Performance Evaluation of an Underground Penstock Bifurcation A Case Study

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ABSTRACT
Complex geometry of the underground penstock bifurcation makes it very much involved in terms of evaluation of stresses during functioning and in turn of its performance. A hydrostatic test is conducted to know the performance of bifurcation without accounting for rock participation which was actually considered in the design. This paper discusses the hydrostatic test conducted on penstock bifurcation of Varahi H E (430MW) project, Karnataka by measuring strains at seventeen pre selected critical locations. The bifurcation was tested up to the 50 kg/cm² internal pressure based on test criteria. The pressure was applied in steps of 5 kg/cm² up to 40 kg/cm² and thereafter in steps of 2 kg/cm², up to 50 kg/cm². From the test it was concluded that the performance of bifurcation will be satisfactory with 50% rock participation as the stresses developed (Maximum hoop stress of 3164 kg/cm²) were well within the design limits.

1. INTRODUCTION
Bifurcations are the vital parts of any water conductor system. Complex geometry of bifurcation makes it very difficult for the evaluation of stresses developed in the bifurcation during functioning in turn to evaluate its structural performance. Hydrostatic test is considered to be the most reliable tool for evaluation of stresses, assessment of structural integrity and identification of weak zones, weld defects if any, prior to commissioning. This paper discusses the hydrostatic test conducted on Varahi H E project stage-II, Varahi at site inside the tunnel during the last week of March 2007.

2. SALIENT FEATURES
The Varahi hydroelectric project, Karnataka, envisages utilization of the water of river Varahi, a 72 km long west flowing river in the Shimoga and Udupi districts of Karnataka for generation 460MW (115X4) Hydro power. The project comprises, a 58 m high Mani dam storage reservoir, a 40 m high pick up dam, a 40 m high forebay dam interconnected by a 780 m long channel and a 360 m long approach channel from the forebay dam terminating in an intake structure. The first two units were commissioned in 1989 and running successfully. This test was conducted for the remaining stage II two units.

3. SCOPE OF STUDIES
The scope of studies conducted by CWPRS Pune included the measurement of strains at critical locations, the evaluation of stresses to assess the structural integrity, identification of weak zones and weld defects if any, prior to commissioning by conducting hydrostatic test up to 1.5 times of designed pressure or 50% of ultimate tensile strength or 75% of yield strength of the steel whichever reached earlier. After conducting hydrostatic test, the penstock bifurcation was embedded in rock mass with an overburden of 200 m high Granite Gneiss rock mass to account 50% rock participation.

4. DESIGN DATA
The penstock wye branch linking the main pipe to the two branches (Fig. 1) constitutes an important structural element in the water conductor system with the following design parameters.
Gross Head : 475.4 m
Design pressure : 55.73 kg/cm²
Internal diameter of main pipe : 4000mm
Internal diameter of branch pipe : 3000mm
Thickness of both pipe : 50mm
Bifurcation Angle : 50°
Thickness of sickle plate : 100 mm
Steel used for fabrication : ASTM-A-537 class II
Minimum yield strength : 4219 kg/cm²
Ultimate tensile strength : 5625-7031 kg/cm²
Allowable stress : 2110 kg/cm²
Rock Participation : 50%

5. INSTRUMENTATION

Electrical resistance strain gauges uniaxial, biaxial and rosette type were used to measure strains developed during hydrostatic test and in-turn based on measured strains hoop and axial stresses were evaluated.

Selection of Critical Locations

Seventeen critical locations were selected on the outer surface of the penstock bifurcation and on the surface of sickle plate inside the bifurcation (Fig. 1 & 2) at which the rosette, biaxial and uniaxial strain gauges were installed. The gauges on main (header) pipe, Branch pipe & sickle plate are identified by M, B & S notations respectively.

Installation

The strain gauges were installed after thorough cleaning of surface area of size 100mm x 100mm with Acetone liquid (Fig. 3) and using tube Araldite adhesive for ensuring perfect bonding with the surface. A total of 38 strain gauges were installed on the entire penstock bifurcation. Two dummy strain gauges were also pasted on two steel plates of same material (250mm x 250mm) for studying temperature and other local effects. A 48 hrs curing time was allowed after strain gauge installation. The strain gauges installed on the sickle plate were made waterproof by covering them with liquid epoxy (Fig. 4). The cables from these gauges wire taken out through pipe bend and the pipe bend was filled with epoxy to check leakage of water from bifurcation.

6. HYDROSTATIC TEST

Arrangements

The penstock bifurcation was supported along its length at three points using saddle supports on plain rigid floor after leveling in horizontal plane. Both ends were closed by welding parabolic bulkheads. Free movement of branches was allowed by applying lubricant on saddle supports. Electrical resistance strain gauges were installed at critical locations on sickle plate and surface of the bifurcation. A reciprocating pump of Worthington make VTE-1 vertical power pump, capable of developing internal pressure upto 150 Kg/sqcm was used to pressurize the filled water.

Test Pressure

As per test criteria (agreement between Karnataka Power Corporation Limited, Bangalore, the client & Indian Hume...
Pipe Company, Pune, the contractor) the test pressure is the 1.5 times of designed pressure or which produces a hoop stress in penstock bifurcation at any point equal to 50% of the minimum ultimate tensile strength (UTS) or 75% of yield point of the steel used in the fabrication of penstock bifurcation whichever reaches earlier. The penstock bifurcation thus formed was subjected to an internal pressure of 50 kg/cm² resulting hoop stress of 75% of yield point strength.

Test Procedure
After fabrication of bifurcation, all the welded joints were radiographed to locate welds defects and repair the same for ensuring 100% weld efficiency before conducting hydrostatic test. After recording initial observations of all the strain gauges with the penstock bifurcation empty, the penstock bifurcation was filled with water using hydraulic pump. After filling the pipe completely, small internal pressure was applied and air vent valve was operated to allow entrapped air to escape from pipe and pressure was brought down to zero. This cycle was repeated 3 times to completely remove entrapped air from pipe (E. Divatia et al. 1974) and then strain gauge readings were recorded at zero applied internal pressure. Accordingly, the internal pressure was applied in steps of 5 kg/sq cm up to 40 kg/sq cm and thereafter in steps of 2 kg/sq cm. At each step, the applied internal pressure was held constant for at least 10 minutes and strain observations were recorded. At internal pressure equal to 44kg/sq cm, the hoop stress of the order of 2814 kg/sq cm resulted hoop stress of 3164 kg/sq cm (equal to 75% of minimum yield strength of the steel) at strain gauge location B2. However, after discussions with design engineers, KPCL officers and IHP officials, it was decided to carry on the hydrostatic test up to 75% of yield point of the steel without endangering the safety of the structure. Accordingly, internal pressure was applied further in steps of 2 kg/sq cm up to 50 kg/sq cm internal pressure which resulted hoop stress of 3164 kg/sq cm (equal to 75% of yield point) at strain gauge location B2. This pressure was held constant for 15 minutes and the entire penstock bifurcation was monitored minutely for leakage and sweating of joints. Considering the criteria viz., lesser of 50% minimum ultimate tensile strength and 75% of yield point of the steel used in fabrication of penstock bifurcation, the internal pressure was not increased further in consultation with design engineers and project officials. The pressure in the pipe was reduced gradually from 50 kg/sq cm in steps of 2 kg / sq.cm up to 40 kg/sq cm thereafter in steps of 5 kg/sq cm. The strain gauge observations were recorded at each step during depressurizing also. During the entire test, no leakages or sweating of joints were noticed. % recovery of stresses was also monitored and was found satisfactory as per test criteria.

7. RESULTS AND DISCUSSION
The following standard formulae are used to calculate theoretical hoop and longitudinal stresses in a circular pipe using the following standard formulae;

$$\sigma_h = \frac{pr}{t} \quad (1)$$
$$\sigma_l = \frac{pr}{2t} \quad (2)$$

Where $\sigma_h$ = hoop stress (Kg/sqcm) $\sigma_l$ = Longitudinal stress (Kg/sqcm); \(p\) = pressure (sqcm); \(r\) = radius of pipe (cm); \(t\) = thickness (cm). The principal stresses developed in sickle plate based on strain gauge observations are calculated using the following standard formulae;

$$\sigma = \frac{E}{2[1-(\nu^2)]}\left[(\epsilon_h + \epsilon_c) \pm \sqrt{(\epsilon_h + \epsilon_c)^2 + (2\epsilon_h - \epsilon_c)^2}\right] \quad (3)$$

Where $\sigma$ = Principal stress (Major/Minor); \(E\)=Young's Modulus of Elasticity; \(\epsilon_h/\epsilon_c\) = Hoop / longitudinal strain along circumferential; \(\nu\)=Poisson ratio of steel. The recorded strain gauge observations were used to calculate hoop, longitudinal strains, which were in turn converted to hoop & longitudinal stresses using formula

$$\sigma = \epsilon_h E \quad (4)$$

Where $\sigma$=Stress (Kg/sqcm); $\epsilon_h$=Hoop / longitudinal strain; \(E\)=Young’s modulus of elasticity= 2.1*10⁶ Kg/sqcm. The maximum stress of the order of 3164 kg/sq cm was found to be developed (Technical Report No.:4469, 2007) at an internal pressure of 50 kg/sq cm on location B2 at half diameter point near the intersection of header and conical pipes which works out to be 75% of minimum yield strength of steel used in fabrication of the bifurcation. The stresses at all other locations are less than 75% of minimum yield strength of the steel at an internal pressure of 50 kg/sq cm. The hoop stress along the diameter at 50kg/sq cm internal pressure varies from 2086.6 to 2360.6 Kg/sqcm in header pipe whereas in branch pipe from 328.4 to 3162.6 Kg/sqcm. The major principal stress at 50kg/sq cm internal pressure varies from 985.5 to 1008.8 Kg/sqcm at the centerline of the sickle plate. The computed stresses for selected locations based on measured stresses for M1&M4 (Table 1), for B2 & B3 (Table 2), & the distribution of principal stress calculated based on measured strain at the centerline of sickle plate at S1 & S2 (Table 3) for internal pressure 0,10,30,44 & 50 Kg/cm² are as given below in Table 1-3.

<table>
<thead>
<tr>
<th>Location-→</th>
<th>Pressure</th>
<th>M1</th>
<th>Axial</th>
<th>M4</th>
<th>Hoop</th>
<th>Axial</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>417.3</td>
<td>162.6</td>
<td>413.2</td>
<td>127.0</td>
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</tr>
<tr>
<td>30</td>
<td>1252.0</td>
<td>487.8</td>
<td>1431.1</td>
<td>445.4</td>
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<tr>
<td>44</td>
<td>1836.2</td>
<td>715.5</td>
<td>2115.6</td>
<td>635.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>2086.6</td>
<td>813.1</td>
<td>2360.6</td>
<td>689.5</td>
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Table 2: Stresses Vs Pressure in Kg/sqcm in Branch Pipe

<table>
<thead>
<tr>
<th>Location</th>
<th>B2</th>
<th>B3</th>
</tr>
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<tbody>
<tr>
<td>Pressure</td>
<td>Hoop</td>
<td>Axial</td>
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<tr>
<td>0</td>
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<td>0</td>
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<td>10</td>
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<tr>
<td>30</td>
<td>1898.4</td>
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<tr>
<td>44</td>
<td>2784.3</td>
<td>610.5</td>
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<tr>
<td>50</td>
<td>3164.0</td>
<td>693.8</td>
</tr>
</tbody>
</table>

Table 3: Stresses Vs Pressure in Kg/sqcm in Sickle Plate

<table>
<thead>
<tr>
<th>Location</th>
<th>S1</th>
<th>S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>Major</td>
<td>Minor</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>10</td>
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<td>44</td>
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<tr>
<td>50</td>
<td>985.5</td>
<td>409.5</td>
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</tbody>
</table>

8. CONCLUSIONS

No leakage or sweating of the joints was noticed during the hydrostatic test. The maximum principal/hoop stresses calculated based on measured strain were found to vary from 1058 to 3164 kg/cm² for an internal pressure of 50 kg/cm². The maximum hoop stress developed at half diameter point near the intersection of header and conical pipes works out to be 75% of minimum yield strength of the steel at an internal pressure of 50 kg/cm². The stresses developed satisfy the hydrostatic test criteria as per agreement between KPCL and IHP. After conducting hydrotest it was concluded that the bifurcation will be structurally safe with 50% rock participation (IS: 4880(Part VII)-1975) as considered in design.

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REFERENCES


Technical Report No.:4469(2007), Central Water Power Research Station, Pune, India