Research on Safety Assessment Method and System of a Heightened Concrete Face Rockfill Dam in Zhejiang Province

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Abstract. In view of many special analysis and long working period of the dam safety appraisal of water conservancy system, taking a heightened concrete face rockfill dam in Zhejiang Province as an example, starting from the analysis of the main impervious structure system affecting engineering safety, comprehensively using safety monitoring, inspection and detection methods, a relatively convenient and efficient dam safety assessment method and system has been established. The evaluation results show that the concrete face rockfill dam can play functional benefits according to design requirements, and the safety condition is good. The evaluation conclusion is of great significance for the reservoir operation management unit to quickly grasp the dam safety traits. The evaluation method and system have reference significance for the continuous development of the dam safety appraisal work in new era.

1. Introduction

At present, hydraulic engineering have undergone a transition from emphasis on their construction and neglect of their management to emphasis on their construction and management in China. With the reduction of the number of new water conservancy projects, the project operation management and reinforcement (maintenance) become more and more important in China. In the 2019 National Water Conservancy Work Conference, Minister E Jingping’s speech entitled “Filling the Short board of Engineering, Paying Attention to Supervision of the Industry, Struggling to Open a New Situation of the Water Conservancy Cause in the New Era” further clarify the key points of future work in the water conservancy industry. Under the background of water conservancy industry in the new era, it is increasingly important to promote the normalization and institutionalization of water conservancy project safety appraisal and evaluation work. It is increasingly important to fully grasp the safety status of water conservancy projects such as the dams. A survey has been organized on the safety appraisal of water conservancy projects in Zhejiang Province. In the future, with the increase in the service life of the dam and the continuous development of safety appraisal, the reinforcement and maintenance of the dam will become the new normal as a means of filling the short board of engineering. For dams that have been reinforced and maintained, it is of great significance for their management unit to quickly
grasp the safety status of the dam. In view of the long working period of the dam safety appraisal of the 
water conservancy system, from the perspective of grasping the main contradiction of the safety of the 
project, a heightened concrete face rockfill dam in Zhejiang Province is taken as an example to explore 
the establishment of its safety assessment method. It provides reference for the safety assessment of 
earth-rock dams, and provides technical support for the reservoir operation management unit to quickly 
grasp the safety status of the dam.

2. Status of Dam Safety Appraisal in Zhejiang Province
With the advent of the new era of water conservancy industry, the dam safety appraisal will be paid 
more and more attention. The first dam safety appraisal should be carried out within 5 years after 
completion acceptance, and every 6-10 years thereafter. At present, the dam safety appraisal of large 
reservoirs in Zhejiang Province has usually been carried out to 2-3 rounds. Some of these reservoirs 
have been reinforced and the safety status of the dam has been greatly improved. Therefore, it will be 
normal for the dam to be identified as the first class of dam in the future. According to the "Guidelines 
for Reservoir Dam Safety Evaluation" (SL258-2017), in each round of the dam safety appraisal, eight 
special analysis methods such as on-site safety inspection and detection, safety monitoring data analysis, 
project quality evaluation, operation management evaluation, flood control capacity review, seepage 
safety evaluation and structural safety evaluation are used to evaluate the dam safety category. There 
are many repetitive tasks in each round of safety appraisal, for example, whether the design of the 
construction content and the construction quality meet the requirements of the current code should be 
evaluated in each round of project quality evaluation, the same parameters are adopted for the calculation 
and analysis of the same structure in each round of seepage and structural safety evaluation, etc. 
Therefore, in view of the main problems in the design, construction and appraisal of dams in previous 
constructions, and the structural characteristics, grasping the main contradictions related to project 
safety to analyze the current situation, reducing repetitive work, the dam safety appraisal work will be 
done with half the effort. In view of this, it is necessary to combine the historical and structural 
characteristics of the project to explore the establishment of a convenient and efficient dam safety 
assessment method, which is of great significance for the future dam safety appraisal work method and 
for the reservoir management unit to quickly grasp the dam safety traits. This paper takes a heightened 
concrete face rockfill dam in Zhejiang Province as an example to explore the establishment of 
convenient and efficient dam safety evaluation method.

3. Project Overview
The crest elevation of the concrete face rockfill dam is 121.50m, the top elevation of the wave wall is 
122.77m, and the maximum dam height is 70.2m. The dam body is composed of the original clay core 
wall sand dam area and the elevated area. The 0.8m thick concrete cutoff wall is set for seepage control 
in the core wall of the original clay core wall sand dam below elevation 99.77m, and the 0.3m 
thick reinforced concrete face is set for seepage control on the upstream side of the dam above elevation 
99.77m. The concrete cutoff wall and the concrete impervious facing are connected through the bottom 
toe slab of the face and water stop are set between the head of concrete cutoff wall and the toe slab. The 
upstream slope of the dam above elevation 99.77m is the concrete impervious facing and its area below 
elevation 99.77m is the upstream slope of the original core wall sand dam. The downstream dam slopes 
have three-level berms at elevations of 102.42m, 85.40m and 68.40m respectively.

4. Establishment of Dam Safety Assessment Methods and Systems
According to the special analysis of the dam safety appraisal, on-site safety inspection and detection, 
deformation and seepage monitoring data analysis, and flood control capacity review are the core basis 
for the safety assessment conclusion. As far as the assessment object is concerned, the dam's impervious 
structure system is the focus of the assessment. According to the structural characteristics of the concrete 
face rockfill dam, the impervious structural system consists of wave wall, concrete impervious facing, 
toe slab, water stop system of parting, clay core wall and concrete cutoff wall. Therefore, it is the key to
comprehensively and accurately evaluate the current status of the impervious structure system by using various safety monitoring, inspection and detection methods and means. According to the above ideas, the safety assessment method and system of the concrete face rockfill dam are shown in Figure 1.

![Figure 1. Dam safety assessment methods and systems](image)

5. Safety Assessment of the Heightened Concrete Face Rockfill Dam

5.1. On-site Safety Inspection and Detection

On-site safety inspection and detection mainly adopts the combination of traditional methods such as eye, ear, hand touch and measurement and 3D laser scanning of the dam with Trimble TX8. The evaluation object is the external impervious structure and overall structure of the dam. The conclusions are as follows:

1. Investigation on the Remaining Problems of the Completion Acceptance of the Concrete Face Rockfill Dam: no historical problems.

2. External Impervious Structure: The wave wall has no abnormalities such as cracking, crushing, overhead, breaking and tilting. The surface of the concrete impervious facing above elevation 99.77m is flat, the structure is basically intact, and there is no uneven settlement. Vertical fracture and peripheral joint’s opening displacement, settlement displacement and shear displacement is normal. The SR cover sheet of surface water stop of vertical fracture is partially damaged and aged. Stainless flat steel fixing the SR cover sheet of surface water stop of vertical fracture between the head of concrete cutoff wall and the bottom toe slab of the 24th concrete impervious facing is distorted. The 59 cracks of the concrete impervious facing found in 2005 did not continue to deteriorate. In this inspection, 13 new hairline cracks were found. Most of the cracks were located in the middle of the concrete impervious facing. The crack shape is longitudinal, the crack is long, and its width is 0.10~0.15mm.

3. Overall Structure of the Dam: Abnormal deformation such as cracks, depression and damage were not be found on the top and the slope of the dam. Dankness, seepage, soil flow, piping and uplift were not found in the dam toe area. Volume, color and temperature of seepage water, etc. were normal at the downstream cutoff wall. There were no cracks, collapse pits, seepage water, ant caves, beasts, etc. in the end zone of the dam. Cracks, collapse and slide were not found on bank slope of the end of the dam. 3D laser scanning with Trimble TX8 was used for review of three-dimensional body shape of the dam as shown in Figure 2. According to extraction and analysis of the data of the scanning point cloud, small difference was shown between this review and the original design at crest elevation of the dam,
top elevation of the wave wall, crest elevation of the original clay core wall sand dam, elevation of three-level berms of the downstream dam slopes, and dam slope ratio. It shows that the current dam body shape can meet the design requirements.

Figure 2. Point cloud of 3D laser scanning of the concrete face rockfill dam

5.2. Flood Control Capability Review

According to higher design flood level and check flood level, considering wave run-up, banked-up water levels of wind, safety height, wave height, height difference of the wave center line and safe superelevation, the top elevation of the wave wall and the concrete face rockfill dam were reviewed as shown in Table 1. The measured crest elevation of the concrete face rockfill dam is $121.45 \sim 121.52$ m, which is higher than the check flood level ($P=0.01\%$) $119.73$ m, which is higher than required crest elevation $119.03$ m of the dam under normal operation conditions. The measured top elevation of the wave wall is $122.73 \sim 122.77$ m, which is higher than its calculated value. From the results of flood control capability review, the top elevation of the wave wall and the concrete face rockfill dam can meet the requirements of flood control safety.

Table 1. The results of flood control capability review of the concrete face rockfill dam

| Conditions             | Design flood level+ Superelevation of normal operation | Normal water level + Superelevation of normal operation | Check flood level+ Superelevation of abnormal operation |
|------------------------|--------------------------------------------------------|--------------------------------------------------------|--------------------------------------------------------|
| Highest flood water(m) | 118.53                                                  | 109.67                                                  | 119.73                                                  |
| Total superelevation(m)| 3.22                                                    | 6.09                                                    | 1.91                                                    |
| The required crest elevation of the dam(m) | 119.03                                                  | 110.17                                                  | 119.73                                                  |
| The required top elevation of the wave wall (m) | 121.75                                                  | 115.76                                                  | 121.64                                                  |
| The measured crest elevation of the dam(m) | 121.45$\sim 121.52$                                     |                                                         |                                                         |
| The measured top elevation of the wave wall (m) | 122.73$\sim 122.77$                                     |                                                         |                                                         |

5.3. Seepage Monitoring Data Analysis

Seepage discharge of the concrete face rockfill dam is monitored by right triangle measuring weir set at cutoff wall in Dam Foundation. The safety status of external and internal impervious structure of the dam are evaluated through hydrograph analysis of seepage discharge, correlation analysis between reservoir water level and seepage discharge and analysis of seepage discharge statistical model.
(1) Hydrograph of seepage discharge of the dam is shown in Figure 3. The correlation between reservoir water level and seepage discharge is obvious. The seepage discharge of the dam is basically consistent with the change of the reservoir water level, which is positively correlated, and the seepage discharge is obviously affected by the rainfall. Since 2013, the seepage discharge of the dam keeps steady and has not increased significantly.

(2) After eliminate the effect of rainfall on seepage discharge(considering hysteresis effect of rainfall on seepage discharge is small, the monitoring value of seepage discharge with zero rainfall on the day of monitoring and the previous day to the first four days is selected), correlation between reservoir water level and seepage discharge is shown in Figure 4. The seepage discharge of some scatter points is abnormally large, and there are 8 points with large seepage discharge (excluding the point where the rainfall is zero on the day of monitoring and the previous day to the first four days), which occurred from February 25, 2016 to March 5, 2016 and from July 6, 2016 to July 7, 2016. According to the investigation and analysis, the large seepage discharge from February 25, 2016 to March 5, 2016 is mainly related to the water level in cutoff wall affected by exorbitant water level of Bibo Lake in the dam toe area during the monitoring period. The large seepage discharge from July 6, 2016 to July 7, 2016 is mainly related to the water level in cutoff wall affected by exorbitant water level of downstream river course when the spillway discharges flood during the monitoring period.

In general, the reservoir water level is positively correlated with the seepage discharge of the concrete face rockfill dam, and the seepage discharge increases with the increase of the reservoir water level. When the reservoir water level is less than 97m, the slope of the relationship curve is small, indicating that the increase of seepage discharge is not sensitive to the increase of reservoir water level. When the reservoir water level is greater than 97m, the slope of the relationship curve is larger than the reservoir water level less than 97m, indicating that the increase of seepage discharge is more sensitive to the increase of reservoir water level than the reservoir water level less than 97m. In general, when the
reservoir water level is greater than 97m, the slope of the relationship curve does not increase significantly with the increase of the reservoir water level, and remains stable. According to the on-site safety inspection, no abnormal phenomena such as turbidity in cutoff wall were found, indicating that the dam’s impervious structure system works normally. Another consideration is that the dam has experienced elevation, the concrete cutoff wall is set for seepage control in the core wall of the original clay core wall sand dam below elevation 99.77m, and the concrete face, toe slab and water stop system of parting are set for seepage control above elevation 99.77m. The anti-seepage performance of the joint between the head of concrete cutoff wall and the bottom toe slab of the face should be focused on. According to the relationship curve, when the reservoir water level exceeds the elevation of 99.77m, the seepage discharge of the concrete face rockfill dam does not increase suddenly, and the slope of the curve does not change significantly, indicating that the anti-seepage performance of the joint between the head of concrete cutoff wall and the bottom toe slab of the face is working normally.

(3) The seepage discharge of earth-rock dams is mainly affected by the upstream and downstream water depth, rainfall infiltration, siltation before dam and time-varying process of anti-seepage body. Since the earth-rock dam material (dam body and dam foundation) changes little with temperature, the temperature component is generally not considered, and the statistical model of seepage discharge of earth-rock dam is:

\[
Q = a_0 + \sum_{i=1}^{2} a_u (H'_1 - H'_1) + \sum_{i=3}^{6} a_u (\overline{H}_{11} - \overline{H}_{10}) + a_d H_2 \\
+ \sum_{i=1}^{5} d_i (\overline{p}_i - \overline{p}_o) + c_1 (\theta - \theta_o) + c_2 (\ln \theta - \ln \theta_o)
\]

In the formula: \(a_0\) is a constant term. \(a_u\) —Regression coefficient of upstream water depth component( \(i = 1 \sim 6\)); \(H_1\) —Upstream water depth in the monitoring day; \(H_{10}\) —Upstream water depth on the initial monitoring day; \(\overline{H}_{11}\) —The average upstream water depth of the first day, the first two days, the first three to four days, and the first five to fifteen days before the monitoring day( \(i = 3 \sim 6\)); \(\overline{H}_{10}\) —The average upstream water depth of the first day, the first two days, the first three to four days, and the first five to fifteen days before the initial monitoring day( \(i = 3 \sim 6\)); \(a_d\) —Regression coefficient of downstream water depth component; \(H_2\) —Downstream water depth in the monitoring day. \(d_i\) —Regression coefficient of rainfall component( \(i = 1 \sim 5\)); \(\overline{p}_i\) —Average rainfall of the monitoring day and the first day, the first two days, the first three to four days, and the first five to fifteen days before the monitoring day( \(i = 1 \sim 5\)); \(\overline{p}_o\) —Average rainfall of the initial monitoring day and the first day, the first two days, the first three to four days, and the first five to fifteen days before the initial monitoring day( \(i = 1 \sim 5\)). \(c_1\), \(c_2\) —Regression coefficient of aging; \(\theta\) —The cumulative number of days \(t\) from the monitoring day to the initial monitoring day divided by 100; \(\theta_o\) —The cumulative number of days from the monitoring day to the initial monitoring day of the modeling data sequence divided by 100.

The modeling period of the seepage discharge monitoring data of the concrete face rockfill dam is from August 2013 to April 2018. The stepwise regression analysis method is used to establish a regression model for the seepage discharge monitoring data by the formula (1). The regression coefficient and complex correlation coefficient (R) of the seepage discharge monitoring point regression model are shown in Table 2. The measured value, fitting value and aging process line of seepage discharge are shown in Figure 5.
Table 2. The regression coefficient and complex correlation coefficient of the seepage discharge statistical model of the dam

| Regression coefficients | Monitoring points |
|-------------------------|-------------------|
| Name                    | Coefficient number | WE1   |
| Constant term           | $a_0$             | -2.335|
| Upstream water level    | $a_{u1}$          | -7.872|
| Average water level of the first day before the monitoring day | $a_{u2}$ | 0.046 |
| Average water level of the first two days before the monitoring day | $a_{u3}$ | 0.944 |
| Average water level of the first three to four days before the monitoring day | $a_{u4}$ | / |
| Average water level of the first five to fifteen days before the monitoring day | $a_{u5}$ | -0.959 |
| Downstream water level  | $a_d$             | /     |
| Average rainfall of the monitoring day | $d_1$ | 0.082 |
| Average rainfall of the first day before the monitoring day | $d_2$ | 0.177 |
| Average rainfall of the first two days before the monitoring day | $d_3$ | 0.078 |
| Average rainfall of the first three to four days before the monitoring day | $d_4$ | 0.021 |
| Average rainfall of the first five to fifteen days before the monitoring day | $d_5$ | 0.058 |
| $\theta-\theta_0$       | $c_1$             | -0.193|
| $\ln \theta-\ln \theta_0$ | $c_2$ | 0.976 |
| Complex correlation coefficient | R | 0.893 |

Figure 5. The measured value, fitting value and aging process line of seepage discharge of the concrete face rockfill dam

The complex correlation coefficient R of the seepage discharge statistical model is 0.893, and the regression model has high precision. The upstream water level, rainfall and aging factors were selected in the regression model, indicating that the upstream water level, rainfall and aging have different effects on the seepage discharge of the dam. The overall variation of the aging component from 2013 to 2018 is stable, indicating that the dam seepage discharge changes stably and the impervious structure system of the dam works normally.
5.4. Deformation Monitoring Data Analysis
A one-direction, two-direction and three-direction joint meter is installed between the bottom toe slab of the face and the head of concrete cutoff wall, the left and right bank concrete impervious facing and the toe slab, and the bottom of the face and the toe slab to monitor opening displacement, settlement displacement, shear displacement of the joint. Joint deformation directly affects the operation of the water stop system. External deformation monitoring points are buried in the dam crest and downstream dam slope, and the overall external deformation of the dam is reflected by settlement and horizontal displacement monitoring. Through the deformation monitoring data analysis, the safety of water stop system and overall structure were evaluated.

(1) Water stop system of the concrete face: According to the analysis of joint deformation monitoring data, the joint’s opening displacement, settlement displacement and shear displacement between the panel, the toe slab and the head of cutoff wall are stable, and the deformation values are all within the normal range, indicating the joint deformation will not adversely affect the water stop system of the concrete face.

(2) The overall structure of the dam: the external vertical displacement and horizontal displacement of the dam are stable, the deformation values are within the normal range, and the overall deformation is coordinated.

5.5. Safety assessment conclusion
(1) The concrete face, SR cover sheet of surface water stop and the stainless flat steel have local defects, and the overall appearance quality is good.

(2) The dam deformation is stable and coordinated, and the magnitude is within the normal range, which is in line with the general law of dam deformation.

(3) The top elevation of the wave wall and the concrete face rockfill dam can meet the requirements of flood control safety.

(4) The seepage discharge of the concrete face rockfill dam is stable and the value is within the normal range. When the reservoir water level is less than 97m, the slope of the relationship curve between the reservoir water level and the seepage discharge is small and stable. When the reservoir water level is greater than 97m, the slope of the relationship curve slightly increases compared with the reservoir water level less than 97m. As the reservoir water level rises, the slope of the relationship curve remains stable and there is no significant increase. When the reservoir water level exceeds the crest elevation 99.77m of the original clay core wall sand dam, the seepage discharge of the concrete face rockfill dam does not increase suddenly, and the slope of the relationship curve has no obvious change. In addition, According to the on-site safety inspection, no abnormal phenomena such as water turbidity in cutoff wall were found, indicating that the anti-seepage performance of the joint between the bottom toe slab of the face and the head of the cutoff wall is normal, and the dam anti-seepage system works normally.

In summary, the elevation 99.77m joint of anti-seepage structure and the overall anti-seepage structure of the heightened concrete face rockfill dam are normal, the overall appearance quality of the dam is good, the deformation of the dam is within the normal range, and the deformation is stable and coordinated. The top elevation of the wave wall and the concrete face rockfill dam can meet the requirements of flood control safety. The above indicates that the dam can function as a design and the safety condition is good.

6. Conclusion
(1) In this paper taking a heightened concrete face rockfill dam in Zhejiang Province as an example, from the perspective of the main contradiction of project safety, through investigating the historical legacy problems of project in design, construction, stage acceptance and safety appraisal and in-depth analysis of the impervious structure composition related to dam safety, the dam safety status is evaluated comprehensively using safety monitoring, inspection and detection methods. The evaluation results show that the concrete face rockfill dam can play functional benefits according to the design
requirements, and the safety condition is good. The evaluation conclusion is of great significance for the reservoir operation management unit to quickly grasp the dam safety traits.

(2) In view of many special analysis and long working period of the dam safety appraisal of water conservancy system, combining with the dam legacy problems research and its structural characteristics, a relatively convenient and efficient dam safety assessment method and system has been established. The evaluation method and system have reference significance for the continuous development of the dam safety appraisal work in new era.

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