STRUCTURAL ENGINEERING AND CONSTRUCTION CHALLENGES FOR THE TE MIHI GEOTHERMAL POWER STATION IN NEW ZEALAND

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ABSTRACT: *The recently constructed Te Mihi Geothermal Power station with two 83MW turbine-generator units on the north island of New Zealand, provided unique challenges in design and construction. Examples provided indicate how the collaboration of design and construction was required to meet the complexities of some of the large concrete and steelwork elements such as those supporting the heavier turbine, generator and condenser equipment in the turbine hall. A brief outline is also provided on other project areas where construction support in design enabled efficiencies in design to be recognised, such as the large cooling tower base slabs. The paper outlines design and construction integration providing safe erection on structures with complex interfaces.*

KEYWORDS: Design construction coordination, modelling, turbine generator table, erection, safety

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1 BACKGROUND

The Te Mihi geothermal power station project in Photograph 1, is a staged replacement of the existing Wairakei A and B power station on the north island of New Zealand and will play a significant part in contributing to the nations electricity supply through geothermal energy. The new power station consists of two 83 Megawatt (MW) steam turbine generator units and is one of the single largest geothermal projects at the time of construction. As part of its commitment to renewable geothermal energy, Contact Energy Ltd commissioned joint venture partners McConnell Dowell Constructors, SNC-Lavalin and Parsons Brinckerhoff (MSP JV) to design, build and commission the plant.

Photograph 1: *Aerial photograph of the Te Mihi Geothermal Power Station*

2 INTRODUCTION

Buildings, plant and equipment across the site required careful, planned construction sequencing of the works, often with partially erected structures supporting equipment. The 3D model of the overall plant layout is provided at Figure 1. The main structures of the plant include a 110 m long high turbine hall housing two turbine generator units (Unit #1 and Unit #2) on elevated concrete tables, condensers, generator circuit- breakers, associated pipework and equipment. On one side of the turbine hall are the 132 m long cooling towers and on the opposite side, the transformer enclosures and power distribution buildings, and the administration and workshop building (Photograph 1). Other structures include an acid dosing plant, rock mufflers, and support for pipework, IP and LP steam scrubbers, LP separators and other equipment.

From concept to construction, structural design on the project involved working closely with the construction team. Construction methods and staging had to be considered in the structural analyses including sequence to install larger/heavier equipment.

Design performance meeting operating and maximum design seismic events governed the design of the larger concrete structures supporting heavier components of the plant. Element size and seismic reinforcement detailing on these critical concrete elements created challenges requiring designers to work closely with the construction team to coordinate the works.

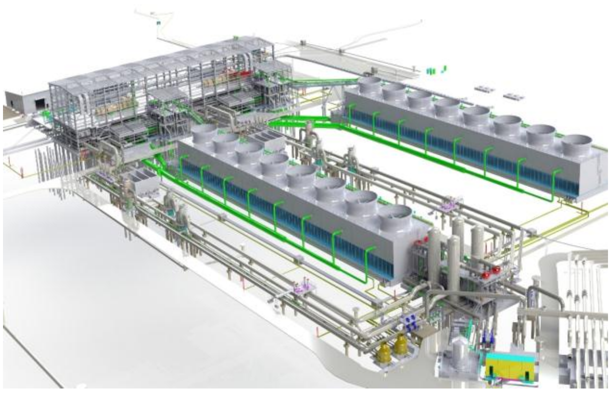


Figure 1: *Overall 3D model of the main plant elements on Te Mihi*

This paper considers the constraints and solutions developed by the combined design and construction teams on key elements and equipment installations at the plant. The integration of design and construction has been an essential part of the success of these works.

3 DESIGN – CONSTRUCTION COORDINATION IN THE TURBINE HALL

3.1 TURBINE HALL STRUCTURES

The 110 m long x 27 m wide x 24 m high turbine hall building incorporates two units with a separate operating floor at the level of the turbine and generators, lower mezzanine floors, hotwell pumps and NCG plants. A central loading bay within the building provides access for equipment installation and maintenance. An overhead 60t (SWL) gantry crane with a 15t (SWL) auxiliary hoist, and a lower 5t secondary gantry crane are provided above the operating floor for maintenance. Removable access hatches in a number of locations across the operating floor allow for access to equipment at lower levels. The NCG roof and hotwell pump roof structures are connected to the Eastern side of the building. Numerous pipework, electrical and mechanical services and equipment are contained within the building.

The building consists of a series of steelwork portal (sway) frames spanning the width of the building with additional sway restraint provided by operating floor 'strong' primary beams, internal columns and hotwell lean-to portal frames. Steel tension braced systems provide stability in the building long direction. A series of secondary beams make up the remaining floors.

Elevated concrete tables for the turbines and generators are isolated from the building frame above ground floor. The table concrete frame incorporates six large columns extending to a lower basement floor level 6.9 m below ground level.

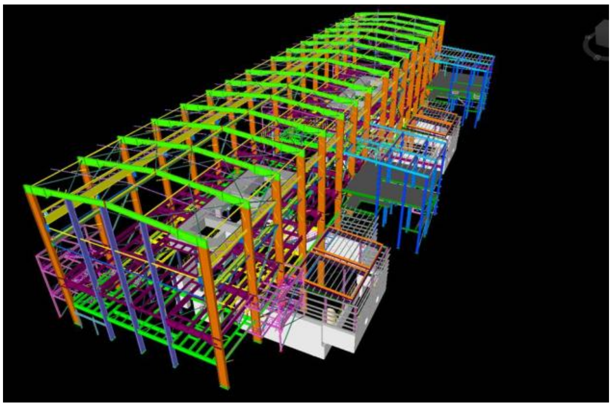


Figure 2: *3D model view of the turbine hall structures*

Given the construction program and complexity of spatial fit of all elements; incorporating erection sequence of the building framing and turbine table with equipment, pipework and service installations within the turbine hall in the structural design was paramount to success. The design needed to accommodate the turbine table construction, installation of turbine and generator equipment, condenser, IP and LP ductwork, valves and other various components / equipment within a staged building erection program.

Photograph 2: *Partially erected turbine hall steelwork with the condenser pre-assembly and turbine table*

3.2 TURBINE GENERATOR TABLE

Located within the turbine hall, the 25.4 m long x 10 m wide concrete framed tables of complex geometry, with typical beam sections of 1.8 m to 2.3 m depth and concrete columns up to 2.45 m x 2.45 m support the turbine and generator equipment. The table supports the combined turbine generator weight in excess of 500 tonne at 15.9 m above the lower basement floor and 9 m above ground floor. The turbine-generator table concrete frame is tied into basement retaining walls and also the ground floor slab. Finite element modelling including soil-structure interaction, combined with other analysis catered for all key stages of the construction sequence in design.

Construction of the elevated concrete table was delivered through a complicated, technically challenging sequence of events. The need to combine design detailing accommodating turbine and generator operating and seismic load conditions and thermal performance, together with tolerances and accessibility in construction required careful planning and coordination. Anchors and cast-in items needed to be detailed to achieve installation within tight position tolerances. Including construction staging in finite element analysis together with 3D modelling of the concrete profiles and cast-in items assisted in planning activities.

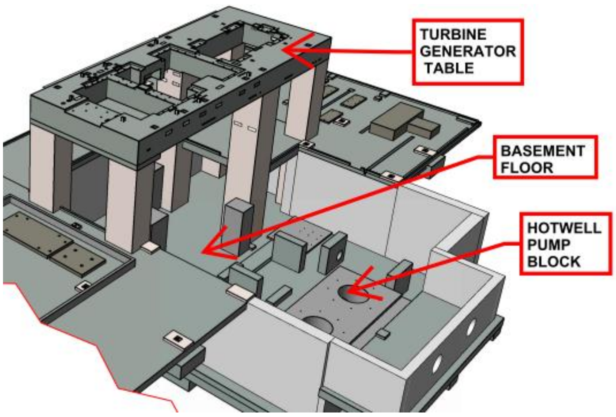


Figure 3: *Diagrammatic View of the concrete profiles of the turbine table and basement*

Close collaboration between the design and construction teams to integrate all requirements of design in the safe erection of the structure was paramount. The design and construction teams had to coordinate a staged construction sequence working with site access limitations in the basement excavation, tight equipment vendor tolerances and incorporating provisions to control risk of early thermal cracking in the large concrete sections.

Following completion of a 1200 mm thick basement slab supported on 64 no. cast in-situ bored piles, the six large concrete columns supporting the concrete tables were constructed. Incorporating a high level of column reinforcement with detailing to meet seismic design considerations, facilitating concrete placement required careful planning for constructability. Provision for construction of basement retaining walls between columns was also incorporated into design detailing. Prefabricating column reinforcement cages to speed erection; installing couplers on intermediate floors and inserts for mechanical installation and formwork through-ties, all tested the workforce to new limits. The columns were poured in 2 number 7 m high lifts, using a specially-designed concrete mix with a reduced aggregate size and composition to suit strength, workability and placement techniques. The design incorporated UC steel stub columns cast into the top of each upper column pour, extending 3 m above the finished concrete level. These stub columns would be used to support a large bolt template frame at a later construction stage.

Photograph 3: *Turbine table and columns in construction*

On completion of all six columns, a falsework system was erected to the soffit of the large turbine table (top of concrete columns). A complete proprietary system was imported from Germany and erected over a four week period. The system incorporated a 3 m wide platform around the entire table to afford access to the perimeter of the table at soffit level. Reinforcement requirements, couplers, inserts, conduits formwork through-ties and the large number of cast-in elements added to the congestion. Voids and rebates within the table were formed, upon which the turbines and generator would sit. The design and construction teams worked in close collaboration to coordinate the installation sequence for reinforcement and cast-in elements. The 3D model of the concrete elements and all cast-in elements in the table played a key role and contributed to the fact that all construction sequence and performance set-out tolerances requirements were subsequently met.

The key to the success of the table construction concrete pour was to set some 80 number bolts into recesses in the table top (around the top perimeter of each void) to anchor down the turbines and generators. In addition, in excess of 100 cast-in elements (plates / bench marks / anchors / jacking posts) were installed, some of which would be used to align the turbines / generators and fix additional pipework etc. during erection and for maintenance purposes. The tolerance for fixing of these bolts, 50 mm diameter, and plates was ±1 mm. In order to facilitate these high tolerances, a specially-designed bolt template frame was required. Support for the frame was incorporated into the concrete column design and detailing, hence avoiding the need to provide a separate support system.

After a number of iterations and amendments, a bespoke frame design was completed (Figure 4). The frame was designed using a pair of main longitudinal members which comprised 800 deep longitudinal beams at 27 m length forming the base with transverse beams and bracing to create a stability to maintain tolerances during concrete placement. The transverse beams were welded to the top of the longitudinal beams and were used for seating the frame on the cast-in steel columns. Additional beam members with diagonal bracing were welded across the top of the main members to provide stability, from which a number of sub-frames were hung.

Each sub-frame was constructed from SHS/RHS members used to hang and secure holding down bolt assemblies.

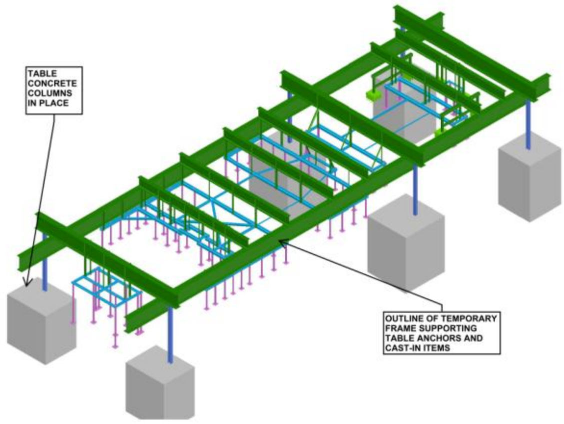


Figure 4: *Isometric 3D View of temporary frame to support turbine and generator anchor/cast-in elements*

The frame was constructed in a climatically-controlled workshop off-site (a 20°C temperature differential during the day on site would have resulted in a 5 mm longitudinal expansion of the frame), and upon completion measured 27 m long, 10 m wide, and 5 m high – it was delivered to site as an integrated and complete unit.

Photograph 4: *Temporary anchor support frame prior to lifting into position*

Temporary concrete foundations were cast adjacent to the turbine table at ground level, and upon delivery, the frame was off-loaded and placed upon these foundations (Photograph 4) – this enabled final checking and alignment of the frame prior to lifting into place onto the turbine table. The frame incorporated provisions for lifting and seating on the steel stub columns cast into the top of each concrete column.

The 25 tonne frame was lifted onto the steel column supports using the site's 180 tonne crawler crane. Alignment of the frame was undertaken, with the whole frame set to within 2 mm, and welded to the column supports. Final adjustment to the required ±1 mm tolerance was achieved using sleeves placed within the sub-frames and, upon final setting, welded into place. The sleeves were also to be used for the frame removal post pour. Cast-in plates were then welded to the frame at their precise location while it was in-situ.

The concrete reinforcing steel had been partially fixed prior to lifting the frame in place. Once the frame was set, the remaining reinforcement was placed, and then all internal shutters (to form the voids) and external shutters

(to form the table) erected. The shutters were all individually designed to ensure lifting into place and fixing was possible in and around the main frame and sub-frames. Sockets were placed around the perimeter of the table, to allow future installation of brackets which would support hand railing during ongoing construction.
As with the columns, a special concrete mix was used to ensure good flow around the congested steel. A high strength, early strength gain, low heat of hydration mix with a maximum 13 mm aggregate size was specifically designed for the pour with trial mix testing conducted.

Photograph 5: *Turbine generator table concrete pour*

Thermal Modelling by the design team to investigate measures to limit risk of early thermal concrete cracking in the large section pours was combined with construction techniques to establish a practical solution incorporating available formwork systems combined with top surface insulation. After completion of the pour and initial setting of the concrete, a 100 mm thick sand carpet was placed on the upper surface and kept within pre-determined moisture levels. After approximately 5 days, the formwork through-ties were removed and internal and external shutters released slightly, but left in place to maintain insulation of the concrete. Thermocouples were placed within the central core and surface zones of the concrete pour to monitor the temperature differentials on a daily basis, results then compared with analysis predictions to confirm timing for allowing removal of forms and the top surface insulation.

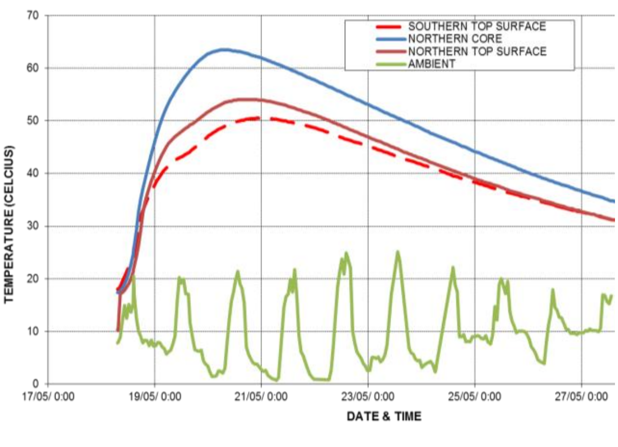


Figure 5: *Example Plot: Thermal couple readings from the surface and core of the table concrete pour*

The results from one table concrete pour are shown in the graphs in Figure 5. Maximum temperatures within the concrete reached 65-70°C in the central core zone, although, more importantly, the differential temperature gradient across to the section to the surface was controlled. By leaving the formwork shutters in place after early release for an agreed time period and adding the sand carpet to the top of the table, the risk of early thermal cracking of concrete was controlled.
Additional concrete test samples were also taken and compressive strength testing completed to ascertain strength gains and permissible timing of falsework soffit removal.
The welds holding cast-in plates were ground out, and all holding down nuts / washers from the turbine / generator anchor bolts were removed from the frame. The sleeves placed between the anchor bolts and sub-frame were removed, thus leaving more clearance for frame removal – without the sleeve removal the frame would have been tight around the bolts with little or no clearance for removal, damage to the bolts being a key concern. The 180 tonne crawler crane lifted the entire frame in one complete unit and landed it back on the concrete stub columns back at ground level, in readiness for its second use on Unit 2.
Post pour checks on both unit pours revealed a complete success of both pours – a high quality finish, with no evidence of early thermal concrete cracking, high concrete strength, negligible settlement of the falsework system, and all equipment bolts cast within the high tolerances specified – no additional work to the bolts was required prior to installation of both turbines and generators.

3.3 CONDENSER INSTALLATION

The installation of the Condenser positioned under the turbine generator table (Figure 6) is an excellent example of designer / constructor collaboration. The 10 m wide x 11 m long x 15 m high condenser unit, with a prefabricated weight of 240 tonnes had to be placed snuggly between columns supporting the turbine-generator table. In addition to building design supporting a condenser operating load of 490 tonnes and test load of 1310 tonnes, construction loading to facilitate the installation work sequence impacted the turbine hall steelwork design and basement floor detailing.
The Toshiba supplied condenser was delivered, from Japan, into Tauranga Port and thence on to a fabrication yard in Mount Maunganui in 18 separate sections. To reduce site fabrication, each of 3 adjacent sections were welded together in the yard and the larger 6 sections subsequently delivered to site.
The condenser sits on five concrete pedestals located underneath the main turbine table, in the hot well basement. Program time constraints dictated that the turbine table was constructed, but also that the steel frame to the turbine hall building was also erected. This posed a logistical problem involving trying to install the condenser in through the side of the building frame, underneath the turbine table, within the basement.

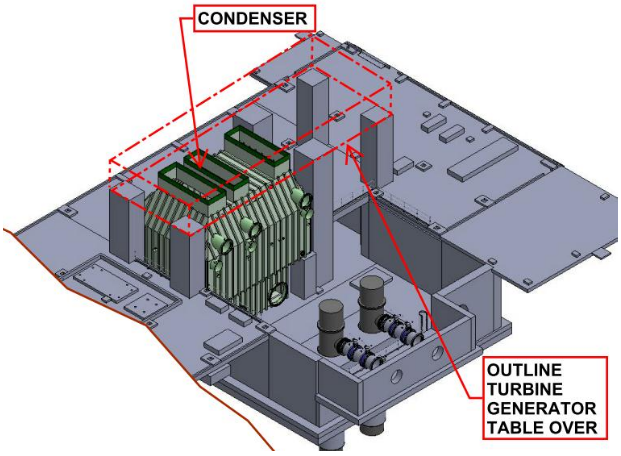


Figure 6: *Model view of condenser in final position*

Detailed discussions with the design and planning teams and installation contractor resulted in an agreed way forward – the condenser unit would be pre-assembled in the hot well basement, outside of the main turbine hall frame. To facilitate installation, upon completion of assembly, the turbine hall main portal column on one side of the building would be partially (lower half) removed, the condenser slid into place under the completed concrete turbine-generator table, and the portal column replaced. The design also had to allow for operation of the 5 tonne overhead crane required for other construction activities with the part-column removed.

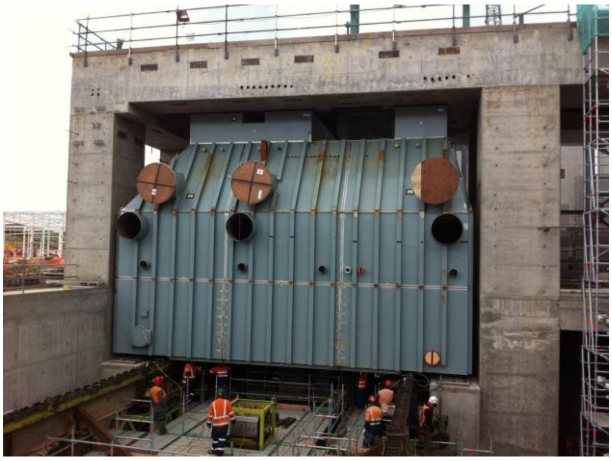
The detail centred on enabling removal of the lower portion of one of the main building portal columns. Of the 16 portal frames, 2 in each unit had columns extended down into the hot well basement on one side of the building (in each unit) – one of these would need to be removed. In addition, at the time of construction it was envisaged that the roof would be installed, and some or all of the mid-height operating concrete floor in place, adding to the weight that would need to be supported.

Incorporating an overhead temporary vertical truss system in the building wall framing design combined with the operating floor horizontal floor bracing system accommodated the requirements of the construction program. An additional column splice was added to the main portal column at 3 m above basement level – the condenser would then traverse clear over that connection. An additional splice was also added just below operating floor level, sufficiently high enough for the condenser to slide beneath. Between the 2 additional splices, a 12 m section of column could be temporarily removed. In order to facilitate its removal, additional steelwork creating the vertical truss with diagonal stays were incorporated in the building wall framing to distribute load to adjacent columns. Turnbuckles were added to the stays to facilitate any vertical adjustment – it was recognised that any potential vertical displacement of the upper (remaining) column would prevent subsequent replacement of the removed column section.

With early agreement of the temporary works scheme agreed, the structural design was able to incorporate these requirements into the permanent design.

The additional steelwork was procured, fabricated, painted and delivered all as part of the main building frame, saving significant time in site coordination and allowing for optimum program flexibility.

The resulting scheme was a huge success and would not have been possible without the design-constructor collaboration developed on the project.



Photograph 6: *The Pre-assembled 240 tonne condenser skated into position under the turbine-generator table*

3.4 GENERATOR INSTALLATION

The generator installation inside the turbine hall building at Te Mihi was another example of early coordination between design and construction contributing to project success.

The Toshiba-supplied generator was delivered from Japan, into Tauranga Port and thence onto site at Te Mihi where it was stored under controlled conditions prior to installation. The main constraint of the installation was the heavy lift involved had to be completed within the confines of a partially erected building structure. The generator main component weighing 190 tonnes had to be manoeuvred into the loading bay of the turbine hall, raised up to height, traversed over the operating floor and placed on top of the elevated turbine generator table. The ground floor slab design, operating floor and turbine table arrangement were designed for temporary loading for the lifting sequence.

The installation procedure was discussed and protocol agreed between the structural design team, temporary works team, planning team, and installation contractor. The generator would be driven into the loading bay of the partially completed turbine hall building on a specialist low loader, whereupon it would be jacked-up from ground level to operating floor level (10 m) utilising main beams supported on four large trestles. From there the generator would be swapped over to a beam system spanning from the trestles to the turbine table. The generator would then traverse from the loading bay to the turbine table, where it would be finally lowered into place and positioned.

The first hurdle to overcome would be the high point loads from the trestle tower frames applied to the ground floor ‘loading bay’ which would carry the weight and

impact of the low loader and generator, followed by the generator supported on the trestles. The building ground floor is a suspended concrete slab supported on piles and the load capacity had to be increased in the loading bay to accommodate the temporary works. Additional piles were installed at each trestle position, and slab reinforcement added to mitigate risk of cracking from all loading stages. By planning the operation months in advance, this temporary works scheme was incorporated into the permanent works design.

Due to the large dimensions involved, additional constraints were encountered. The low loader proved to be too wide for the gap between trestles. One pair of trestles was initially erected and the low loader was brought into the loading bay, the generator was jacked-off the low loader bed and the loader was then driven out of the bay. The generator was lowered to the floor before the final pair of trestles could be erected.

The next stage of the installation required jacking the generator up from ground level to operating floor level requiring a total 10 m lift. Computer-controlled jacks were utilised that were capable of jacking the assembly up 100 mm at a time. At operating floor level, two pairs of deep 'running' beams were set, spanning the 20 m between the top of the trestles in the loading bay to the turbine table. After investigating various design options, spanning the full distance clear of the operating floor to the table provided the best solution. The design team completed checks on the permanent works for the turbine table and ground floor, to ensure the point loading of the beam supports and all lifting operations would not cause any detrimental effect to the structures.

The generator was traversed from the loading bay, over to the turbine table, by running jacks mounted on the running beams. When the table was reached, the jacks would lower the generator onto pre-set, holding down bolts allowing for alignment / installation to commence.

The whole operation from arrival of the generator in the loading bay to seating on the elevated table, took approximately 48 hours; detailed planning and interfacing between design and construction teams facilitated what proved to be an issue-free operation.

Photograph 7: *190T Generator section in position on turbine-generator table using temporary frames spanning to loading bay*

3.5 HOTWELL PUMP SUMP

Two large hotwell pumps take warm geothermal condensate from the base of the Condenser of each turbine unit and pump it up to the cooling towers. A combined concrete hotwell pump block approximately 3m high tied into the basement retaining walls and floor slab supports the pumps and is designed for all pump operating conditions, including seismic loading. The pump sumps extend approximately 7 m below the basement floor.

Given the limited access for construction activities within the basement excavation, the design of the pump sump called for a staged construction sequence that maintained a safe work area. Working closely with the construction planning team and the pump vendor, the design solution consisted of a pump sump constructed from a fibre reinforced plastic (FRP) barrel placed inside a steel caisson, with the barrel extending up through the concrete pump block. A 2.6 m diameter x 16mm thick steel caisson was augured into the ground and the inside excavated using a drilling rig. After the basement floor construction was completed, the 2.13 m diameter FRP barrel was then lowered into the caisson and the gap filled with concrete. The pump blocks were constructed later within the planned erection program.

Photograph 8: *Hotwell pump sump steel caisson before and after installation*

The design of the FRP barrel accommodated soil-structure interaction behaviour under hydrostatic or seismic loading, and the steel caisson/liner provided a safe work barrier until the basement slab could be constructed.

Photograph 9: *Hotwell pump blocks in construction above the sumps*

4 COOLING TOWER BASIN

The 132 m long x 20 m wide concrete basins of the Cooling Towers are post-tensioned concrete liquid retaining structures with 250 mm thick walls and floor containing approximately 1.1 m depth of geothermal fluid. The basin supports the large Cooling Tower and fans above. To achieve an efficient design to provide lateral stability of the Cooling Tower under seismic loading conditions, friction between the basin slab and prepared ground was utilized rather than constructing additional lateral resisting elements to the basin perimeter. Hence, establishing the level of frictional restraint between the Cooling Tower Basin slab and subgrade was a critical aspect of the design.

The design required the cooling tower basins to have a specific range of coefficient of friction (0.8 to 1.0) at the interface between the slab and subgrade to achieve lateral earthquake resistance, but also be less than a maximum limit to ensure sufficient slip occurred for post-tensioning of the slab to occur. A finite element model (FEM) incorporating the slab-to-base friction behaviour was used to test the sensitivity of the design for a range of friction coefficient under horizontal and vertical earthquake loading.

Photograph 10: *Completed cooling tower basins prior to erection of cooling tower framing system*

The design team worked closely with the construction team to ensure the base surface for the slab construction would meet design requirements. A series of site friction tests were conducted to determine an appropriate value for the friction coefficient for the various ground conditions including compacted crushed rock (Gap 65) and the as-built concrete blinding, and testing for variability across different surface finishes. For each test a small block of concrete was cast onto the surface and load applied until slip failure occurred, or the test halted. A 5 tonne digital load cell was used to record results. The results of the tests are summarised in Table 1.

Test results indicated casting the base slab concrete on polyethylene sheet over a blinding achieved the desired result with the friction coefficient ranging between 0.77 and 0.95, noting that the target range was 0.8 to 1.0. For the cases with concrete cast onto crushed rock or directly onto blinding, the friction coefficients were many times greater than 1.0 and if adopted would result in a risk that the required slip would not occur at the slab-ground interface during post-tensioning. In addition, with coordination between design and construction, results of the testing enabled procedures to be put in place to achieve uniformity in the surface of the blinding layer surface.

Figure 7: *Test Concrete block poured on polyethylene sheet over a concrete blinding layer*

Table 1: *Concrete Block Friction Test Results*

Block ID	Basin Slab Construction	Friction Coefficient
1	Concrete cast on polyethylene sheet on blinding Area 1	0.77
2	Concrete cast on polyethylene sheet on blinding Area 2	0.82
3	Concrete cast on polyethylene sheet on blinding Area 3	0.95
4	Concrete cast directly onto blinding poured could not be moved at test load limit.	> 3.6
5 & 6	Concrete cast directly onto slab: not fully tested (based on other Central W result friction coefficient from Central W, result assumed)	> 3.6
7	Concrete cast directly on Gap 65	2.7

The cooling tower concrete basins for both Units were successfully constructed and post tensioned using the polyethylene layer over the blinding concrete, achieving an efficient construction solution to resist lateral seismic loading.

5 CONCLUSIONS

The key to the project success, evident in some of the above examples, was the close working relationship between the design and construction teams from concept through design and in construction; often providing opportunity for innovative solutions. The presence of experienced on-site design support engineers for construction a key to the whole process. Understanding the equipment interfaces within the plant, sequences to

install heavy equipment often in partially erected structures, equipment vendor requirements and construction access limitations on large structural elements played a significant part to success.

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