CONSTRUCTION OF PRESTRESSED CONCRETE PENSTOCKS
AT BENMORE

David S Brathwaite

INTRODUCTION

In 1962, the New Zealand Ministry of Works, as consultant to the New Zealand Electricity Dept made a decision to build the substantial penstock installation at the Benmore Power Project in prestressed concrete. The reasons for selecting that construction material are briefly described. The design and construction of the penstocks has been described in previously published papers [1,2,3]. This paper is intended to support a visual presentation of the construction of the penstocks, and includes an appendix with some data to illustrate the magnitude of the work. The construction was done in the years 1962-64. The pictures are mainly photographs from the author’s collection, but include also some drawings and diagrams from previously published papers and reports written by the author.

SELECTION OF PRESTRESSED CONCRETE

In the 1950’s, the power stations being built on the Waikato and Clutha rivers had short steel penstocks passing through a concrete dam into the power house on the downstream toe of the dam. The penstocks were built of steel up to about 5.5m diameter. Prefabricated rings were assembled using the overhead “flying fox” cableway which was part of the construction gear for those projects. The configuration of the Benmore power station required 6 penstocks 5.3m diameter 130m long laid on a rock spur on a slope of 35°. The static head was twice that which obtained at the earlier projects. No aerial cableway was available over the penstock area.

The penstock installation formed a significantly larger proportion of the power generating equipment than had been the case on the earlier power schemes. The cost of welding large quantities of mild plate up to 65mm thick, or high tensile plate up to 35mm thick, carried a significant risk of escalation, and of delay, due to the possibility of industrial action by the Boilermakers Union, which was exerting it muscle strongly in those times. These considerations prompted a decision to explore the feasibility of reinforced concrete, with or without a thin steel liner. Initial design studies showed up very significant problems of access and construction on the chosen site, and pointed the way to the option of precasting. Because of the comparative structural efficiency of prestressed concrete over reinforced concrete for pressure containment, design studies moved to the former.

The possible advantage of dispensing with the steel liner, including the cost of future maintenance painting, was an added attraction.

The development of these ideas, supported by a program of testing of various construction techniques and details, lead to the decision in 1961 to proceed with the unlined precast prestressed concrete option. The decision had to balance the perceived risk of delay and of cost escalation of the tried and true steel option, against the obvious though different risks of doing something completely new. The author has often, over the years, reflected on the courage of the Chief Engineer, Power, whose responsibility it was to make that decision.

PRELIMINARY TESTING PROGRAM

The method of jointing the precast units was crucial to the success of the precasting option. The pipe wall was to be about 450mm thick. The first choice was to investigate the effectiveness of a mortar joint 35mm thick between plain flat ends of the units. Tests were done to prove water-tightness using concrete with variously prepared and treated surfaces. The design of the mortar mix was also tested in pumping trials as well as usual tests for flow, bleeding and compressive strength. The incidence of bleeding was found to be the vital issue, inasmuch as the tracking of bleed water across the joint face might promote a future leakage path. An additive was devised to inhibit bleeding, to promote flow, and to compensate for settlement of solids.
The circumferential prestressing cables, comprising 12No. 12mm dia 7wire strands, were to be curved on a radius of 2.7m. Friction losses were therefore of vital importance in the design. Tests were done on curved cables cast into beams, to measure the friction loss in sheathings of various types and diameters. Simultaneously, the tension forces in the 12 separate strands were measured, to assess whether any variability was significant. It wasn’t. Work was also done to develop a technique for reducing the pull-in loss at blocking of the 150tonne cables in their cast steel anchorages.

The preliminary testing program culminated in the building of two precast penstock units, jointed as devised, and tested under pressure over a period of 2 months. Applied pressure was up to normal operating pressure (900kPa), then to maximum water hammer pressure (1200kPa) with fluctuations as rapidly as could be applied, and finally to failure. After repeated cracking and spraying water at 2000kPa the test continued for several weeks at normal pressure with no signs of distress.

CONSTRUCTION PLANNING

The decision to proceed was made in July 1961. The preparation of the penstock slope began soon afterwards, including rail tracks for the handling gantry and servicing gantries. 318 precast units were required. In the time available, the average rate of construction required that units be assembled at an average rate of one unit every 1.6 days. Allowing for initial familiarisation and likely teething troubles, the target assembly rate was set at one unit per day. The sequence of operations to place, joint, and stress a unit took three days; these factors lead to the need to progress three penstocks simultaneously. The sequence of work required in the precasting process was targeted at eight days from setting up the inner formwork to dispatch of the completed unit.

A precasting yard was set up at the nearest available clear site, 1.5km from the top of the penstock slope. 10 Casting pads were built, and 3 sets of formwork. The bed was serviced by two rail mounted 5 tonne cranes for formwork and materials handling, and a purpose built travelling gantry to lift and transport the precast units. Power cables for various machines and travelling cranes, and water and steam lines (for temperature adjustment of curing water) were built in. A three bay building was erected alongside for storing and fabricating various components, for cable making and for precasting the heavily reinforced prestressing anchorage blocks. Concrete was supplied by a Winget 2 x 0.75cu.m batching plant dedicated to the penstock job, separate from the Johnson 4 x 1.5cu.m plant which supplied mass concrete to other parts of the project.

CONSTRUCTION

Formwork of the precast units was stripped after 8 hours, to prevent undue heat build-up caused by high cement content and the thick plywood facing of the formwork. Continuous water spray curing under a canvas tent was applied for three days. Three hoops of circumferential cables were fully tensioned and grouted before the unit was lifted and carried to a sandblasting bay for preparation of the end faces for jointing. The remainder of the cables and all the longitudinal bars were then loaded into their ducts.

Precast units were carried to the assembly site on a purpose built high deck tricycle vehicle, which was pulled and pushed by two partly loaded dump wagons. These were called in from earthmoving operations on the project when a unit was ready for dispatch. At the top of the penstock slope, the transporter was manoeuvred under a rail mounted gantry, which had facility to lift the unit off the transporter, carry it down the slope, and rotate into the attitude needed to lay against the previously placed unit.

A “servicing gantry” straddled the uppermost 15m of each penstock. This gantry had facilities for forming the joints for the pumped mortar filling, hoists for handling circumferential prestressing jacks, and for giving access to the upstream face of the penstock for tensioning and grouting longitudinal prestressing bars.

Joint mortar was mixed in the Winget batching plant and transported to the top of the slope, where it was transferred into a Colmono grout pump; it was winched down the slope to the joint to be filled. The site was shaded from the sun for several months of the year, with sub-zero temperatures lasting for periods of weeks on occasions. In Summer, high temperatures were equally prevalent. The conditions required the use of ice in mixing water in Summer, and bagged cement for prestressing duct grout was stored in a chiller. In Winter, heated water was circulated in the joint space before mortar was pumped in.
PROGRESS

Assembly of the first penstock began in October 1962; the last unit was placed at the beginning of September 1964. The planned maximum rate of construction was achieved after half the first three penstocks had been built. Completion of all six was just one week late at the end of the two year program. Five precast units were rejected for use because of faults in the concrete which could not be safely repaired.

ACKNOWLEDGEMENTS

The penstocks were designed by engineers in the Hydro Design office of the NZ Ministry of Works, Wellington.

Construction planning, design of specialised equipment, and the execution of the job was done by civil and mechanical engineers and staff of the NZ Ministry of Works at the Benmore Power Project.

Design reviews were done by M. Yves Guyon of Société technique pour l’utilisation de la précontrainte (S.T.U.P.)

Photographs used in this presentation are from the Author’s own records, and from the archived records of the Ministry of Works, now held by Opus International Consultants Ltd.

The Benmore power station is now owned by Meridian Energy Ltd.

REFERENCES

APPENDIX: CONSTRUCTION DATA

Dimensions
Total length of prestressed penstocks: 775m
Precast unit:
Number: 318
Length: 2.4m
internal diameter: 5.3m
o/a outside dimensions: 6.6mx6.7m
wall thickness: 450mm
Mass: 57tonne

Operating Pressure
Normal working pressure, lowest point: 900kPa
Maximum pressure incl. waterhammer: 1200kPa

Prestressing
Circumferential cables: 12/12mm 7wire strand
Number: 6420
Length (each): 12m
Radius of curvature: 3m
Spacing of cables: 200-300mm
Tensioning force: 1543kN
No. of jacks and pumps: 12

Longitudinal bars: Macalloy 28mm
Number: 8904
Length: 2.4m
Tensioning force: 547kN
No of jacks and pumps: 6

Concrete
Two mixes used. Rounded aggregates screened from greywacke river terrace deposits.
Milburn rapid hardening cement.
WRDA additive

<table>
<thead>
<tr>
<th>Quantity</th>
<th>agg size</th>
<th>spec.strength</th>
<th>slump</th>
</tr>
</thead>
<tbody>
<tr>
<td>m3</td>
<td>mm</td>
<td>MPa</td>
<td>mm</td>
</tr>
<tr>
<td>Main mix</td>
<td>9200</td>
<td>35</td>
<td>35 (7d)</td>
</tr>
<tr>
<td>Anchorage</td>
<td>800</td>
<td>10</td>
<td>45 (28d)</td>
</tr>
</tbody>
</table>

Concrete Testing, main mix.
6 blocks from each precast unit;
Tested: 3 at 7days, 3 at 28 days,150x200 blocks
No. of tests: 320
Mean strength 7d: 41.3MPa. CoV 8%
Range: 30 – 53MPa

Joint Mortar
Sand: AP 2.36mm, 1% passing 200
Cement: Milburn RH
Additive: Intraplast A
Sand/cement ratio: 1.0
W/C ratio: 0.5
Flow time: 20sec
US Army flow cone
Temperature limits
Strength at longitudinal stressing: 3.5Mpa (usually 18hrs)
Strength 28d: 20Mpa

Time Line
Conception: 1958
Initial design studies: 1958 – 59
Preliminary testing: 1960 -61
Decision to proceed: 1962
Detailed design: 1961-62
Construction Planning: 1961-62
Construction: 1962-64
Completion: September 1964
Commissioning: December 1964

An impression of size