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COMPREHENSIVE ANALYSIS ON SEEPAGE AND STRUCTURAL STABILITY OF EARTH-ROCK DAM: A CASE STUDY OF XIQUANYAN DAM IN CHINA

Qingqing GUO [1,2,3], *Zheng HAN* [4,5*], *Shaohe ZHANG* [1,2], *Yange LI* [4,6]

1. School of Geosciences and Info-Physics , Central South University , Changsha, Hunan 410083, China
2. Key Laboratory of Metallogenic Prediction of Nonferrous Metals Ministry of Education , Central South University , Changsha , Hunan 410083, China

3. Hydropower seventh detachment , Chinese people’s Armed Police Forces, Yingtan, Jiangxi 335000, China
4. School of Civil Engineering, Central South University, Changsha, Hunan 410075, China
5. Department of Civil and Structural Engineering. Geo-disaster Lab, Kyushu University, Fukuoka, 819-0395, Japan
6. State Key Laboratory of Geohazard Prevention and Geo-environment Protection,, Chengdu University of Technology, Chengdu, 610000, China

ABSTRACT

Earth-rock dam is commonly used in the high-dam engineering around the world. It has been widely accepted that the analysis on structural and seepage stability plays a very important role, and it is necessary to take into account while designing the earth-rock dam. In performing the analysis of structural and seepage stability, many remarkable methods are available at current stage. However, there are still some important issues remaining unsolved, including: (1) Finite element methods (FEMs) is a means of solutions to analysis seepage process, but it is often a difficult task to determine the so-called seepage coefficient, because the common-used water injection test is limited in the practical work due to the high cost and complex procedure. (2) It has long been discussed that the key parameters for structural stability analysis show a significant spatial and temporal variations. It may be partly explained by the inhomogeneous dam-filling during construction work and the developing seepage process. The consequence is that one constant value of the parameter cannot represent the above variations. In this context, we solve the above issues and introduce the solution with a practical earth-rock dam project. For determining the seepage coefficient, the data from the piezo metric tube is used to calculate the potential value, based on which the seepage coefficient can be back-analysed. Then the seepage field, as well as the seepage stability are numerically analysed using the FEM-based SEEP/W program. As to the structural safety, we take into account the spatial and temporal variations of the key parameters, and incorporate the Monte-Carlo simulation method into the commonly used M-P method to calculate the frequency distribution of the obtained structural safety factor. In this way, the structural and seepage safety can be well analysed. This study is also beneficial to provide a mature method and a theoretical insight into the earth-rock dam design. The earth-rock dam of Xiquanyan Reservoir near Harbin city in China is also selected as case study to illustrate the described method.

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KEYWORDS

Earth-rock dam; seepage stability; Structural stabiltiy; Monte-Carlo simulation; numerical simulation

INTRODUCTION

Earth-rock dam is one of the commonly used types in dam construction engineering worldwide. Recent years in China, the earth-rock dams, especially the high earth-rock dams have been developed rapidly both in theoretical studies and engineering applications [1]. However, dam failure due to seepage of the earth-rock dams becomes a severe problem. Previous studies have long indicated that seepage stability and structural stability are two important issues that should be taken into account in designing the earth-rock dams. The analysis on the structural stability of the dam plays an essential role relating to the dam structural safety, while the analysis on the seepage stability can be beneficial to control the damage by infiltration. Several lines of evidence also suggest that both the two issues relate to the safety and economy in designing an earth-rock dam [2-5]. They implied that the dam-failure cases due to seepage problems may even extend up towards to nearly 30% to 40% of total cases [6]. In this sense, the history of earth-rock dam development can be regarded as the one of theoretical research on structural and seepage stability.

Theoretical analysis method on the seepage issue of earth-rock dam is a means of solution to investigate the construction quality and safety. This kind of methods majorly treat the seepage process of the earth-rock dam as a steady laminar flow with a phreatic surface, and can be analyzed nu the Darcy’s seepage law [7-11]. Some other studies also made supplement that internal flow features, as well as the dam soil properties should be known beforehand to investigate the advection law of the flow among soil particles. However, it is still a great scientific challenge to know the internal reaction between soil particles and flows. For this reason, some theoretical simplifications had to be made in the practical work. Recently, with the rapid development of computer performance, numerical simulation technique has been greatly developed [22-25], and seepage analysis using numerical simulation methods are being highlighted, especially the well-known Finite Element Methods (FEM). FEM has long been demonstrated as a satisfying method to simulate seepage process with a low cost, high efficiency and accuracy. It performs well when the cross-section shape of the dam is regular, and advanced in taken into account a variety of conditions [12]. The emerging of numerical simulation method also extends the seepage analysis from the steady laminar flow condition to a more complex non-steady flow condition [13-15]. While performing a seepage simulation, determination of the seepage coefficient is a basic but important issue. The seepage coefficient shows a significant influence to the simulation results, and it was commonly measure by the permeability test in traditional methods. However, the measurement data show a significant dispersion, and also the test is costly and complicated to conduct. Therefore, a method that able to accurately and easily determine the permeability coefficient of the dam is necessary when using the FEM to analyze the seepage process.

As to the structural stability analysis of earth-rock dam, the commonly used method is majorly based on the Morgenstern-Price (MP) method [16] or the Bishop method [15]. In both methods, the dam slope is usually simplified as a homogeneous slope, and stability factor can be calculated. These methods are easy-to-use, and able to attain a result with good accuracy. However, due to nonlinear spatial distribution of the complex filling material and different compaction degree when constructing the dam, the core parameters, the cohesion strength c, and frictional angle φ presents significant random spatial distribution. This random distribution feature has also been revealed in both the laboratory and in-situ measurement. Besides of that, these soil strength parameters are also gradually reduced with the seepage development. In view of these, the simulation results will be illogical because one set of representative values of c and φ is not able to present the random spatial and temporal distribution as described.

As a consequence of the limitations from the determination of seepage coefficient and random distribution of soil strength in the dam, the seepage and structural stability analysis could not be well analysed, which also affect the safety of the earth-rock dam. In this context, we solve the above issues and introduce the solution with a practical earth-rock dam project. For determining the seepage coefficient, the data from the piezo metric tube is used to calculate the potential value, based on which the seepage coefficient can be back-analysed. Then the seepage field, as well as the seepage safety are numerically analysed using the FEM-based SEEP/W program. As to the structural safety, we take into account the spatial and temporal variations of the key parameters, and incorporate the Monte-Carlo simulation method into the commonly used M-P method to calculate the frequency distribution of the obtained structural safety factor. In this way, the structural and seepage safety can be well analysed. This study is also beneficial to provide a mature method and a theoretical insight into the earth-rock dam design.

ENGINEERING BACKGROUND

The engineering background of this study is the gravity earth-rock dam at the so-called Xiquanyan reservoir, which locates near the Harbin city, north-eastern China. The earth-rock dam is the gravelly clay core dam. The maximum height of the dam is 29.1 m, with crest elevation of 215.1m. In the cross-section of the dam along the river, the width of the dam crest is 8.0 m. Inside of the dam, the clay core is 4.0 m in the top width, and 8.0 m in the bottom width. The length of dam across the river is 400.6 m. The construction work of the dam was finished in 2000, and since then the reservoir was formally operated to store water for irrigation. However, several years' right after the operation, the "Frosted" phenomenon at the spillway of the downstream slope was reported in winter. The phenomenon implied that the spillway surface should be cracked, causing the water leakage. And some local residents reported that dam slope at the downstream side slipped slightly. All the evidences indicated that the dam was under risk, and detailed analysis on both structural and seepage stability was in a pressing need.

SEEPAGE STABILITY ANALYSIS

Simulation method and analyzing cases

In our study, Finite Element Method is selected to simulation the seepage process of the dam. The SEEP/W software from Geo-Studio Company in China is used. It is one of the commonly used commercial software to investigate the seepage issue based on the FEM [17]. The simulation domain is described below. X-axis points the direction downstream the river, z-axis denotes the direction along the dam height. The depth of the dam foundation is about 1/3 to the dam height, i.e., the foundation depth is around 10.0 m. The seepage in the dam is simplified as a steady laminar one, and three kinds of calculation cases are selected, the normal water level, the designing water level, and the conservative checking water level as shown in Table 1. Numerical simulation of this three cases will be carried out to investigate the seepage stability of the dam under different conditions.

The selected cross-sections for seepage stability analysis

Two cross-sections are selected to analyse the seepage stability of the dam (Fig.1). The cross-section 1 (No. 0+285) is near the thalweg of the river, where the dam height of the cross-section approximates the maximum height of the dam, i.e., 29.1 m, and the cross-section 2 (No.

0+164) is along the spillway of the dam. According to the in-situ engineering geological survey, the two selected cross-section can be simplified into seven zones: (1) the dam shell zone of pebbly clay, (2) the core wall zone of gravelly soil, (3) the downstream zone of gravel, (4) the dam foundation zone of gravel layer, (5) the foundation zone of clay-containing sand and gravel, (6) the curtain grouting zone, (7) the rhyolite zone.

Tab. 1: Calculation cases for seepage simulation of the earth-rock dam

Calculation Cases	Upstream (m)	Downstream (m)
Normal water level	209.90	187.00
Designing water level	212.38	187.00
Checking water level	214.23	187.00

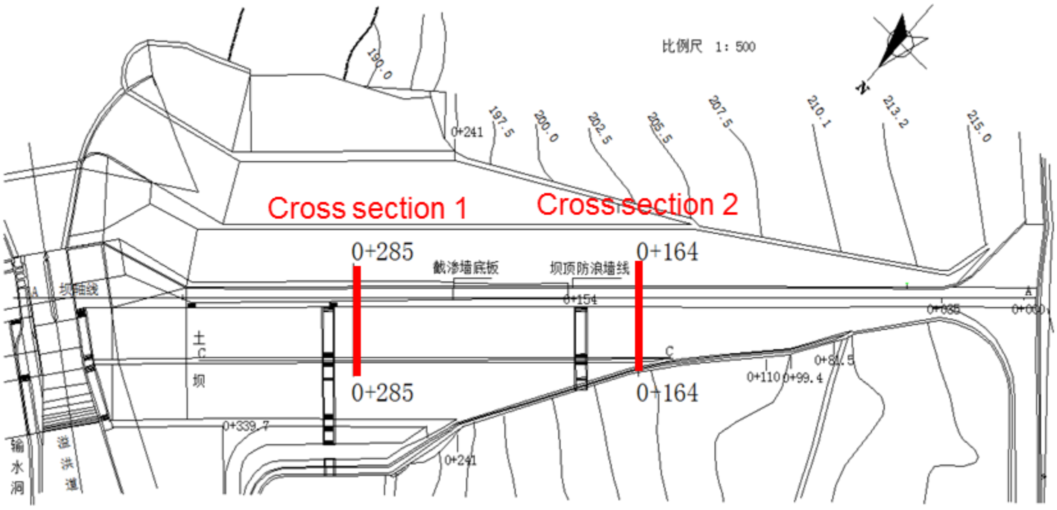

Fig. 1: Selected cross-sections 1 and 2 for seepage stability analysis.

Back-analysis of seepage coefficient

As described in the introduction section, seepage coefficient plays an important role for analysing the seepage stability. At the current stage, the commonly used methods include empirical methods based on the Terzaghi equation, laboratory testing method, and field permeability testing method. With rapid development of computer performance, the back-analysis of seepage coefficient using iteration solution with numerical model is available. In this study, we use the above back-analysis to indirectly search a best fitting seepage coefficient for the described seven different zone in section 3.2.

To determine the initial value of the seepage coefficient, field geotechnical tests and empirical values are used. The initial value of the seepage coefficient in the Zone (2), (6), (7) are based on the field geotechnical tests that mean values are used. The initial value of the seepage coefficient in the Zone (3) is empirically determined. While the initial value of the seepage coefficient in the Zone (1), (4), (5), the data from the piezo metric tube is used to calculate the potential value Φ

$$\Phi = \frac{H - H_2}{H_1 - H_2} \tag{1}$$

where H denotes the water level in the piezo metric tube, H_1 and H_2 denote the water level of upstream and downstream the dam respectively. The initial seepage coefficient will be used to simulate a dummy potential value using SEEP/W software. The dummy potential value is then compared to the value from the piezo metric tube to adjust the initial seepage coefficient. The simulation will be iterated until the simulated dummy value approaches the value from piezo metric tube. Back-analysis results are shown in Tab.2.

Tab. 2: Back-analyzed seepage coefficient of each zone of the dam

Cross-section	Dam zone		Initial value (cm/s)	Best fitting value by back-analysis (cm/s)
Cross-section 1 (0+285)	k_1	Zone (1)	6.41×10^{-4}	6.52×10^{-4}
	k_2	Zone (2)	2.31×10^{-4}	2.31×10^{-4}
	k_3	Zone (3)	2.81×10^{-2}	2.81×10^{-2}
	k_4	Zone (4)	2.81×10^{-2}	3.81×10^{-4}
	k_5	Zone (5)	2.78×10^{-4}	7.00×10^{-3}
	k_6	Zone (6)	2.45×10^{-4}	2.45×10^{-4}
	k_7	Zone (7)	6.39×10^{-5}	6.39×10^{-5}
Cross-section 2 (0+164)	k_1	Zone (1)	4.43×10^{-4}	6.41×10^{-4}
	k_2	Zone (2)	1.56×10^{-3}	1.56×10^{-3}
	k_3	Zone (3)	3.81×10^{-2}	3.81×10^{-2}
	k_4	Zone (4)	6.41×10^{-4}	4.01×10^{-4}
	k_5	Zone (5)	2.81×10^{-2}	8.59×10^{-2}
	k_6	Zone (6)	2.78×10^{-4}	7.00×10^{-3}

Numerical simulation of seepage stability

The basic model of the earth-rock dam is shown in Fig.2. The cross-section of the dam is divided into 157 blocks (blue fonts in the figure), with 190 nodes (black fonts in the figure). Each block is set as a quadrilateral one because this kind of shape is flexible to consider the complex geometry and anisotropic material in the seepage field of the dam.

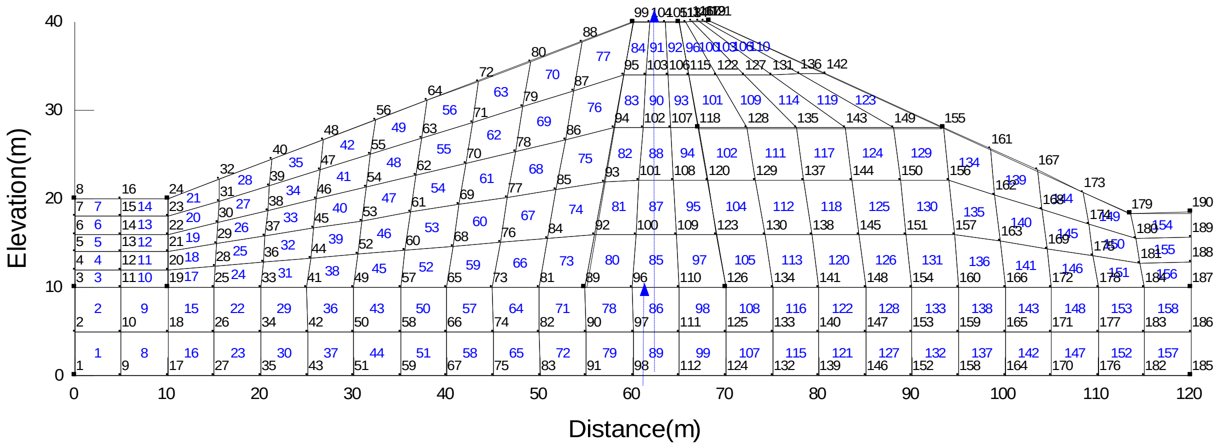

Fig. 2：Schematic illustration of the earth-rock dam model

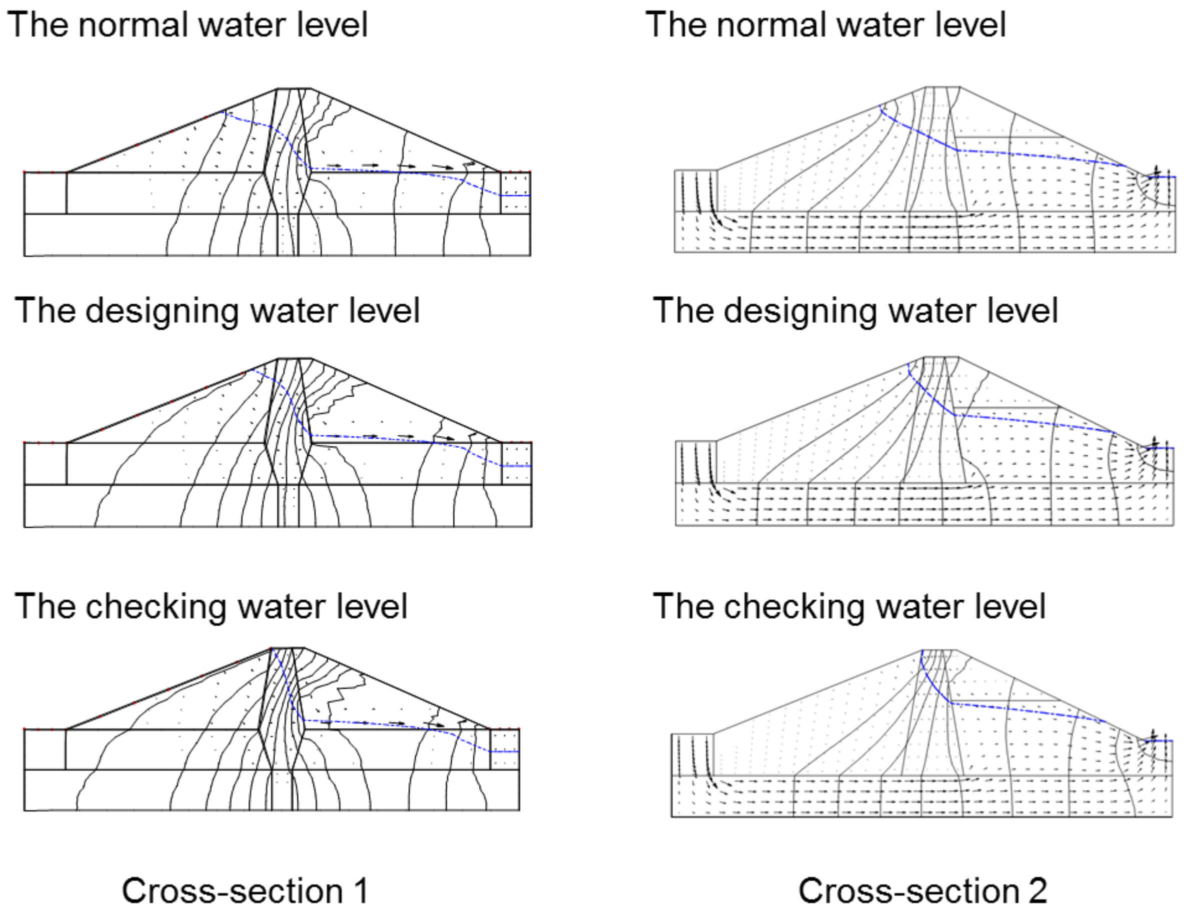

Fig.3: Equal potential line and free surface of the both cross-sections under the water level conditions

Seepage coefficients used in the numerical simulation have been listed in Tab.2. Three calculation cases are considered, the normal water level, the designing water level under the flood with a reproduction period of 100 years, and the checking water level under the flood with a reproduction period of 1000 years. In both the selected cross-sections 1 and 2, the seepage field of the dam and dam foundation are simulated. The corresponding equipotential line distribution, velocity vector, zero-pressure seepage surface are shown in Fig.3, and key features of the seepage process in both cross-sections are summarized in Tab.3 and Tab.4.

Tab. 3 Hydraulic features of the seepage process in the cross-section 1 under different water Levels

Water level (m)	Hydraulic features	Dam zone			Seepage Discharge（m3/m.d）
		Bottom of the core wall	Gravel layer	Dam foundation layer	
Normal 209.90	Hydraulic head (m)	2.391	0.629	0.432	7.630
	Hydraulic gradient	0.223	0.098	0.066	
Designing 212.38	Hydraulic head (m)	2.613	0.904	0.577	8.189
	Hydraulic gradient	0.251	0.140	0.088	
Checking 214.23	Hydraulic head (m)	2.795	0.957	0.609	9.079
	Hydraulic gradient	0.263	0.148	0.093	

Tab. 4 Hydraulic features of the seepage process in the cross-section 2 under different water Levels

Water level (m)	Hydraulic features	Dam zone			Seepage Discharge（m3/m.d）
		Bottom of the core wall	Gravel layer	Dam foundation layer	
Normal 209.90	Hydraulic head (m)	12.815	1.66	1.686	16.383
	Hydraulic gradient	1.608	0.169	0.174	
Designing 212.38	Hydraulic head (m)	13.966	1.93	1.954	19.236
	Hydraulic gradient	1.749	0.197	0.202	
Checking 214.23	Hydraulic head (m)	15.000	2.079	2.048	20.912
	Hydraulic gradient	1.875	0.215	0.207	

As shown in Tab.3 and Tab.4, seepage discharge of cross-section 2 is much larger than cross-section 1. It can be explained in part by the fact that the seepage coefficient of the core wall zone in cross-section 2 is too large, i.e., that material with seepage coefficient 1.56×10^{-3}cm/s should belong to the strong-permeability material. It is even twice as large as the seepage coefficient in the dam shell zone, which is only 6.41×10^{-4} cm/s. Overlarge seepage coefficient in the core wall of the dam is supposed to result from the poor construction quality. Besides of that, the seepage coefficient of the dam foundation zone is 7.0×10^{-3}cm/s, which means that the clay and gravel layer consisting of the dam foundation should be also the strong-permeability material. As such, the core wall and foundation of the earth-rock dam should be rather weak to prevent the seepage and water leakage.

This prediction is also supported by the analysis in Tab.4. It is indicated that the hydraulic gradient of the core wall zone of the cross-section 2 ranges from 1.608 to 1.875 under different water levels. It is beyond the allowed maximum hydraulic gradient 0.35 as demonstrated in the current Chinese standard, and direct consequence is that seepage may occur in this zone. On the contrast, the cross-section 1 performs better to prevent the seepage. As shown in Tab.3, the hydraulic gradient of all the zones under different water levels is within the allowed maximum hydraulic gradient 0.35.

Overall, the averaged seepage discharge of both cross-section ranges from 12.01 m^3/m.d to 14.99 m^3/m.d. Since the length of the dam across the river is 400.56 m, the seepage of the dam per day is around 4800~6000 m^3, and annual seepage is around 175.2~219.0 million m3.

STRUCTURAL STABILITY ANALYSIS

As to the structural stability analysis of the earth-rock dam, it is suggested by the recent research [18] and current Chinese standard [19] that the structural stability of the earth-rock dam can be evaluated by the safety factor against slipping. In order to calculate the safety factor, it is necessary to know the soil strength including cohesion strength c, and frictional angle φ. In previous study, only one group of representative values is used. However, considering the complex spatial and temporal variation of these parameters, one group of representative values should be limited, especially in the earth-rock dam engineering. And many studies, e.g., laboratory experiments and in-situ surveys, have long supported this view by illustrating the significant randomness of soil strength parameters. For this reason, we use a method incorporating with Monte-Carlo simulation to investigate the probability of dam structural failure.

The Monte-Carlo method uses repeated random sampling to simulate data for a given mathematical model and evaluate the outcome. Monte-Carlo method has been already applied in geotechnical researches. The first step in the Monte-Carlo method is to define the input parameters. Sensitive parameters in terms of the entrainment process, c, φ are selected. These parameters are assumed to follow a certain distribution. To do a valid simulation, the second step is to create a large, random data set for each input parameter so that the spatial and temporal uncertainties can be covered by this data set. Safety factors are calculated for many times and the combined effect of uncertainties in the input parameters can be shown.

Generally, the soil strength of the dam is represented by the cohesion strength c, and frictional angle φ. Each of the parameters is regards as an independent and random variable, obeying the lognormal distribution. Several geotechnical test of soil strength at different parts of the dam have been conducted, and all the testing data are collected to determine the distribution. Mean value and standard deviation of both parameters can be expressed as

$$\mu_x = \frac{1}{n}\sum_{1}^{n} x_i \qquad (2)$$

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$$\sigma_x = \sqrt{\frac{1}{n-1}\sum_{1}^{n}(x_i - \mu_x)} \qquad (3)$$

where *x* denotes the selected parameters, *n* denotes the total number of the obtained data.

As suggested by the standard of GB50007-2011 in China, the correction factor regarding total number *n* can be evaluated by the following equation

$$\varepsilon = 1 - \left(\frac{1.740}{\sqrt{n}} + \frac{4.678}{n^2}\right)\delta_x \qquad (4)$$

where *δx* is the variation factor of parameter *x*. Thus the corrected mean value of the parameter *x* can be expressed as

$$\mu'_x = \varepsilon\mu_x \qquad (5)$$

According to the procedure from Eq.(2) to (5), the distribution of the parameters in Monte-Carlo simulation is shown in Tab.5.

Tab. 5: The distribution of the soil strength parameters in Monte-Carlo simulation

Zone	density （g/cm3）	Cohesion strength *c* (kPa)			Internal friction angle *φ* (°)		
		Mean value	Standard deviation	Variation	Mean value	Standard deviation	Variation
Core wall zone	1.65	30.9	15.8	0.29	8.1	1.17	0.12
Dam shell zone	1.91	10	3.0	0.30	30	3.60	0.12

The procedure for Monte-Carlo simulation as illustrated above has been implemented in the code. We programmed the core function of the procedure in the MATLAB environment. MATLAB was chosen because of its powerful capability for matrix operation and visualization features. We use 1000 trials of the Monte-Carlo simulation. Each trial generates a group of random values for the cohesion strength *c*, and frictional angle *φ*, and consequently a safety factor of the dam can be calculated. The commercial software SLOPE/W is used to calculate the safety factor based on the Morgenstern-Price (M-P) method from the limited equilibrium theory, and different water levels can be taken into account. After 1000 trials of Monte-Carlo simulation, 1000 sets of safety factors can be obtained. By analyzing the mean value and variation of these results, the probability of dam structural failure can be finally obtained.

Fig.9 shows the frequency distribution of safety factor under different water levels. Gray zones in the figure denote the structural failure range where the safety factor is smaller than 1.05. As to the cross-section 1 (left column in Fig.4), nearly 70% of results range between 1.30 to 1.80, showing that the dam slope is stable under all the three water-level conditions. While for the cross-section 2 (right column in Fig.4), the safety factor decreases from around 1.40 under the normal water level to around 1.20 under the checking water level. The direct consequence is that 15.5% of the results are within the gray zone (structural failure range) in the figure. It indicates that the probability of the dam structural failure will extend up towards to 15.5%, and the cross-section will be under risk.

The probability of the dam structural failure in both cross-sections are summarized in Fig.5 and Tab.6. It demonstrates that failure probability of the cross-section 1 is not sensitive to the water level, and dam slope is rather stable. While the cross-section 2 increases significantly with the water level, the maximum failure probability will be 15.5% under the checking water level. For this reason, it is necessary to reinforce the dam slope for safety.

In fact, reports from local government also support our prediction. It has been reported that uneven settlement at the surface of the dam crest were observed, as well as some slight slip near the cross-section 2. For the seepage stability, it is reported that noticeable water leakage were observed at the downstream slope of dam, and also the "Frosted" phenomenon in winter. All the evidences support our view that this earth-rock dam is under risk and need some reinforcement to ensure the safety.

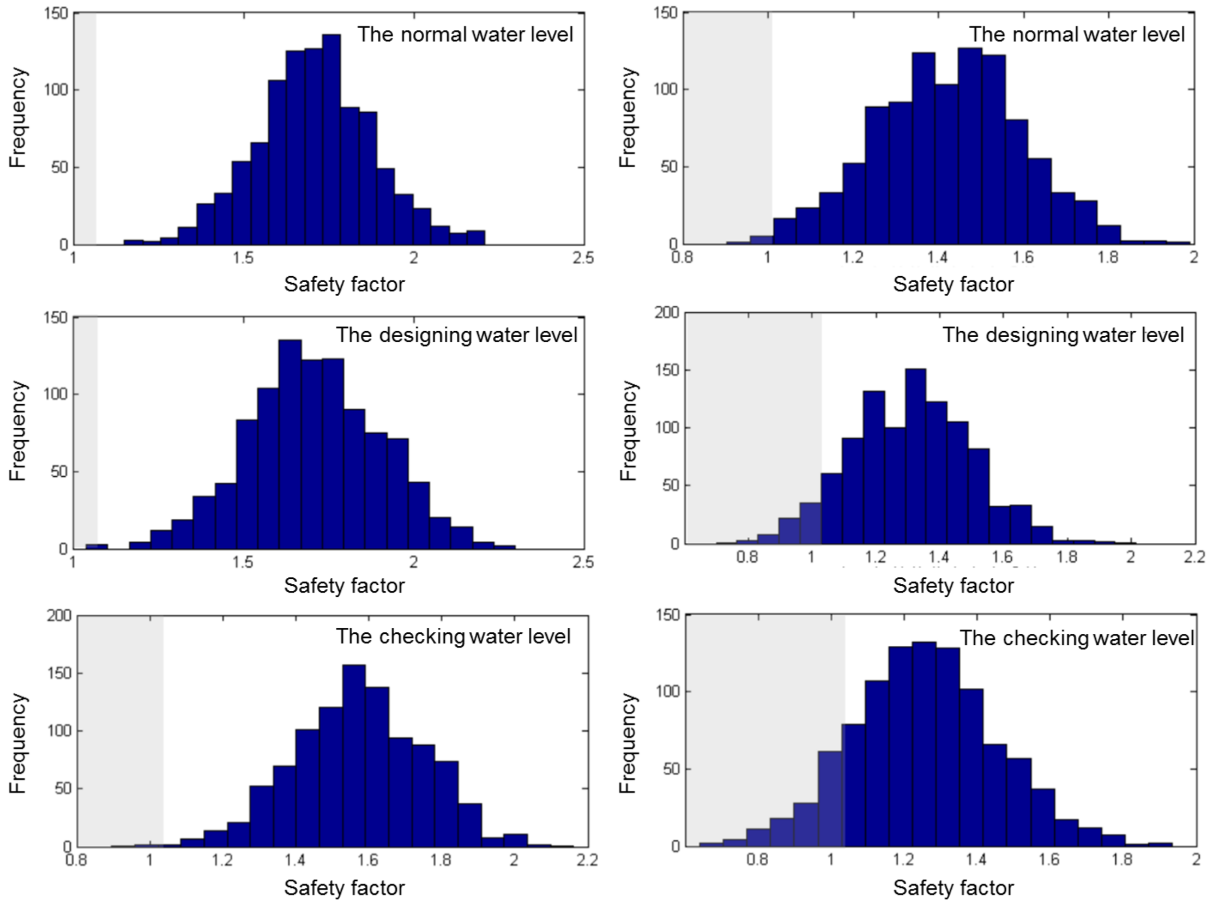
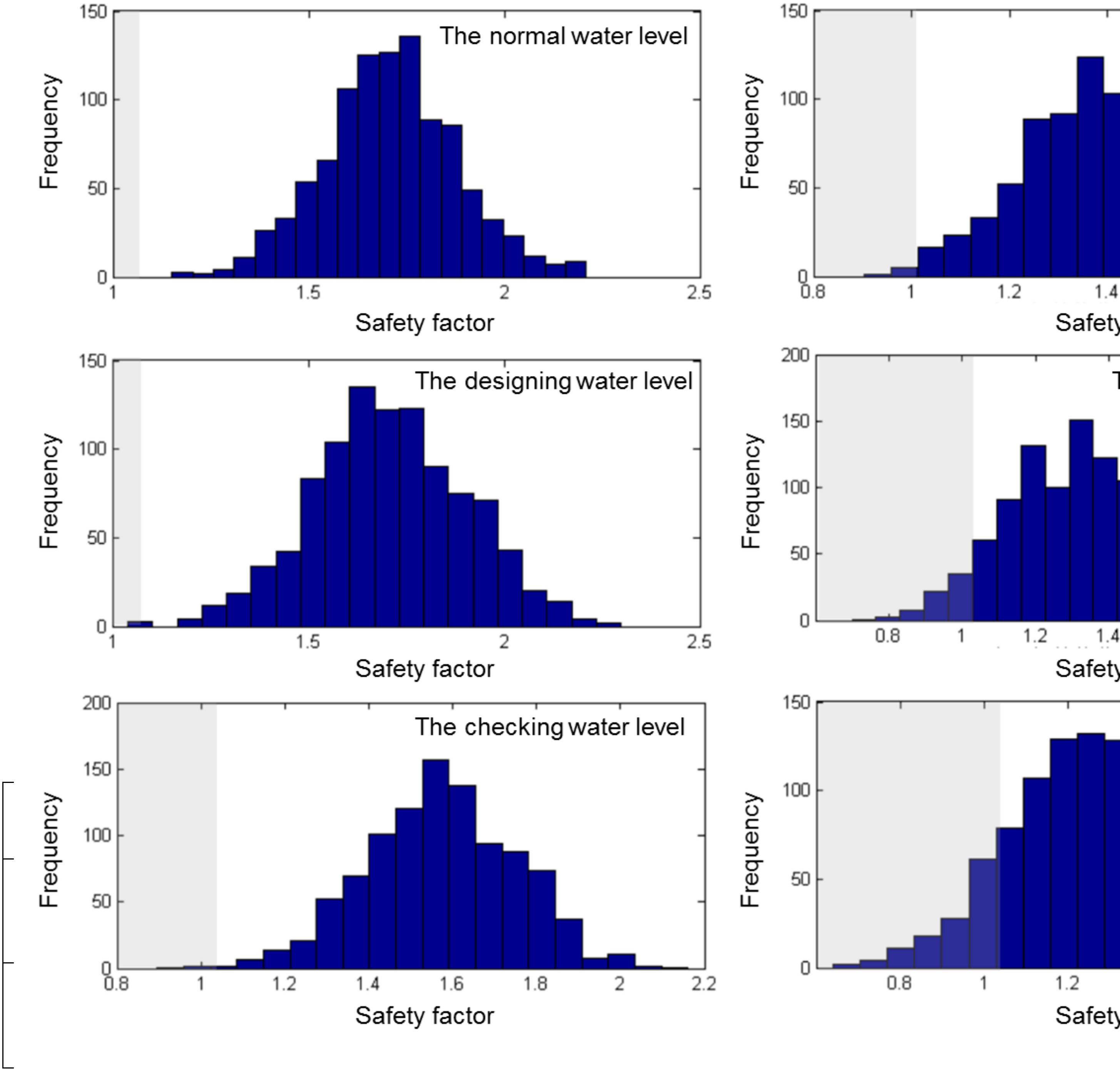


Fig.4: Frequency distribution of the safety factor in 1000 trials of Monte-Carlo simulation. Left column is the cross-section 1, while right column is the cross-section 2.



CONCLUSIONS

Analysis on the seepage stability and structural stability are two key issues that should be considered in earth-rock engineering. In this paper, we discussed a method to solve the above issues. The method is able to provide a solution to determine the hard-to-value seepage coefficient, and also taken into account the spatial and temporal distribution of soil strength. In detail,

(1) For determining the seepage coefficient, the measurement data from the piezo metric tube wer used to calculate the potential value, based on which the seepage coefficient can be back-analyzed. Then the seepage field, as well as the seepage safety were numerically back-analyzed using the FEM-based SEEP/W program.

(2) As to the structural safety, we took into account the spatial and temporal variations of the key parameters, and incorporated the Monte-Carlo simulation method into the commonly used M-P method to calculate the frequency distribution of the obtained structural safety factor. In

this way the probability of dam structural failure can be quantitatively analyzed.

(3) The earth-rock dam of Xiquanyan Reservoir near Harbin city was selected as case study. Both the seepage and structural stability analysis implied that the earth-rock dam was under risk, and reinforce should be required. Reports from local government also supported our analysis that many evidences had been reported showing the water leakage and structural failure of the dam.

This study is also beneficial to provide a mature method and a theoretical insight into the earth-rock dam design.

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REFERENCES

[1] LIU Jie，XIE Ding-song. 2011. Advances of earth-rock dam seepage control theory in China. Chinese Journal of Geotechnical Engineering, 2011, 33(5): 714-718.

[2] JIANG Fan ,MI Yong-ning , ZHANG Ru. 2006. Development of Research on Seepage of Embankment Dam[J]. Journal of Water Resources and Architectural Engineering, 4(4): 94-97.

[3] WU Zhi-wei, SONG Han-zhou, 2015. Numerical simulation of embankment dam seepage monitoring with temperature based on thermal-hydro coupling model. Rock and Soil Mechanics, 2015, 36(2), 584-590.

[4] WANG Jin-yu. 2015. Seepage Control during the construction of rock-earth dam. Technical Supervision in Water Resources, 6, 96-98.

[5] LIU Ying-long, FU Shu-yan, SHENG Tao-zhen, ZHU Kai, ZHANG Kai, 2015. Seepage Safety Status Analysis of Composite Geomembrane Earth-Rock Dam Considering Lag Effect. Water Resources and Power, 33(10), 46-49.

[6] SUN Lin-song, WANG De-xin, PEI Kai-guo. 2000. Stress-Oriented Shape Optimization of Arch Dams[J]. Journal of hohai university, 28(1): 57-60.

[7] Mao Changxi. 2003. Seepage calculation analysis and control. Beijing: China Water Power Press.

[8] Gu Weici. 2000. Seepage calculation principle and application [M]. Beijing: China Building Materials Industry Press.

[9] Li Wei, 2000. Hydraulics. Wuhan: Wuhan University of Hydraulic and Electric Press, 2000.

[10] Wang Junlian. 2004. Groundwater calculation for engineering [M] Beijing: China Water Power Press.

[11] Luo Huanyan, Chen Yusun. 1998. Numerical simulation for groundwater movement [M] Beijing: China Building Industry Press.

[12] Wu Zhongru, Ruan Huanxiang, Chen Dasong. 2002. Dam safety monitoring theory and its application [M] Beijing: China Education Press.

[13] HE Hui-tuan , ZHAO Wei-bing. 2005. Summarization on Study of Earth Pressure. Journal of Water Resources and Architectural Engineering, 3(4):10-14.

[14] Robert P, Chapuis, Djaouida Chenaf. 2001. A user' s approach to assess numerical codes for saturated and unsaturated seepage conditions. Canadian Geo Technical Journal, 38:1113-1126.

[15] LIU Sheng-yao, SHEN Kong-cheng, ZHANG Wei. 2009. Analysis of stability on earth-rock dam under seepage process[J]. China Water Transport, 09(1): 145-147.

[16] HU Hui , DONG Mei , YAO Lei-hua. 2008. Study of safety factor based on the non-differential form of Morgenstern-Price Method. J. Xi‘an Univ .of A rch .& Tech .(Natural Science Edition), 40(2): 201-206.

[17] CHEN Xiang-yang, TUO Tao. 2011. The Gravity Dam Seepage Stability Analysis Based on the SEEP/W. CHINA WATER POWER & ELECTRIFICATION, 81(10): 20-32.

[18] Qian Jiahuan, Yan Zongze. 1996. Geotechnical principles and calculation. Beijing: China Water Power Press.

[19] People's Republic of China Ministry of Water Resources roller compacted embankment dam design specification. 2002. Beijing: China Water Power Press.

[20] Han Z, Chen G, Li Y, He Y. 2015. Assessing entrainment of bed material in a debris-flow event:. A theoretical approach incorporating Monte Carlo method. Earth Surface Processes and Landforms, 41, 1877-1890.

[21] Chen Zuyu. 2003. Soil slope stability analysis - principles, methods, procedures. Beijing: China Water Power Press.

[22] Han Z, Chen G, Li Y, Wang W, Zhang H. 2015. Exploring the velocity distribution of debris flows: An iteration algorithm based approach for complex cross-sections. Geomorphology, 241(0), 72–82.

[23] Han Z, Chen G, Li Y, et al. 2015. Numerical Simulation of Debris-flow Behavior Incorporating a Dynamic Method for Estimating the Entrainment. Engineering Geology, 190, 52–64.

[24] Han Z, Chen G, Li Y, Xu L, Zheng L, Zhang Y. 2014. A new approach for analyzing the velocity distribution of debris flows at typical cross-sections. Natural Hazards, 74(3), 2053–2070.

[25] Han Z, Chen G, Li Y, He Y, Zhang H. 2016. Elementary analysis on the bed-sediment entrainment by debris flow and its application using the TopFlowDF model. Geomatics, Natural Hazards and Risk, in press. DOI: 10.1080/19475705.2014.966868.