Defect Detection and Cause Analysis of Steel Tube Tunnel in Storage Power Station

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Abstract. Defects of draft tube such as void between steel liner and concrete will be formed for the influence of complex environment, resulting in the reduction of its bearing capacity. According to the characteristics of draft tube defects, a fast testing and evaluation method for draft tube structural defects was proposed combined with elastic wave imaging method. Taking the draft tube of a storage power station in Fujian Province as the research target, the field test was carried out using elastic wave test. Combined with waveform visualization and K-means clustering analysis method, the image recognition method was proposed, and defect types and distribution of the draft tube were obtained. Compared with results of the three-dimensional scanning, there is good consistency in the distribution of defects. An analysis was performed on the circumferentially coalescence area of the voids, and it is found that the load-bearing capacity of the draft tube in this area is reduced, the pressure it bears is greater than its own resistance, forming several cavities with large deformation.

1. Introduction

China is rich in hydropower resources. A large number of hydropower stations were built after 1950[1]. Draft tube of storage power station is vulnerable to adverse geological environment, leading to the deformation, cracking, void and other defects of draft tube, which has an impact on safety[2]. The damage effect of void on the draft tube structure is particularly obvious, which will greatly reduce the shear capacity of the tube. Under the external load (soil pressure), the draft tube will be destroyed with large deformation[3].

In hydropower engineering, the steel tube-concrete structure is often used in draft tube. However, the connection between the inner surface of the steel tube and the concrete is weak[4]. On the other hand, the steel and concrete have great differences in thermal expansion and cold shrinkage, and the deformation is incompatible[5]. In the long-term operation process, the concrete is easy to produce cracks, and the steel tube and concrete form a separation phenomenon. The draft tube structure is usually in a complex environment, the external water and air enter the gap between the steel tube and concrete through cracks, and finally form a large displacement under the action of large stress, leading to the damage of the draft tube[6,7].

For the detection of draft tube defects, a large number of scholars have carried out relevant research and proposed different detection methods in recent years, including manual knocking method, core drilling sampling method, surface wave method, optical fiber sensing monitoring and ultrasonic method[8,9]. Among them, the manual percussion method relies on the subjective judgment of technical
personnel and lacks the guidance of theoretical basis. Although core drilling sampling method can accurately detect defects, it can’t be used for mass monitoring and is usually used as the confirmation of other non-destructive testing methods[10]. For optical fiber sensing monitoring method, optical fibers should be embed in the construction process, which is expensive and not used for large area detection[11]. For surface wave method, the characteristic that the low-frequency harmonic component is easy to diffract based on the difference between the spectrum change of transmission wave and reflection wave, and the spectrum change of transmission pulse is used to invert the damage degree of defects. The scope of voids and void defects can be determined by counting the change of neutron count rate in the test position and combining with indoor calibration test[12].

Based on the basic principle of elastic wave propagation and cluster analysis, a fast detection and evaluation method of draft tube structure defects was proposed. At the same time, the field test was carried out to determine the distribution of defects and verify it with three-dimensional scanning. And the causes of formation and damage of draft tube defects were analysed.

2. An overview of draft tube project in storage power station

2.1. An overview of engineering geology and draft tube design

The storage power station is located in Putian, Fujian Province (25.5°N, 118.6°E). The installed capacity of the power station is 1200mW (4 × 300mW). The power station hub is mainly composed of upper reservoir, water conveyance system, underground powerhouse system, switch station and lower reservoir. According to the engineering geological exploration, the overburdens in this area are plain fill (Q₄m₁), silty clay (Q₄de₁) and tufflava (J₃nb). The tailrace system is composed of tailrace steel branch pipe, Tailrace Gate tunnel, tailrace bifurcated pipe, tailrace surge chamber, tailrace tunnel, lower reservoir inlet and outlet, as shown in Figure 1. The length of tailrace steel pipe is 108.0m, the buried depth is about 108m, and the inner diameter is 4.8m.

2.2. Defect investigation

There is an obvious surface deformation for the draft tube in long-term service, and the surface bulge is about 30 cm. First of all, 3D laser scanning was carried out in the tube. It has a scanning speed of up to 500,000 points per second with 360° × 270° full field of view to obtain the coordinate data of the tube. The 3D scanning results of the left side and right side of the tube were analyzed, where the distance is 22 meters, as shown in Figure 2. There is obvious deformation in the range of right side (distance: 15-20m, length: 2-4m), the maximum relative deformation is 0.28m, and there is some deformation in the range of left side (distance: 15-20m).

Figure 1. An overview of draft tube design.

Figure 2. General situation of draft tube and Section of draft tube.

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3. Field test of draft tube tunnel

3.1. Testing principle and method
When an excitation is applied to the position of $S_i$ ($i=1,2,3...n$) on the surface of the draft tube, the elastic wave field which is closely related to the internal structure of the medium and the physical properties of the medium will propagate in the medium, as shown in Figure 3. The reflection coefficient of the reflected wave is determined by the difference of the wave impedance. When the internal structure of the medium changes, such as cracks or voids inside, forming a reflective interface, and the received waveform response energy received by the geophone at a point $R_i$ ($i=1,2,3...$) will become higher[13].

3.2. Equipment and survey line
The detection system consists of digital seismic recorder, velocity detector and coupling device, notebook computer, connecting cable, excitation device, power supply, etc. The detection site is shown in Figure 4. The draft tube with distance of 22m was selected as the study area, and the distance between detection points was 25cm. A total of 18 survey lines and 1167 measuring points were arranged on the side wall, top and bottom of the tube. The survey lines are shown in Figure 4.
3.3. Test results
The data acquisition offset is 0.2m, and the sampling interval is 20.833μs, the recording time is 0.1s, and the sampling delay is 0.004s. The waveform was gridded using image processing. The value of elastic wave in each grid represents the energy of the grid. The value of the grid between the wave crest and the wave trough is proportional to its distance to the central axis. Taking line 4 as an example, the collected elastic wave signal was visualized, and the waveform visualization results were obtained, as shown in Figure 5. It can be seen that the elastic wave response presents great differences in different positions, which corresponds to the results of 3D scanning. It is obvious that in the large deformation area, the response of elastic wave field is obviously amplified.

4. Cause analysis of defects in draft tube tunnel

4.1. Defects distribution in draft tube tunnel
In order to quantitatively evaluate the defect distribution, the K-means clustering method is used to classify the elastic wave response energy values of 1167 detection points. The threshold values in the study area are 9.0 and 11.0, which can be considered to represent three states: health state, void and cavity. The response energy value between 0-9 is defined as health state, the response energy value between 9-11 is defined as crack and void, and the response energy value greater than 9 is defined as cavity. There is a large area of continuous defects in the study area, especially in the range of 16-20m. Compared with the 3D scanning results, the void and cavity areas are consistent, and the error is small.
4.2. Simple analysis of defects causes
An analysis was performed on the circumferentially coalescence area of the voids. In the water deliveries stage, the draft tube bears the water pressure in the tube and the external earth-water pressure, as shown in Figure 7. Ignoring the effect of soil cohesion, the earth-water pressure on draft tube is about 0.96MPa. Due to the long-term influence of underground water, cracks begin to appear in the concrete and voids gradually form between the concrete and the steel plate. When the draft tube is in the stage of water cutoff, it only bears the effect of external earth-water pressure:

$$\sigma_R \cdot d < \sigma_a \cdot r$$

(1)

where $\sigma_R$ is the resistance limit of draft tube, $\sigma_R$=179.69MPa in the project, $d$ is the thickness of draft tube steel plate, $d$=25mm in the project, $\sigma_a$ is the earth-water pressure, $r$ is the diameter of draft tube, $r$=6.0m in the project. In the area where there are many cracks and voids in the draft tube, the external pressure is greater than the draft tube resistance, the draft tube steel will be destroyed (large deformation) with partially or completely coalescence for the voids along the outside of draft tube, as shown in Figure 8.

Figure 7. Simple analysis of defects cause.

Figure 8. Formation process of draft tube defects.
5. Conclusion

(1) According to the characteristics of draft tube structure, a fast testing and evaluation method of draft tube defects was proposed based on the propagation characteristics of elastic wave in layered media and the idea of cluster analysis.

(2) The field test was carried out, and the elastic wave method was used to detect and evaluate the distribution of draft tube defects. The distribution error is small with good consistency compared with the three-dimensional scanning results.

(3) An analysis was performed on the circumferentially coalescence area of the voids, and it is found that the load-bearing capacity of the draft tube in this area is reduced, the pressure it bears is greater than its own resistance, forming several cavities with large deformation.

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