The Safety assessment of an earth core dam base on in-situ measurement and back analysis

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Abstract. It is of great significance to get real parameters and real running state of the dam based on back analysis in order to evaluate the dam stability exactly and comprehensively. A back-analysis approach for the parameters of earth-rockfill based the analysis of dam stress, deformation and seepage observation data. After the 3-D back analysis, the real parameters of the dam are determined by simulating the dam construction and operation states with the method proposed. The dam safety is then evaluated in quantitatively according to the proposed criterions.

1 Introduction
There are many uncertainties and even unknown factors that influence the stability of the earth dam. And in-situ monitoring and back analysis is an important means for evaluation dam safety. Researchers such as Shen Zhujiang[1], Portela E[5], E. G.Gaziev[4], Huina Yuan[8], Dongling Si[9] and others[11][12] have made many achievements in evaluation of the dam safety. But the methods on the evaluation of dam safety are still inaccurate and mainly based on experiences. The quantitative evaluation criteria also need to be improved, the main problems in evaluation of the dam safety can be summarized as the follows: (1) Many researchers[3][11][13] are engaged in analysis for the observation data and safety evaluation for concrete gravity dam and arch dam, but for rock-fill dam, due to its complexity of construction materials, relevant analysis theories and methods are needed for further study; (2) How to evaluate the deformation and seepage measurements in the way different from traditional methods such as mathematical statistical approach? (3) How to get the “real” parameters of the dam which must be quite different from the original parameters due to the influences of construction method, construction quality and manage method during and after construction, by back analysis with the consideration of the entire process including construction period and operation period? (4) How to get the “real” stresses, pore pressure and deformation fields of the dam based on the “real” parameters? (5) How to evaluate the dam safety based on not only experience but also the above numerical results: stresses and pore pressure fields by setting up the evaluation criteria for Hei-he earth-fill core dam.

2 Engineering Overview and Construction
2.1 Project Overview
Heihe Jinpeng Water Control Project is the main water source project of Heihe River diversion project in Xi’an. It is a large-scale water conservancy project with urban water supply and comprehensive utilization of irrigation, power generation and flood control. The hub project is located in Xi’an Zhouzhi County within the Heihe Yukou above 1.5km, east of Xi’an City, about 86km. The dam is
designed for Class I buildings with an earthquake intensity of 8 degrees. Dam for the clay core wall gravel dam. Crest elevation \( \nabla \) 600.00m, the maximum dam height of 128.90m.\(^2\)

2.2. Dam Construction and operation process
The dam foundation anti-seepage treatment project was officially started on December 15, 1995, and the closure was successfully realized in October 1998. The main body of the dam was completed on December 25, 2001, and began at 510.0m after the diversion block in November 2000. Of the low water level operation, 2001.1 ~ 2001.12 began to run around 520.0m water level; 2001.12 ~ 2003 began to run at 520.0m ~ 540.0m water level. June 25, 2003 began to gradually stop the water. November 24, 2003 Day to reach the highest water level 590.9m; 2004 annual water level around 585.0m water level, the water level is relatively stable; 2005 ~ 2008 between 582.0 ~ 590.0m run.

3 The Dam Behavior by Observation Analysis

3.1. The Deformation Behaviors of the Dam
According to the dam deformation mechanism, the deformation process of the dam can be divided into three stages, 1) From start filling to complete filling (November 19, 1999 to December 25, 2001), the displacements are mainly due to the dam compression deformation; 2) Later construction (December 25, 2001 to June 9, 2003), the displacements are mainly induced by dam consolidation after filling; 3) Operation period (June 9, 2003 to October 23, 2015), the deformation are mainly caused by wetting of the dam material and seepage pressure from the reservoir water.\(^7\) And the main settlement of the dam is shown in table 1.

| Measuring points | Location | Till December 25, 2001 | Till June 9, 2003 | Till October 23, 2015 |
|------------------|----------|------------------------|------------------|---------------------|
| S1               | Core     | 1083                   | 1173             | 1237.5              |
| S2               | Core     | 1559                   | 1655             | 1750                |
| S3               | Fill-stuff | 475.5              | 475.5            | 475.5              |
| S4               | Fill-stuff  | 114                  | 114.0            | 114                 |
| S5               | Core     | 1165.5                 | 1276.5           | 1329                |

3.2. The Seepage Behavior of the Dam
The observed seepage field of the dam for early stage of the water storage and later operation period are given in figure 1, from which it can be seen, in 2003, because the most part of dam materials is unsaturated, the seepage pressure isoline is concave. From 2004 to 2006, seepage pressure isoline of the dam are gradually convex, which demonstrates a clear characteristics of the steady seepage flow.
4 Back Analysis of the Dam on Measurements

4.1. The Assumption of back analysis
It is assumed that the deformation of grit and pebble fill-stuff material is complete instantaneously; The behavior of core clay material is modeled with Biot consolidation theory with consideration of dissipation process of pore pressure during layered filling construction period, and the top and side of each layer is seemed as drainage boundary and the bottom is seemed as impermeable boundary, and also the unsaturated behavior of clay material is considered by lowering the water modulus in Biot consolidation equation. The constitutive model of Ducan-zhang E-B is introduced to simulate the soil stress-strain relationship.

4.2. Selecting Soil Parameters for back analysis
In the analysis, the constitutive model of Ducan-zhang $E - B$ is adopted which has eight parameters. Since rock-fill dam is made of many materials, so there are too many parameters need to be back analyzed. For simplicity, just four parameters such as $K$, $n$, $K_b$, $m$ of dam material are select for back analysis.

4.3. The Method and Process for Back Analysis
There is a clear temporal and spatial characteristic for dam deformation. The dam is under different loads at different times and it is important to determine counterparts of the deformation and load for back analysis using finite element method. Based on the behavior of the observation data of the Hei-he Dam, the deformation of the dam divided into two parts, the deformation for construction period and the other for operation period, the corresponding load is soil gravity and water effect such as wetting and seepage force.

From the behavior analysis based on observation, the maximum settlement of the dam is 1559mm when filing is completed, it is reached 1655mm in later construction period and the deformation is tend towards immobility before impounding, so the deformation of the dam under soil gravity is 1655mm. The dam deformation is reached 1750mm three years after impounding, also it is tend towards immobility. So the process of back analysis is divided two period with construction period and operation period. For construction period, the back analysis is implement with two steps: (1) Ignoring the time factor, back analyzing the parameters such as $k$, $n$, $K_b$, $m$ with the total construction deformation; (2) And then back analyzing the permeability coefficient of core clay material with the relation deformation, $V_s \cdot t$. For operation period, the back analysis is also implemented with two steps: (1) Assume that basic soil parameters are fixed (parameters including in E-B model), apply the water pressure and get dam
deformation under seepage loads. (2) Get the wetting deformation of the dam with subtracting the dam deformation under seepage loads from the observation of total deformation, then back analyzing the wetting parameters with dam wetting models. The whole process of back analysis is illustrated in figure 2.

4.4. Finite Element Model for Back Analysis
The Heihe reservoir dam is located on the rock foundation, the rock modulus relative to the dam material, can be regarded as rigid body. So it can be set to its vertical and horizontal displacement are zero. This boundary is assumed to be consistent with the bottom of the measured loop on the bedrock during the measured sedimentation data.

5 Evaluation on the Stability of the Dam

5.1. Uneven Settlement of the Dam
The vertical settlement in the horizontal plane of 1/2 dam height along the stream is shown in figure 4, it can be seen that the vertical settlement of the dam is very uneven: the vertical settlement in clay core is larger than that in grit and pebble fill-stuff material. The deformation of the grit and pebble fill-stuff material in dam is completed when dam filling is finished, while the deformation of clay core is still increasing. It can be also seen that grit and pebble fill-stuff material in upstream side of the dam has a obvious wetting deformation, and the maximum wetting deformation reached 200mm.
In order to analyze the uneven settlement and determine whether there is cracks in clay core, a coefficient $\eta$ is introduced as: $\eta = \frac{u_{Y1} - u_{Y2}}{\Delta L}$, where $u_{Y1}$, $u_{Y2}$ are the settlements in different point respectively and $\Delta L$ are the distances between two points. According to many experiences, the cracks will be produced in the clay core when $\eta$ is larger than $0.01 - 0.015$. While the maximum $\eta$ for Heihe dam is not larger than 0.011, and the position of the maximum $\eta$ is located in up middle part of the clay core. So it is justified that there are no cracks in the dam.

5.2. Core Hydraulic Fracturing

Hydraulic fracturing is another important problem to evaluation the stability of the core dam. In order to analyze whether there will be hydraulic fracturing in clay core. Two criteria are introduced: (1) If the total minimum stress is larger than pore pressure, the hydraulic fracturing will not happen in clay core. (2) If effective maximum stress is larger than water pressure at the same elevation, the hydraulic fracturing will not be produced either in clay core. The numerical analysis for Heihe dam indicates that the total minimum stress is larger than pore pressure and the maximum effective stress is also larger than water pressure at the same elevation of Heihe dam, So it is believed the core of the dam there will not have hydraulic fracturing.

5.3. Seepage Stability

To evaluate the seepage stability of the dam, the allowable hydraulic gradient is determined by lab tests. And with permeability coefficient from back analysis, a seepage analysis is executed to reproduce the real dam seepage state and the hydraulic gradient in different zone of the dam are then gotten. The maximum hydraulic gradient in different zone are lower than allowable hydraulic gradient. So the seepage failure will not happen in the dam.

5.4. Stability of Upstream and Downstream Slope

The upstream dam-slope is 1:2.2 and the downstream dam-sloe is 1:1.8. Four load cases is selected to evaluate the dam stability: ① The stability for downstream dam-slope in normal high water level in upstream and normal water level in downstream. ② The stability for downstream dam-slope in normal high water level in upstream and normal water level in downstream under earthquake. ③ The stability for upstream dam-slope in the most disadvantaged water level. ④ The stability for upstream dam-slope in the most disadvantaged water level under earthquake. The searching of most dangerous arcs are executed based on real stress and seepage fields by numerical methods with real parameter. And the Safety factor of the dam slope in different case is allowable.
6 Conclusion

1) The investigation for stress, deformation and seepage behavior by the in-situ measurement in HeiHe core rock-fill dam are executed in this paper and it is indicated that the stress, deformation and seepage behavior is consistent with the general law and the dam safety status is good in qualitatively.

2) Based on study for the in-situ measurement data and the 3-D back numerical analysis, the real parameters are determined by simulating the dam construction and operation states with the method proposed.

3) The real stress, deformation and seepage field during different periods are obtained by the “real” parameters from the back analysis and the safety of the dam is evaluated in quantitatively according to the proposed criterions.

4) The numerical results demonstrate that there are no cracks produced in clay core; and the hydraulic fracturing, seepage failure are neither happen in the dam and finally, the upstream and downstream dam slope are stable.

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