrying out 10 times of fitting, their average values are respectively taken as the parameters of the function. Therefore, the water level values are obedient to the normal distribution with parameters of 2.9667 and 0.2733.

Therefore, the water level fitting function of the selected river reach according to the fitting results is a normal function, the average value is 2.9667, and the standard deviation is 0.2733, which are the basis for the dyke failure probability calculation as well as flood coverage simulation and prediction.

Table 4. Data of normal fitting.

Times	1	2	3	4	5	6	7	8	9	10	Mean
Mean	2.9686	2.9639	2.9683	2.9641	2.9654	2.9690	2.9669	2.9668	2.9690	2.9645	2.9667
Standard deviation	0.2704	0.2739	0.2721	0.2755	0.2747	0.2718	0.2710	0.2755	0.2744	0.2735	0.2733

3.2. Piping

Piping is caused by the concentrated seepage formed by flowing soil deformation occurring at the weak place where the vertical upward pressure head to the covering soil mass is greater than the impermeability strength of the soil mass, and when span growth caused by the constant increase in external water pressure is greater than the critical head of the covering clay layer, a piping occurs as well. The limit state equation is as follows (Buijs, Vail Gelder, & Hall, 2004):

$$Z_1 = m_p h_p - [(h - h_b) - 0.3L] \tag{1}$$

Here,
m_p is the model uncertain parameter of critical head;
h_p, h_b is the internal water level;
L is the seepage length.

The critical head represents the head when in the piping occurs. The head is determined by the characteristics of the clay layer.

Based on porous media filtration equations, Bernoulli equation coupling and the critical traction conditions, taking into account the role of the porosity of the soil mass when the critical head is produced, Ojha, Singh, and Adrian (2003) established a formula to determine the critical head:

$$h_p = a\frac{(1-n)^2}{n^3} + b \tag{2}$$

$$a = \frac{150vL}{gd^2}\sqrt{\frac{cd}{r_w}} \tag{3}$$

$$b = \frac{cd}{2r_w} \tag{4}$$

Here,
h_p is the critical head;
c is the coefficient reflecting the type of the material.
For sandy soil, $c = 10\,\text{kg/m}^3$;
L is the seepage length;
n is the porosity;

Table 5. Distribution law of the parameters.

Variable	Variable description	Distribution type	μ	Unit	σ/μ
$h-h_b$	Difference between river water level and inner water level	Normal distribution	2.9667	m	0.30
ρ_k	Density of wet clay layer	Determined value	1900	Kg/m^3	–
d_k	Thickness of clay layer	Normal distribution	3.5	m	0.20
r_w	Density of water	Determined value	1000	Kg/m^3	–
n	Average porosity of sandy soil	Determined value	0.4	–	–
d	Average particle size of sandy soil	Normal distribution	0.0008	m	0.02
m_p	Model uncertain parameter	Normal distribution	1.67	–	0.20
L_1	Width of foreshore	Design variable	variable	m	–
L_2	Width of dyke foundation	Design variable	variable	m	–

Note: L_1 and L_2 are design variables, here $L_1 = 60\,m$, $L_2 = 40\,m$, $L = L_1 + L_2 = 100\,m$.
D: Determined value; LN: Logarithmic normal distribution; E: Exponential distribution; *N*: Normal distribution; D/V: Design variable.

r_w is the bulk density of water;
g is the acceleration of gravity;
d is the average particle size of clay;
v is the viscosity coefficient of water, at 10 °C, $v = 0.0013053$pa.s.

To substitute Equation (2) for Equation (1), a complete implicit state equation of piping can be obtained:

$$Z_1 = \left(\frac{150vL}{gd^2}\sqrt{\frac{cd}{r_w}}\frac{(1-n)^2}{n^3} + \frac{cd}{2r_w}\right)m_p - [(h-h_b) - 0.3L] \tag{5}$$

To substitute each determined value for the Equation (5), of which the distribution law of random parameters is taken in accordance with Table 5 (obtained by actual investigation and referring the literature (van Gelder and Virjling, 2004)), to take 1000, 5000, 25,000 and 100,000 times of samples to carry out 10 Monte-Carlo simulation and sub-simulations calculation, respectively: the results are shown in the following Table 6, analyzing the simulation results (see Figure 7), it is found when the sampling times increase, failure probability infinitely approaches to 0.9904%, so 0.9904% is taken as the piping failure annual probability of the dyke.

3.3. Dyke landslide

When slide moment M_s is greater than anti-slide moment M_r, i.e. F_s is less than 1, a dyke loses its stability and landslide occurs (Joana, 2005).

$$F_s = M_r/M_s \tag{6}$$

Here,
F_s, dyke safety factor;
M_r, anti-slide moment;
M_s, slide moment;

Table 6. Results of Monte-Carlo simulation.

Times	1000 (%)	5000 (%)	25000 (%)	100000 (%)
1	0.9901	0.9903	0.9905	0.9903
2	0.9888	0.9917	0.9902	0.9906
3	0.9912	0.9906	0.9905	0.9902
4	0.9932	0.9880	0.9901	0.9904
5	0.9934	0.9889	0.9902	0.9905
6	0.9855	0.9906	0.9907	0.9904
7	0.9879	0.9903	0.9905	0.9904
8	0.9888	0.9908	0.9904	0.9903
9	0.9879	0.9900	0.9908	0.9904
10	0.9921	0.9888	0.9908	0.9902
Mean	0.9898	0.9900	0.9905	0.9904

The minimum safety coefficient for stability against sliding is calculated using the simplified *Bishop* method and the most dangerous circular sliding surface (0.6 m below foundation) can be determined, and the safety factor is calculated by the formula below (Kanning, 2005):

$$F_s = \frac{\sum \frac{1}{m_{a_i}}\{C'_i l_i \cos\theta_i + (W_i - u_i l_i \cos\theta_i)\tan\phi'_i\}}{\sum W_i \sin\theta_i} \tag{7}$$

$$m_{a_i} = \cos\theta_i + (1/F_s)\sin\theta_i \tan\phi'_i$$

Here,

ϕ'_i, angle of internal friction for chosen sub-slice i;

c'_i, geotechnical shear strength for chosen sub-slice i;

u_i, pore water pressure in landslide mass for chosen sub-slice i;

l_i, width of sub-slice for chosen sub-slice i;

W_i, weight of sub-slice for chosen sub-slice i.

Using the simplified *Bishop* method (Jonkman, van Gelder, & Virjling, 2002; Vrijling, 2001), and to set dyke safety factor F_s as 1, it creates the limit state equations for dyke slope stability are as follows (De Mello, 1975):

$$Z = \sum_{i=1}^{n} \frac{Ai}{\cos a_i + \tan\varphi_i \sin a_i} - \sum_{i=1}^{n} r_i V_i \sin a_i \tag{8}$$
$$A_i = c_i l_i \cos a_i + (r_i V_i - u_i l_i \cos a_i)\tan\varphi_i$$

Here,

Z, function of structural performance;

a_i, included angle between ground where calculated sub-slice lies and horizontal surface;

φ_i, angle of internal friction;

r_i, unit weight of landslide;

V_i, volume of calculated sub-slice;

c_i, geotechnical shear strength;

l_i, width of sub-slice;

u_i, pore water pressure in landslide mass;

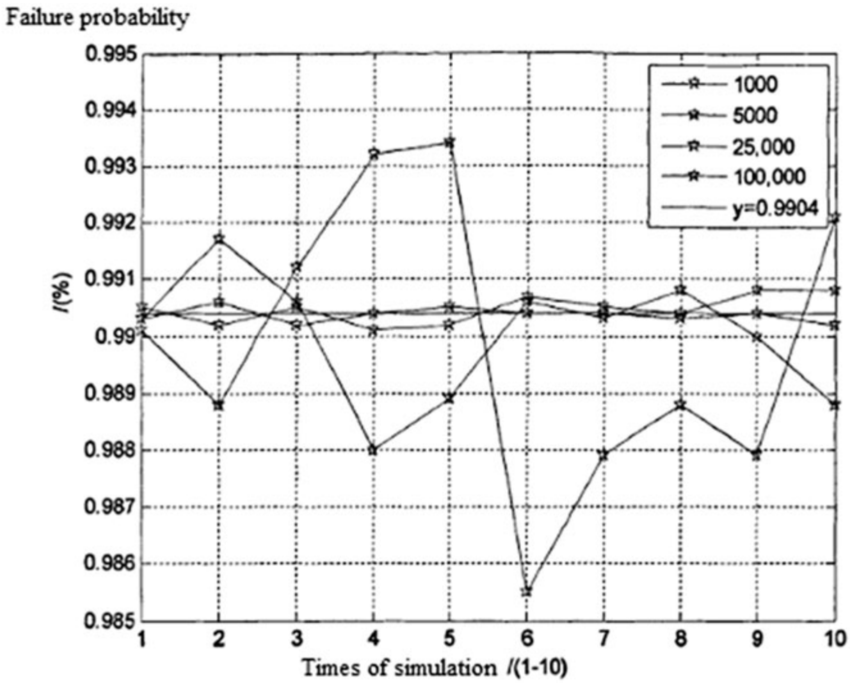


Figure 7. Analyzing diagram of simulation results for piping.

Due to that all parameters influencing the stability of landslide masses are random variables, all of which are not effected with the same degree, so that in order to simplify the calculation, those random variables having little effect can be taken as the determined values. Among uncertain factors influencing the stability of landslide masses, the effects of $c, \varphi, r$are the largest, so that these three factors are selected as the random variables.

In Table 7 (van Gelder and Virjling, 2004; Qiang, Changsheng, & Wu, 2001; Bo, 2007), c, φ, r were assigned different distribution patterns with certain parameters corresponding to different situations while other parameters are considered as the determined values. For instance, geotechnical shear strength c was chosen as random variable with normal distribution.

It is indicated from the calculation conducted using Monte-Carlo method and by sampling 1000, 5000, 25,000 and 100,000 times; the landslide probability of dyke P_f is 1.39×10^{-2} yr^{-1}.

4. Results

It has been indicated that the annual probability of piping (No.2) and dyke landslide (No.3) is 0.9904×10^{-2} yr^{-1} and 1.3904×10^{-2} yr^{-1} respectively that is typical for inclined-wall-type dyke. In order to simplify the calculation

Table 7. Chosen Random Variables and Statistics of Landslide Mass.

Variables	Description	Distribution type	μ	Unit	σ/μ
c_i	Geotechnical shear strength	*N*	10	KN/m^2	0.20
φ_i	Angle of internal friction	*N*	20	(°)	0.20
γ	Unit weight of clay	*N*	22	KN/m^3	0.04
l_i	Width of sub-slice	*V*	0.5	m	–
a_i	included angle between ground where calculated sub-slice lies and horizontal surface	*N*	30	(°)	0.20
V_i	Volume of calculated sub-slice	*N*	20	m^3	0.50
n	Number of sub-slice	*V*	50	–	–

D: Determined value; LN: Logarithmic normal distribution; E: Exponential distribution; N: Normal distribution; V: Design variable.

process, the approximate distribution patterns of other five bottom events are summarised in Table 8 by referring to available literatures and subjective estimates (Papoulis, 1965; De Mello, 1975; van Gelder & Virjling, 2004).

It is concluded from the sampled simulation according to the distribution pattern of each bottom event that the total probability of dyke failure is 2.3808×10^{-2} yr^{-1}. But it needs to be noted that the result above is only obtained on the premise that the typical inclined-wall-type dyke always keeps its largest water level that is determined by the distribution of water level at the selected river and dyke.

5. Discussions and conclusions

A detailed analysis of underlying physics in failures of dyke has been presented. Then a simplified fault tree was established, in which every failure mode was derived and discussed. Consequently, the limit state equations for each failure mode were formulated. After analyzing the distribution pattern of random variables and the parameters of each limit state equation, the probability of each failure mode was calculated using the Monte-Carlo simulation, and finally the total probability of dyke instability was obtained.

In the case study, a simple example was proposed to illustrate the analysis process and the results of the mode were also discussed. In the end, the flood risk was determined. The total probability of dyke failure is 2.3808×10^{-2} yr^{-1} for the targeted river. Further, for typical inclined-wall-type dyke, the approximate branching probability estimates are widely used in today's dyke design in Fujian province and Guangdong province in the south of China.

More to this point, the annual failure probabilities in Table 8 are achieved under the largest water level at the selected river and dyke. If it applies to other locations, the results indicate the extreme local situation including the extreme water level and its failure probability we would face with. It reveals, if we want to defend the dyke, how much efforts we should

Table 8. Approximate Branching Probability Estimates.

Bottom events	Approximate Probability	Estimates
No:9-sand liquefaction	1×10^{-2}	Subjective estimates
No:10-the formation of the cantilever	1×10^{-2}	From literature and document
No:8-coverging layer instability	1×10^{-1}	From literature and document
No:7-revetment stripping	1×10^{-1}	Subjective estimates
No:6-revetment erosion	1×10^{-1}	From literature and document

endeavor to. So, it is very clear that the method proposed here is a systematic and deep analysis that will make significant contribution to the flood risk evaluation and dyke design.

Disclosure statement

No potential conflict of interest was reported by the author.

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