Valley deformation and Stability assessment of Plunge Pool slope

Xu ZHANG\textsuperscript{1,2}, Shaowu ZHOU\textsuperscript{3}, Haibo DUAN\textsuperscript{4}, Wendu LI\textsuperscript{5}, Cheng ZHANG\textsuperscript{6}

\textsuperscript{1}Postdoctoral Centre, China Three Gorges Corporation, Beijing, P.R.China
\textsuperscript{2}Department of hydraulic engineering, Tsinghua University, Beijing, P.R.China
\textsuperscript{3}Shanghai Investigation, Design & Research Institute Co., Ltd., Shanghai, P.R.China
\textsuperscript{4}China Yangtze Power Co., Ltd. Yichang, Hubei Province, P.R.China
\textsuperscript{5}Yangtze Three Gorges Technology & Economy Development Co., Ltd., Kunming, P.R.China
\textsuperscript{6}China Gezhouba Group Machinery and Ship Co., Ltd, Yichang, P.R.China

Corresponding author’s e-mail: 1228086003@qq.com

Abstract. In order to study the valley deformation and rock mass stability of plunge pool slope at the Wudongde hydropower station. We analyzed the deformation law of valley base of site displacement monitoring. Based on the finite element method, the slope stability of different typical profiles on both banks and valley deformation is investigated. The numerical and monitoring results of deformation have a good consistency, and demonstrate that excavating and other perturbations can quicken the creep deformation of rockmass. Through deformation monitoring combined with simulation, rock mass stability analysis and evaluation are reasonable. The nonlinear large deformation of rock mass is considered, and the slope safety factor is obtained quickly. Meanwhile, it is convenient to simulate the instability state and failure process of sliding surface with any landscape and arbitrary shape as well as intuition and applicability.

1. Introduction
Since the 1980s, hydropower station such as lijiaxia (165 m), lashiwa (250 m), ertan (245 m), xiaowan (292 m), xiluodu (278 m), and jingping first stage (305 m) \textsuperscript{[1]}, have built a large number of super-high arch dams in the western part of China where is rich in hydropower resources. Valley deformation is a common problem faced by high arch dams. For one thing, due to the complex topography and geological conditions in the dam site area, both the magnitude and gradient of mountain crustal stress value are large \textsuperscript{[2]}. For another thing, the engineering scale is large, the waterhead is big, the water filling process disturbance is intense. The disturbance of natural slope body, such as slope excavation \textsuperscript{[3,4]} and reservoir water level change \textsuperscript{[5]}, will accelerate the deformation of the slope, and various preliminary unconsidered or potential defects will gradually appear \textsuperscript{[6,7]}. Yang jie et al. \textsuperscript{[8]} attributed the valley deformation of li jixia arch dam to the contraction of the fracture zone of rock mass, the increase of seepage pressure and the reduction of rock mass parameters. Jia jinsheng et al. \textsuperscript{[9]} believed that the rheological deformation of lower part of the mountain caused by engineering disturbances such as excavation and water storage were the dominant factor of valley amplitude deformation. Zhang jinlong et al. \textsuperscript{[10]} analyzed the deformation law of Jinping slope rock mass during construction.
period. Liu caihua et al. [11] summarized the effect of pore pressure and sliding surface strength reduction on the reservoir basin. Yang qiang et al. [12] had made a preliminary study and discussion on the deformation mechanism of high-arch dam valley.

2. Geology Conditions
The water cushion pool is located after the arch dam of Wu dongde hydropower station in Yangtze river. The slope of the pool is on both sides of the mountain after the dam. The strata distribute Pt21~Pt216. The stratigraphic lithology is the medium and thick layers of limestone, marble clip a thin layer of limestone, the massive layer of dolomite, thin and interbed dalitic dolomite marble and a small amount of phyllite. The strata strike intersects with the slope strike at a large Angle. The strata dip Angle is 60° to 80°, general tendency to downstream. Limestone, marble, dolomite and so on in Pt21~ are slightly new in shape, only the extremely thin and thin layer of dalitic dolomite in Pt21 and phyllite Pt21~ are weakly weathered of subzone rock mass. The horizontal depth of the natural slope’s strong unloading lower limit is generally 5 m to 20 m, and there is no obvious strong unloading in the lower part. The horizontal depth of the weak unloading zone is usually 15 m to 35 m, and the horizontal unloading depth decreases gradually from top to bottom.

3. Deformation Monitoring And Analysis Of Valley
The superposition of the horizontal deformation value of the slope monitoring point with the same elevation but the opposite direction of the canyon is the amplitude deformation of the high arch dam in gorge area. Three effective displacement monitoring points are selected which are located on the 988 m elevation of both sides of the plunge pool, and they are TP01, TP02 and TP06. Since the points are not completely opposite to each other, two valley amplitude measuring lines are set. Valley amplitude survey line 1 is formed by TP01 and TP02, and the line 2 is TP02 and TP06, as shown in Figure 1.

Figure 1. Layout of valley survey line in plunge pool after dam.
The sum of the absolute value of the horizontal displacement of TP02 point on the left bank and TP01 point on the right bank is equivalent to the valley amplitude of line 1. Similarly we can option the valley amplitude of line 2. The first monitoring time is August 2016. The valley amplitude deformation process of the two survey lines is shown in Figure 2. The valley amplitude is positive and increasing, indicating that the rock masses on both sides of the area are deformation towards the space, showing the trend of valley amplitude contraction deformation. The variation laws of the two lines are similar and have good consistency, the survey line 1 is slightly larger than that of survey line 2. But the deformation value of valley amplitude at the height of 988 m after the dam shows a trend of gradual increase without water storage in recent two years, and the current maximum is about 20 mm.

4. Slope Stability Analysis

4.1. Excavation scheme and numerical model

The elevation of the slope horse road on both sides of the plunge pool is consistent with that of the dam abutment. From bottom to top, the elevation is 735 m, 765 m, 795 m, 825 m, 885 m, 915 m, 945 m and 975 m, respectively, the width is 2.5 m, except the 825 m and 855 m road with the addition of the left bank elevation 900 m upstream horse road are 6 m. The slope excavation ratio is set as follows along the topography below the elevation of 855 m, which is 1: 0.1 to 1: 0.4. The slope excavation ratio above the elevation of 855 m should be as steep as possible to reduce the slope excavation height. However, considering that the upper part is mainly a strong unloading rock mass, the excavation slope ratio is designed as no less than 1:0.1, and the maximum elevation of the opening line on both sides is about 1000 m.
According to the engineering geological conditions of the plunge pool slope, concurrently consider the outcrop location of geological section and the slope shape as well as preliminary research results of the distribution of atomization rain, two typical profiles of SDT2-2' and SDT6-6' of the plunge pool are selected to establish a two-dimensional numerical analysis model. Based on saturated/unsaturated seepage and stress coupling theory of finite element analysis, the deformation, stress, seepage state and distribution of plastic zone of the working conditions of natural, the slope excavation, flood discharge atomization, water drop and the earthquake are analyzed. The strength subtraction method and Morgan Stanley rigid body limit equilibrium method are both used for solving the safety factor of slope under various conditions. The calculation results of the two methods are used to evaluate the overall stability of the plunge pool slope. The calculation models are shown in Figure 3 and 4.

4.2. Stability analysis and calculation
The finite element method is used to calculate the stability of the dam plunge pool slope. The rock mass is considered as an ideal elastoplastic model, the Mohr-Coulomb criterion is used as the yield function of the constitutive model. The distribution of plastic zone in different sections under different working conditions is shown in Figure 5 and 6.

In the excavation working condition, under the influence of unloading, the rock mass of the slope produces the deformation outward from the slope, and the deformation is mainly caused by unloading rebound. Through the strength reduction analysis, the instability mode of the plunge pool slope in the limit state is mainly the integral sliding of the strong unloading rock mass along the lower interface.
Based on the stable state after excavation and the forecast analysis of flood discharge atomization, the slope deformation caused by flood discharge atomization is mainly concentrated in the rock mass of the shallow strong unloading zone and the weak unloading zone, and the incremental deformation is mainly horizontal. Under the condition of limit state, the range of plastic zone of the slope expands continuously, the existing plastic zone produced by the excavation condition extends from the foundation to the interface of the inner part, the strong unloading zone and weak unloading zone. At the same time, the plastic yield degree is increasing, and so as the maximum equivalent strain value.

The condition of water plummet is that the designed flood water level in the downstream drops from 846.36 m to 825.5 m. In this condition, the slip path of the engineering slope is basically consistent with that in the excavation condition. The stability of engineering slope is analyzed by time-history method and quasi-static method respectively under seismic conditions. The failure mode of slope instability obtained by the quasi-static method is basically the same with the time-history method, but the safety coefficient is small.

### Table 1. Safety factor of plunge pool slope.

| Calculation conditions | Left bank SDT2-2' | Left bank SDT6-6' | Right bank SDT2-2' | Right bank SDT6-6' |
|------------------------|-------------------|-------------------|-------------------|-------------------|
|                        | strength reduction| limit equilibrium | strength reduction| limit equilibrium | strength reduction| limit equilibrium | strength reduction| limit equilibrium |
| Excavation             | 1.87              | 2.16              | 2.42              | 2.63              | 2.23              | 2.38              | 1.81              | 2.04              |
| Flood discharging atomization | 1.44              | —                 | 1.59              | —                 | 1.62              | —                 | 1.33              | —                 |
| Rapid drawdown         | 1.72              | —                 | 2.28              | —                 | 2.09              | —                 | 1.64              | —                 |
| Earthquake             | 1.33 (1.30)       | 1.61              | 1.64              | 1.96              | 1.40              | 1.56              | 1.28 (1.22)       | 1.48              |

Record: value in front of brackets in the table is the calculated result of numerical process method, value in brackets in the table is the calculated result of quasi-static method.

The stability calculation results of the typical slope profile of SDT2-2' and SDT6-6' under excavation, flood discharge atomization, water plummet and seismic conditions are summarized in Table 1. According to “Rules for the design of slopes in hydroelectric engineering” (DL/T 5353-5353), the plunge pool slope belongs to grade II slope, the combination of Table 1 shows that the overall stability of the slope is good, safety margin is large, the safety coefficient can satisfy the requirements of specification.

### 5. Conclusions

Based on the monitoring data of valley amplitude of the plunge pool slope of the high arch dam, the deformation law of valley amplitude is analyzed. The stability of different typical slope profiles are calculated by finite element method. The simulation results are in good agreement with the deformation monitoring results. The stability calculation results of multiple working conditions show...
that the overall stability condition of the slope is good. Practice shows that through the deformation monitoring combined with simulation, analysis of hydropower station dam rock mass stability assessment is reasonable and feasible. This method of analysis can takes account of the nonlinear large deformation of rock mass, so it has the following advantages: the slope safety factor can be obtained quickly, the instability and failure process can be convenient to simulate of any landscape, any slip plane, and this method is of intuition and applicability.

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