Comparative Analysis of Monitoring Results of a Pumped-storage Diversion Bifurcated Pipe with and without Hydraulic Pressure Test

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Abstract. The diversion system of a pumped-storage power station has a high water head, and its steel bifurcated pipe has a complex hydraulic structure. When the steel bifurcated pipe is assembled, a hydraulic pressure test needs to be performed to release the residual pressure inside the structure, so as to make sure the steel bifurcated pipe will be in good operation condition when the flow channel is filled with water. The bifurcated pipe is provided with deformation, stress and osmotic pressure monitoring items, which are able to meet the requirements for safe monitoring of the steel bifurcated pipe during operation. Based on the hydraulic pressure test of the steel bifurcated pipe of ② diversion system and the prototype monitoring data, it is unnecessary to perform hydraulic pressure test for the steel bifurcated pipe of ① diversion system. According to the prototype monitoring data feedback after filling ① diversion system with water for operation, the steel bifurcated pipe meets the design requirements, and it is in good operation condition, which shortens the construction period and saves cost for the project.

1. Introduction
One-tunnel three-unit water supply mode supported by 2 hydraulic units is applied to the diversion system of a pumped-storage power station. Each main diversion tunnel is divided into 3 branch pipes via 2 steel bifurcated pipes. The bifurcated pipe is provided with deformation, stress and osmotic pressure monitoring items, including multipoint displacement meter, bolt stress meter, plate strain meter, joint meter, steel rebar meter, strain meter, osmometer and other monitoring instruments [1]. Hydraulic pressure test needs to be conducted to release the residual pressure inside the steel bifurcated pipe after welding of the steel bifurcated pipe, so as to make sure the steel bifurcated pipe will be in good operation condition when the flow channel is filled with water. It is proved that it is unnecessary to perform hydraulic pressure test of the steel bifurcated pipe of ① diversion system through hydraulic pressure test of the steel bifurcated pipe of ② diversion system, finite element calculation and feedback of monitoring results. Moreover, it is able to save construction period, reduce cost and provide reference for similar projects in the future.

2. Project Overview
The pumped-storage power station project is large (1) Class I project. The main structures of the power station complex include upper storage reservoir, water conveyance system, powerhouse and
lower storage reservoir. The power station is installed with 6 reversible pump-turbine generator sets with the unit capacity of 250 MW, the total installed capacity of 1,500 MW and the rated productive head of 259 m. Both the diversion tunnel and the tailrace tunnel are subject to one-tunnel three-unit layout. Among them, the diversion system consists of the water inlet & outlet of the upper storage reservoir, the main diversion tunnel, the diversion steel bifurcated pipe and the diversion branch tunnel. The overall length of single diversion tunnel is 1,969 m - 2,153 m [1].

3. Monitoring Layout of Bifurcated Pipe
Sections A3 and B3 of the branch tunnel of the diversion system are provided with 8 joint meters, 3 osmometers, 9 one-way plate strain meters, 6 two-way plate strain meters, 3 multipoint displacement meters, 7 bolt stress meters, 3 strain meters and 2 zero stress meters [2]. See Fig. 1-2 for the section layout.

4. Fabrication and Installation of Steel Bifurcated Pipe
The 800 MPa steel of the steel bifurcated pipe is provided by Nippon Steel Corporation (Japan). For the bifurcated pipe, the diameter of the main pipe is 7 m, the maximum wall thickness is 60 mm, and the thickness of the crescent rib plate is 120 mm. LB-116 welding rod is used. The contents of alloy elements Ni, Cr and Mo are higher than that in national standards, which is beneficial to improving welding seam strength without reducing its toughness.

To ensure welding quality, welders are selected from the superior ones in the persons who have welding qualification for 600 MPa high-strength steel and passed corresponding trainings. Each welding seam was subject to ultrasonic testing and TOFD testing. Besides, crescent ribs were subject to magnetic particle testing on this basis. According to the tests above, the quality was acceptable [3].

5. Analysis of Monitoring Results
The monitoring instruments for stress, combination joint, etc. of the steel plates of ② and ① steel bifurcated pipes were provided with high-frequency monitoring during the water filling test of the diversion system to correctly get hold of the stress adjustment and change before and after water filling, and further prove the impact on structural safety with and without hydraulic pressure test.
5.1. Water Filling Test of Diversion System

Water filling of diversion system was started on December 16, 2015 and finished on February 14, 2016 with the filling head of 298 m.

5.1.1. Stress of Steel Lining

The section was provided with 9 one-way plate strain meters (measuring points 1 and 2 were to measure the supporting stress of the steel arch) and 6 two-way plate strain meters (for rib measuring points). 1 represents the direction along the water flow, and 2 represents the direction perpendicular to the water flow. During water filling, steel lining stress was developed as tensile stress. Individual measuring points had slight change towards the compressive stress direction, but the overall change was in accordance with general law. Refer to Table 1 for statistics of changes in steel plate stress measuring points.

The measuring point having the maximum tensile stress growth during water filling was PS\textsubscript{2b3-6-2}, whose tensile stress growth was 76.82 MPa. Besides, there were 9 points (19 measuring points in total) having tensile stress growth greater than 30 MPa, accounting for 47.4%. Tensile stress growth of 3 measuring points on the crescent rib was slightly small, of which, the growth of measuring point PS\textsubscript{b3-9} was 50.06 MPa. Generally, tensile stress growth of the left steel lining was slightly greater than that of the right steel lining, but the overall change magnitude was within the design control scope without abnormality.

In this period, the measuring point having the maximum growth in the compressive stress direction was PS\textsubscript{b3-5-2} on the right waist arch, whose compressive stress growth was 11.07 MPa. The other measuring point in this group also had a slight compressive stress change. The measuring point having the second maximum growth in the compressive stress direction was PS\textsubscript{b3-4-2} on the right top arch, whose compressive stress growth was 7.03 MPa. Changes of sections in the compressive stress direction showed up on the right side in general. Furthermore, the steel lining and the concrete combination joint of this part had the most obvious closed development, which might be caused by stress adjustment of its own structure. It can be learnt from the comparison chart of change process that the steel lining compressive stress of the right waist arch has started increasing since the last ten days of January, when the water conveyance level entered the steady pressure stage of the upper adit, and change started tending to be stable.

![Fig. 2 Stress Change Process of the Crescent Rib Steel Plate of Section B3 of Diversion Tunnel](image-url)
Fig. 3 Stress Change Process of PS2b3-6 Two-way Steel Plate of Section B3 of Diversion Tunnel

Table. 1 Statistics of Stress Changes of the Steel Plate of Section B3 of Diversion Tunnel (Unit: Mpa)

| No. of measuring point | December 15 | January 29 (118 m) | February 12 (245 m) | February 25 (248.94 m) |
|------------------------|-------------|--------------------|---------------------|------------------------|
|                        | Reference value | Stress of steel plate | Variable quantity | Stress of steel plate | Variable quantity | Stress of steel plate | Variable quantity |
| PSb3-3                 | -58.41       | -10.81             | 47.6                | 7.12                   | 65.53             | 7.23                 | 65.64             |
| PSb3-4                 | 21.96        | 45.66              | 23.7                | 52.05                  | 30.09             | 59.57                | 37.61             |
| PSb3-5                 | -29.35       | -11.38             | 17.97               | -11.51                 | 17.84             | -4.81                | 24.54             |
| PSb3-6                 | 107.58       | 103.82             | -3.76               | 101.27                 | -6.31             | 102.09               | -5.49             |
| PSb3-7                 | -22.17       | 3.3                | 25.47               | 14.24                  | 36.41             | 13.19                | 35.36             |
| PSb3-8                 | -79.11       | -50.37             | 28.74               | -40.57                 | 38.54             | -40.5                | 38.61             |
| PSb3-9                 | -28.3        | -4.31              | 23.99               | 20.58                  | 48.88             | 21.76                | 50.06             |
| PS2b3-1-1              | 14.75        | 44.95              | 30.2                | 63.77                  | 49.02             | 63.8                 | 49.05             |
| PS2b3-1-2              | 35.44        | 79.78              | 44.34               | 98.81                  | 63.37             | 98.78                | 63.34             |
| PS2b3-2-1              | 63.09        | 81.14              | 18.05               | 88.91                  | 25.82             | 91.28                | 28.19             |
| PS2b3-2-2              | 20.9         | 33.37              | 12.47               | 42.36                  | 21.46             | 43.6                 | 22.7              |
| PS2b3-3-1              | -32.34       | -31.42             | 0.92                | -28.27                 | 4.07              | -29.35               | 2.99              |
| PS2b3-3-2              | 41.14        | 66.66              | 25.52               | 63.01                  | 21.87             | 58.55                | 17.41             |
| PS2b3-4-1              | 1.28         | 21.8               | 20.52               | 26.01                  | 24.73             | 29.41                | 28.13             |
| PS2b3-4-2              | 14.6         | 4.57               | -10.03              | 7.56                   | -7.04             | 7.57                 | -7.03             |
| PS2b3-5-1              | 242.36       | 187.29             | -55.07              | 243.18                 | 0.82              | 242.04               | -0.32             |
| PS2b3-5-2              | 2.45         | -7.2               | -9.65               | -9.79                  | -12.24            | -8.62                | -11.07            |
| PS2b3-6-1              | 18.23        | 33.87              | 15.64               | 50.58                  | 32.35             | 52.93                | 34.7              |
| PS2b3-6-2              | -24.52       | 46.91              | 71.43               | 54.46                  | 78.98             | 52.3                 | 76.82             |

5.1.2. Combination Joint

The section was provided with 8 joint meters in total. Odd number represents measuring points for combination joints between lining concrete and surrounding rock, and even number represents measuring points for combination joints between lining concrete and steel lining. 1, 2, 7 and 8 are measuring points on side walls of two sides, and 3, 4, 5 and 6 are measuring points on the top arch. During water filling, combination joints were subject to closed change with little overall change, which complies with general law. Refer to Table 2 for statistics of changes in combination joint measuring points.

The maximum closing value of combination joints between lining concrete and steel lining is 0.1 mm, which is Jb3-6 measuring point of the right top arch. The maximum open value is 0.04 mm, which
is the measuring point of the left top arch.

Table. 2 Statistics of Changes in Joint Opening Degree of Section B3 of ② Diversion Tunnel (Unit: mm)

| No. of measuring point | December 15 (Reference value) | January 29 (118 m) | February 12 (245 m) | February 25 (248.94 m) |
|------------------------|-------------------------------|--------------------|---------------------|-----------------------|
|                        | Joint opening degree          | Variable quantity  | Joint opening degree| Variable quantity     |
| Jb3-2                  | -3.70                         | 0.02               | -3.68               | 0.02                  |
| Jb3-4                  | 0.34                          | 0.3                | -0.04               | 0.32                  |
| Jb3-6                  | -1.37                         | -0.1               | -1.47               | -0.1                  |
| Jb3-8                  | -0.45                         | -0.03              | -0.50               | -0.05                 |

5.1.3. Other Monitoring Items

One osmometer was arranged on two side walls and the top arch of the section respectively to monitor external hydraulic pressure of the steel lining. Osmometers were embedded in surrounding rock. Seepage pressure barely changed, and there was no abnormity during filling and discharging.

The section was provided with 3 sets of 4-point multipoint displacement meters that were on two waist arches and the top arch. In this period, main surrounding rock deformation was compression change with the maximum value of 0.36 mm without abnormity, which was in accordance with general law.

The section was provided with 7 bolt stress meters in total. Bolt stress was mainly compressive stress change on the whole. The maximum compressive stress growth was 37.92 MPa, and there was no abnormity.

5.2 Water Filling Test of ① Diversion System

Water filling of ① diversion system was started on May 9, 2016 and finished on May 29, 2016.

5.2.1 Stress of Steel Lining

Tensile stress increased obviously along with rising of water level during the test, which was mainly reflected by the first 4 stages, and changes in later period were relatively small. In addition, overall tensile stress growth change was obvious compared with ② diversion bifurcated pipe. The change magnitude was slightly great, but still within the permissible range in the design.

The maximum growth value of steel lining tensile stress was 315.93 MPa, which was measured at PS2a3-1-2 measuring point (circumferential measuring point). The second maximum growth value of steel lining tensile stress was 220.61 MPa, which was measured at PS2a3-2-2 measuring point (circumferential measuring point). Both of such 2 measuring points were on the left side. Tensile stress growth values of other measuring points were within 100MPa, i.e., relatively small.

Among 7 water filling stages, stages 2, 3, 4, 6 and 7 have large water head growth. Main stress changes of ① diversion bifurcated pipe were formed at stages 2 and 3. During stage 5 - stage 7, stress change of measuring points account for 13.6%, 18.9% and 0.4% respectively, which indicates that stress adjustment of the steel lining has basically been completed in the last half of water filling process.

Individual measuring points of the steel lining have compressive stress change. Among them, change of PS2a3-3-2 measuring point is relatively large, which is -238.9 MPa. Before water filling, tensile stress of the measuring points of the first 2 stages increased, but it changed suddenly at the 3rd stage with drop of 270 MPa. Afterwards, measuring points had steady change, which might be caused by self-adjustment. Changes of compressive stress of other measuring points were relatively small.

Refer to Table 3 for statistics of changes in steel plate stress, and refer to Fig. 4 for process chart of typical measuring points.
### Table 3: Statistics of Stress Changes of Typical Measuring Points on Steel Plate A3 of ① Diversion Tunnel (Unit: Mpa)

| No. of measuring point | May 7 | May 25 (water level: 195 m) | May 29 (water level: 254 m) | May 31 (water level: 254 m) |
|------------------------|-------|----------------------------|----------------------------|----------------------------|
|                         | Reference value | Stress of steel plate | Variable quantity | Stress of steel plate | Variable quantity | Stress of steel plate | Variable quantity |
| PSa3-5                 | 19.89   | 56.26                      | 36.37                     | 60.89                    | 41                  | 59.74                 | 39.85                     |
| PSa3-6                 | -7.16   | -11.13                     | -3.97                     | -11.04                   | -3.88               | -12.23                | -5.07                      |
| PSa3-7                 | 61.27   | 100.6                      | 39.33                     | 105.23                   | 43.96               | 105.12                | 43.85                      |
| PSa3-8                 | 23.5    | -19.67                     | -43.17                    | -21.84                   | -45.34              | -25.22                | -48.72                      |
| PSa3-9                 | 12.42   | 106.19                     | 93.77                     | 116.5                    | 104.08              | 111.94                | 99.52                       |
| PSa3-10                | 11.36   | 12.1                       | 0.74                      | 15.62                    | 4.26                | 15.59                 | 4.23                       |
| PSa3-11                | -89.05  | 215.6                      | **304.65**                | 226.93                   | **315.98**          | 226.88                | **315.93**                 |
| PSa3-12                | 63.19   | 103.64                     | 40.45                     | 108.24                   | 45.05               | 108.23                | 45.04                       |
| PSa3-13                | 69      | 281.66                     | **212.66**                | 289.68                   | **220.68**          | 289.61                | **220.61**                 |
| PSa3-14                | 65.37   | 58.04                      | -7.33                     | 55.81                    | -9.56               | 58.11                 | -7.26                      |
| PSa3-15                | 289.51  | 51.67                      | **-237.84**               | 51.75                    | **-237.76**         | 50.61                 | **-238.9**                |
| PSa3-16                | -33.76  | -36.15                     | -2.39                     | -36.11                   | -2.35               | -36.16                | -2.4                       |
| PSa3-17                | 71.4    | 68.92                      | -2.48                     | 68.96                    | -2.44               | 68.90                 | -2.5                       |
| PSa3-18                | 61.43   | 108.78                     | 47.35                     | 114.54                   | 53.11               | 115.67                | 54.24                       |
| PSa3-19                | 65.84   | 101.62                     | 35.78                     | 106.2                    | 40.36               | 108.42                | 42.58                       |
| PSa3-20                | 35.64   | 70.07                      | 34.43                     | 76.88                    | 41.24               | 75.74                 | 40.1                       |
| PSa3-21                | 37.92   | 15.08                      | -22.84                    | 15.15                    | -22.77              | 16.26                 | -21.66                      |

### Table 4: Statistics of Stage Changes of Steel Lining Stress of ① Diversion Tunnel

| Measuring point | Stage 1/4.2 | Stage 2/64.3 | Stage 3/60 | Stage 4/68 | Stage 5/10 | Stage 6/47 | Stage 7/57 | End/0  |
|-----------------|-------------|--------------|------------|------------|------------|------------|------------|--------|
| PSa3-1-2        | 14.54       | 129.12       | 106.88     | 22.51      | 9.14       | 28.06      | 5.73       | 0.03   |
| PSa3-2-2        | 4.6%        | **40.9%**    | **33.8%**  | 7.1%       | 2.9%       | 8.9%       | 1.8%       | 0.0%   |
| PSa3-3-2        | 29.43       | 102.86       | 24.86      | 22.61      | 7.95       | 24.94      | 8.03       | -4.45  |
| PSa3-4-2        | 13.6%       | **47.6%**    | 11.5%      | 10.5%      | 3.7%       | 11.5%      | 3.7%       | -2.1%  |
| PSa3-5-2        | 18.04       | 14.46        | -267       | -2.27      | -1.1       | 1.15       | -1.04      | -1.04  |
| PSa3-6-2        | -7.6%       | -6.1%        | **111.8%** | 1.0%       | 0.5%       | -0.5%      | 0.4%       | 0.4%   |
5.2.2 Combination Joint

During the water filling test, steel lining combination joints were subject to closed change. The maximum compression value of the combination joint between steel lining and concrete lining was -1.22 mm, which was measured at the right Ja3-6 measuring point of the top arch. The left change value was -1.05 mm, so the changes were basically equivalent. Main gap changes of the top arch were concentrated before water filling of stage 4, which were consistent with steel lining stress changes. Changes in later period were slightly small. The other changes were small.

Table 5 Statistics of Changes in Joint Opening Degree of Combination Joint of Steel Lining B3 of ① Diversion Tunnel (Unit: mm)

| No. of measuring point | May 7 | May 25 (water level: 195 m) | May 29 (water level: 254 m) | May 31 (water level: 254 m) |
|------------------------|-------|----------------------------|----------------------------|-----------------------------|
|                        | Reference value | Joint opening degree | Variable quantity | Joint opening degree | Variable quantity | Joint opening degree | Variable quantity |
| Ja3-2                  | -1.32  | -1.34                      | -0.02                    | -1.36                      | -0.04                    | -1.34                      | -0.02                    |
| Ja3-4                  | 1.28   | 0.27                       | -1.01                    | 0.23                       | -1.05                    | 0.23                       | -1.05                    |
| Ja3-6                  | 0.85   | -0.35                      | -1.2                     | -0.35                      | -1.2                     | -0.37                      | -1.22                    |
| Ja3-8                  | -0.11  | -0.11                      | 0                        | -0.09                      | 0.02                     | -0.11                      | 0                        |
5.2.3. Other Monitoring Items

Seepage pressure changes were stable. Growth of seepage pressure of the top measuring point was 0.04 MPa, and no abnormal seepage was seen.

Surrounding rock dislocation changes were stable, and the whole body was subject to compression change with the maximum compression value of -0.29 mm without obvious abnormality.

Overall change of bolt stress was compression with the maximum compressive stress change of -49.46 MPa. Overall change was slightly smaller.

5.3 Conclusions

1) Monitoring items of ① and ② diversion bifurcated pipes are complete, which is able to reflect overall changes of them during water filling test in a comprehensive manner. Steel linings are mainly subject to tensile stress change, combination joints are subject to closed change, rock mass is subject to compression change, bolt stress is subject to compressive stress change, and seepage pressure barely changes. Based on such monitoring results, bifurcated pipes were in good condition without abnormal changes during the water filling test.

2) Since ① diversion bifurcated pipe was not subject to hydraulic pressure test before concrete backfilling, residual stress of bifurcated pipe welding was not fully released and adjusted. For this reason, steel lining stress change of ① diversion bifurcated pipe was obvious with slightly larger change compared with ② diversion bifurcated pipe (maximum growth of ① and ② was 315.93 MPa and 76.82 MPa respectively) during the water filling test, but it was still within the allowable range of the design value (800 MPa).

3) Similarly, combination joint changes of ① and ② bifurcated pipes were also affected by the fact whether there was hydraulic pressure test. The change of ① diversion bifurcated pipe was more obvious (maximum closing values of ① and ② were 1.22 mm and 0.27 mm respectively).

4) For changes in monitoring items such as seepage pressure, rock mass deformation and bolt supporting stress, there was no abnormality during the test [5].

6. Hydraulic Pressure Test and Finite Element Calculation

Internal water pressures during hydraulic pressure test were 0.2 MPa, 1 MPa, 2 MPa, 3 MPa and 3.9 MPa respectively. ② diversion steel bifurcated pipe was provided with 20 strain test measuring points in total. Two cyclic tests have been done for pressure rising and releasing process of the hydraulic pressure test, and comparative analysis before and after the test has been done. The Designer
calculated different pressure conditions of bifurcated pipes with three-dimensional finite element, and analyzed the test results [6]. Conclusions are as follows:

1) Distribution laws of measured stress and calculated stress and positions of maximum stress points are basically consistent. Main large stresses are concentrated on the top and horizontal positions on both sides of the crescent rib. The maximum measured stress is 534.7 MPa, and the maximum calculated stress is 499.9 MPa.

2) Relative differences between measured stress and calculated stress are basically within 15% - 30%.

3) Main causes for the difference between measured stress and calculated stress are as follows: a) Calculated stress is taken from the bevel, but there is slight difference between measurement position and bevel welding seam position due to limit on strain measuring point mounting position; b) The residual stress generated during bifurcated pipe welding was not taken into account for the calculated value.

In conclusion, based on test results and finite element calculation of ② diversion steel bifurcated pipe and analysis of monitoring data, cancellation of hydraulic pressure test of ① diversion steel bifurcated pipe is acceptable.

7. Conclusions
Considering high water head of the diversion system of the pumped-storage power station as well as high technical requirements for material and construction of HP bifurcated pipes, it is necessary to release residual stress through hydraulic pressure test after base metal welding, so as to ensure long-term safe operation in the future. A hydraulic pressure test has been performed for bifurcated pipes of ② diversion system of the Project. In addition, hydraulic pressure test of ① diversion bifurcated pipe was cancelled based on analysis, finite element calculation and hydraulic pressure test results of monitoring data of ② bifurcated pipe. During the hydraulic pressure test of ① diversion bifurcated pipe, all monitoring data was within the design control scope, main bifurcated pipe stress change adjustment was concentrated at the first 4 stages, and hydraulic structures were safe on the whole. In conclusion, cancellation of hydraulic pressure test is feasible. It not only saves 3 months’ construction period and cost for the Project, but also provides reference for hydraulic pressure tests during construction periods of similar projects in the future.

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