Design and Construction of the Turbine-Generator Pedestal at the Nga Awa Purua Geothermal Power Plant, Taupo
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ABSTRACT
A new geothermal power station at Rotokawa near Taupo is being built for the New Zealand Power Generation Company Mighty River Power. Named the Nga Awa Purua geothermal power station, the plant consists of a number of different structures including a large reinforced concrete pedestal that supports the 132 megawatt turbine and generator. The turbine and generator have a combined mass in excess of 400 tons. This paper will focus on the unique design aspects of the turbine-generator pedestal and provide an overview of some of the challenges that are faced during the design and construction of these structures.

INTRODUCTION
Under the auspices of the Japanese companies, Sumitomo Corporation and Fuji Electric Systems, a new geothermal power station at Rotokawa near Taupo is being built for the New Zealand power generation company Mighty River Power (MRP). Named the Nga Awa Purua (NAP) geothermal power station, the new $450m plant will generate 132 megawatts of electricity using steam from the Rotokawa geothermal field. The new plant is due for completion early 2010 and will house the largest single geothermal turbine in the world. Combined with the existing geothermal station at Rotokawa, the new plant will lift the total generation capacity of the Rotokawa field to 165MW. This will provide enough energy to power 130,000 homes [1].

Beca was engaged by the design-build contractor Hawkins Construction Limited (Hawkins) to provide the engineering design for the civil and structural components of the plant. Shown in Figure 1 below, the plant consists of a number of different structures including a vast array of pipe and plant support structures, a series of cooling towers, and the main turbine hall which houses the turbine-generator machinery.

The turbine and generator machinery have a total operating mass in excess of 400 tons which is supported 17m above the foundations on a massive reinforced concrete pedestal [2].

This paper will focus on the unique design aspects of the turbine-generator pedestal and provide an overview of some of the challenges that are faced during the design and construction of these structures. These concepts are not unique to geothermal power stations, and they can be applied to the turbine-generator foundations of most thermal power plants with steam turbines.

Figure 1: Computer rendered model of the finished plant on the Rotokawa site.

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The turbine-generator pedestal, as shown in Figure 2 below, is a large concrete frame structure that supports the four primary parts of the power generation process:

- The turbine which receives the processed geothermal steam that is injected at high, intermediate, and low-pressure points. The turbine converts the thermal energy from the steam into rotary motion.
- The generator which converts the rotary motion from the turbine into electricity. The turbine and generator rotors are aligned and directly connected. The turbine and generator are shown in Figure 3.
- The condenser is attached to the low pressure end of the turbine. The condenser is a large vessel that condenses the turbine exhaust steam to improve the efficiency of the system.
- The hotwell pumps collect the liquid condensate from the condenser, and pump it to the cooling tower [3].

At the NAP plant, the overall height of the structure from the base of the hotwell to the turbine operating level is about 21m.

The process design of the plant typically dictates the geometry of the pedestal. The NAP plant uses a common turbine-condenser arrangement where the condenser sits beneath the turbine. This requires that the turbine and the connected generator are supported over the condenser unit. The hotwell, which is essentially a sump for the condenser, is positioned below the base level of the condenser. This arrangement means that the primary parts of the plant are stacked vertically, with the turbine and generator sharing the top level as shown in Figure 3.

A reinforced concrete grillage supporting the turbine and generator machinery at 10m above ground. The grillage is approximately 20 x 9m in plan and the grillage beams are up to three metres deep. The grillage is supported on:

- Six reinforced concrete columns, ranging from 1.45 x 1.45m to 1.5 x 2.45m in size. These columns found on:
- A 1.6m deep reinforced concrete foundation slab at 7m below ground which is approximately 25m square in plan. The slab is supported by:
- Bored piles 0.9 m in diameter. The piles are founded at around 25 m below the ground surface.
- A 1.2m thick reinforced concrete slab supports the condenser at around 2m below ground. This
slab is supported by a series of longitudinal and transverse concrete walls.

- A series of concrete walls around the perimeter of the pedestal retain the earth in the below-ground parts of the pedestal. These walls are integral with the columns and are supported on the pile-raft.
- The hotwell pit sits at the side of the foundation slab and is integral with the pedestal structure. It founds at around 11m below ground [2].

While the pedestal structure is essentially just a piled reinforced concrete frame and shear-wall arrangement, the nature of the geothermal environment, the massive size of the pedestal parts, and the special demands of power plant operation means that the design and construction of these structures is technically demanding.

**SPECIAL FEATURES OF GEOTHERMAL ENVIRONMENTS**

Geothermal environments are unique for many reasons. Typically they are highly seismic areas, and so the structures must be designed to withstand large earthquakes—not only for stability under a very large earthquake (the ultimate limit state event), but also under lesser earthquakes that the plant could experience during its lifetime (serviceability limit state events). Continuity of plant operation is of paramount importance for these lesser level earthquakes.

Perhaps the most significant feature of a geothermal environment is that the groundwater, soil and atmosphere tend to be chemically aggressive. This environment is a hostile one for most materials, with humidity, heat, hydrogen sulphide, carbon dioxide, sulphates and chlorides in abundance. As such, material durability must be carefully considered.

**TURBINE-GENERATOR PEDESTAL DESIGN CRITERIA**

The design of a turbine-generator pedestal is an involved analysis and design problem that integrates a broad range of engineering disciplines. Table 1 outlines the design codes and references that were used during the design process for the NAP pedestal. The pedestal was designed as a nominally ductile reinforced concrete structure that resists gravity loads, plant operating loads and seismic loads. The Concrete Structures Standard NZS3101 formed the basis of the design, however, parts of the structure that are below the groundwater level needed to be designed as water-retaining structures according to NZS3106.

In addition to the general design criteria for strength, the turbine manufacturer imposed strict limits for deflections and vibration of the pedestal. These limits reflect the sensitivity of the machinery to differential deflections and excessive vibrations in the supporting structure.

| Table 1: Codes of Practice and Sources of Reference for the Turbine Generator Pedestal |
|---------------------------------|---------------------------------|
| **Subject**                     | **Code, Standard or Reference** |
| General                         | NZ Building Code                |
| Loading                         | AS/NZS 1170 Structural design actions, Parts 0, 1 and 5  
Beca site specific seismic hazard assessment for the Rotokawa site. |
| Reinforced Concrete Elements    | NZS 3101 Concrete structures standard |
| Slabs and walls below groundwater level | NZS 3106: Concrete Structures for the Storage of Liquids |
| Earth Retaining Structures      | Transit RRU Bulletin 84 Seismic Design of Bridge Abutment and Retaining Walls |
| Vibration Analysis              | Fuji – Conceptual Explanation for Design of Turbine Generator Foundation  
DIN 4024-1:1988 Machine foundations; flexible structures that support machines with rotating elements  
Various technical papers |
| Mass Concrete Thermal Effects   | CIRIA Report C660: Early Age Thermal Crack Control in Concrete |
| Concrete Durability             | NZS 3101 and various technical papers |
Support structures for any rotating or reciprocating machinery require special consideration of operating loads and dynamic effects. About 120 tons of the total turbine and generator weight is rotating parts that spin at 50 cycles per second.

For the NAP project, the plant supplier was Fuji Electric Systems Co., Ltd. (Fuji). Fuji provided the design criteria for the turbine-generator support structure including load cases and limits for deflection and vibration:

- Operating torque loads. The heavy rotating parts create a reaction force that tries to rotate the turbine and generator casings in the opposite direction to the rotors.
- Short circuit load. An emergency case, short circuit in the generator causes a very large alternating torque that is transferred to the foundation. This is simplified as an equivalent static pair of forces on the generator supports.
- Condenser vacuum load. The vacuum in the condenser and its connection to the turbine tries to pull the turbine and condenser towards one another.
- Friction forces. As the turbine and generator heat up and cool down the expansion and contraction of the parts induces friction force on the bearings.
- Allowable unbalance load. Unbalance load is the load that results from minor eccentricity of the rotor mass. This is an unavoidable load that is normally small in the accurately machined parts, but it can be hugely amplified if resonance occurs in the supporting structure. As such, ensuring that resonant effects are minimised is of utmost importance. This requires an understanding of the dynamic behaviour of the pedestal.

Explicit limits are placed on beam bending deflections, beam twisting rotations and differential displacements. The turbine manufacture also requires that the turbine and generator are installed at least 3 months after the construction of the pedestal to allow for short term concrete shrinkage.

**CONSTRUCTION MATERIALS**

The concrete mix designs for the pedestal were driven primarily by the durability requirements. This required dense, high-quality concrete with ample cover to reinforcement. The supplementary cementitious material, fly-ash, was a part of most concrete mix designs for this reason.

As shown greatly magnified in Figure 4, fly-ash is a very fine pozzolanic material that is a by product from the burning of pulverised coal. When added to concrete mixes, the fly-ash particles react with the cement and the resulting reaction products tend to fill the void spaces in the concrete. This reduces the permeability of the cured concrete to water and aggressive chemicals [6].

The piles for the pedestal found in volcanic soils with groundwater temperatures up to 65°C. CBE Consultancy (CBE) and Building and Construction Research and Consultancy (BCRC) were engaged by Hawkins to provide advice on how the high temperatures would affect the pile concrete during placement, and over the design life. While high curing temperatures can reduce the strength of normal concrete, increased temperatures improve the pozzolanic reactions with fly-ash, improving the overall strength of a fly-ash concrete. A low bleed-rate concrete was recommended by BCRC because the high temperatures at depth can cause rapid setting of the cover concrete which traps bleed water. This can cause delamination of the pile surface concrete [7].

Temperature was also an issue for the very large concrete raft slab, although the source of the heat was primarily caused by the heat that is generated by hydration reactions in the cement from within the concrete. Rapid changes in temperature or differential temperatures across large concrete elements are undesirable because they can cause cracking in the young concrete. This was an even greater concern for the raft slab since it also acts as a water retaining structure, and cracking could compromise the water-tightness of the slab. Fortunately, fly-ash tends to slow down the
reaction rate in the concrete, and CBE produced a special mix design to limit the heat of hydration during curing. The slab was also insulated during the curing period to help reduce differential temperatures across the slab [7].

Grade 500E reinforcement was specified for the pedestal. Due to the magnitude of the loads on the pedestal, most elements were heavily reinforced. The higher strength of 500MPa steel reduces the reinforcement ratios which has a cost benefit and improves constructability. High ductility grade “E” steel also improves resilience of the structural system.

SEISMIC DESIGN PHILOSOPHY

Power stations have a high economic value to the community, and so the pedestal has been designed as an importance level 3 structure according to the New Zealand structural loadings standard, NZS1170. The “importance level” is a function of the consequences of failure for human safety, economic factors, and the environment. Combined with the 50 year design life, the structure must be designed for an expected 1000 year earthquake.

The seismic demands on the TG pedestal governed the design of many of the structure’s parts. This was recognised early in the design process and so a site-specific seismic hazard assessment was carried out for the site. This assessment determines a more accurate value for the “site hazard” factor which dictates the design loads. It considers the location of the site with respect to local earthquake sources and the specific geology of the site. A study of this type reduces the conservatism of the loadings standard (which is more generalised), and can reduce the seismic load for that reason.

The structure has been configured with a clearly defined load path so that loads due to seismic actions together with gravity loads are capable of being transmitted into the ground in a predictable way.

The seismic design must not only consider the one in one thousand year seismic event, but also lesser-level events that may upset the plant operation. These are the ultimate and serviceability limit earthquakes, respectively.

- After a serviceability limit state 1 (SLS1) earthquake, the structure should maintain operational continuity and no repairs are necessary.
- After a larger serviceability limit state 2 (SLS2) earthquake, the structure and non-structure components may be disrupted by the earthquake, but they should not require repair.
- Under the ultimate limit state earthquake (ULS) the pedestal shall be designed for life safety. The pedestal may suffer significant damage but the risk of collapse is appropriately low.

The serviceability limit state load cases are checked by setting lateral deflection limits on the structure and ensuring that that the structure is sufficiently stiff. The ultimate limit state load case is checked by standard methods of strength analysis.

Figure 5: 3D computer rendering of piles, pile-raft slab and hotwell pit structure.

PILE AND RAFT SLAB DESIGN

The bored piles distribute the gravity and seismic loads to the stiff foundation soils. The piles are designed to resist both compression and tension loads from seismic overturning forces. Due to the aggressive ground conditions, it was recommended by BCRC that the normal friction capacity between the sides of the piles and the bored hole was ignored. This is because the surface concrete at the friction interface is likely to deteriorate over time, compromising its ability to transfer the pile loads. For this reason, the 900mm diameter bored piles were belled to 1300m at the base to provide larger end-bearing area, as evident in Figure 5. This increases the compression and tension capacity of the piles.
Figure 6: Photograph showing the foundation prior to the slab pour.

A global analysis of the pile group was carried out assuming a rigid raft slab to determine the reactions on the piles due to the design loads. The lateral soil-structure interaction between the piles and ground was modelled using lateral Winkler springs.

The 1.6m thick pile-raft slab distributes loads to the 34 bored and belled piles below. The slab was designed primarily by hand calculations and strut and tie theory; however, parts of the slab that formed the water-retaining basement required more exact analysis of the two-way bending loads. The program SAFE was used for this analysis. Punching shear from the pedestal columns and piles was also checked.

**BASEMENT AND HOTWELL RETAINING WALLS**

Figure 7 shows the precast wall assemblies at the basement level. The pedestal structure was very much on the critical path for the project, and so rapid construction was one of the key drivers from early in the design phase. In-situ construction of heavily reinforced, tall retaining walls can be time consuming, especially when the walls retain groundwater and must have dense, high quality concrete. Early in the concept phase, precast panel assemblies were chosen for the basement wall structures and the hotwell for this reason (see Figure 9).

The design phase directly involved the contractor and their pre-cast supplier so that it reflected the practical limits of panel sizes and the construction methodology. Drossbach ducts and Reid-bar technology simplified connection and starter details.

Figure 7: 3D rendering showing basement walls and the hotwell pit structure.

The retaining walls are designed for lateral passive earth pressure due to seismic force with due consideration of groundwater pressure. The walls also double as shear walls under lateral loads.

Specifying precast panels did result in an increase in joint waterproofing details. Considerable effort was spent to ensure that the joints in the walls were adequately water-tight. In addition to the specific water-retaining design of the concrete elements, a combination of hydrophilic water-stops (see Figure 8) and barrier-type water stops were used at construction joints and between precast elements. It is believed that the additional effort in the waterproofing details was far outweighed by the speed and finished quality of the system.

Figure 8: A well prepared hydrophilic water stop at a construction joint.
PEDESTAL COLUMNS AND GRILLAGE BEAMS

The largest pedestal columns are 2.5 by 1.5m and the height of columns from the top of raft to the underside of grillage beams is about 15m. The reinforcement was detailed so that columns could be cast in three manageable lifts.

The beams that form the pedestal grillage were one of the biggest challenges of the pedestal structure for both the design and construction teams. Rather than discreet beams, the grillage more closely resembles a deep slab with two large penetrations. The cross-section of each beam varies significantly over its length and the dimensions are such that “deep beam” effects had to be considered.

The largest of the beams support the generator. These beams are 3m wide by 2m deep and are loaded close to one edge. These beams must also take the brunt of the generator short-circuit load (should it occur) and transfer it into the support structure through torsion.

For the purposes of structural modelling, the beams were split into segments corresponding with significant changes in beam dimension so that reasonably accurate beam stiffness could be modelled. For the purposes of design, the smallest dimension over the length of the beam was used to accommodate straight lengths of longitudinal reinforcing steel.

The turbine pedestal was modelled in the program Spacegass with rigid end zones to represent the stiff beam-column joints. This model was verified using a shell element model in the program SAP. Off-centre support from the pedestal columns and loads applied at joints away from the shear centre of the pedestal beams may cause torsion effects that can be more closely modelled using shell elements rather than beam elements. Modelling the beam grillage using shell elements does not require adjustments for rigid end zones or eccentricity at load points and supports because these effects are inherent in the shell model geometry.

Detailing the reinforcement in the beams was a straightforward exercise, but the same cannot be said for the beam-column joints. Each beam-column joint was drawn to scale to ensure that the details were buildable and achievable.
Figure 11: Beam-column joints provided a challenge for the design and construction teams.

From a construction perspective, the grillage beams needed a large amount of falsework due to the sheer size of the beams and the access requirements (see Figure 12). Providing ample access around the pedestal at the top was essential for rapid placement of the beam reinforcement. Credit has to be given to the steel fixers who put the cages together with impressive speed.

Figure 12: The grillage beams required substantial temporary propping.

VIBRATION ANALYSIS

Irrespective of how accurately the turbine and generator machinery have been manufactured, there will always be some unbalance when the turbine and generator rotors are spinning. This unbalance produces an oscillating load that creates a dynamic response in the supporting structure—otherwise known as vibration. The size of the vibration depends on the natural frequency of the supporting structure. When the frequency of the applied oscillating load is close to the natural frequency of the structure, then resonance occurs. The result of resonance for the turbine-generator and its pedestal is that the unbalance loads will be greatly amplified.

A structure’s natural frequency is related to its mass and stiffness, and it can be determined by hand calculations or using computer models. Keeping the resonant response to a minimum involves checking to make sure that the natural frequencies of the support structure are outside the operating frequency of the turbine-generator by a reasonable margin. For the turbine rotating at 50Hz, this means the primary natural frequencies of the pedestal must be less than 40Hz or greater than 62.5Hz, but not in between [4]. The DIN 4024 standard has guidelines on “flexible structures that support machines with rotating elements”. These guidelines are generally accepted throughout the industry for vibration control and analysis of pedestal structures.

Individual parts of the structure (such as beams) may have their own natural frequency, and the structure as a whole will also have natural frequencies in the vertical and lateral directions. Variable materials and support conditions mean that calculations will never determine the frequencies with pin-point accuracy, but sensitivity analyses can be carried out to understand how different properties and assumptions affect the structure.

For example, a beam’s natural frequencies can be checked for both pinned end support and fixed end support. These two cases will give the lower and upper bound natural frequencies for that beam, even if the true end support conditions are not known. If both of these frequencies are outside of the critical range, then no further checks are required. If one of the frequencies falls into the critical range, then a more refined analysis may be needed. The same can be done for varying concrete properties or cracked and un-cracked concrete sections.
Figure 13: Vibration analysis models and outputs from SAP.

The vibration analysis for the NAP pedestal was verified by a number of different methods including hand calculations, full 3D models of the structure, and shell element models. The shell element model was carried out to identify if there was any torsional frequencies that could cause resonance. The model and selected output cases can be seen in Figure 13.

While computer modelling is a useful tool for vibration analyses, the best protection against unacceptable vibration response is to provide plenty of mass in the supporting structure. The general rule of thumb is that the foundation weight should be at least 3 times the total machine weight.

To make sure that the turbine hall building, or parts of the building do not vibrate, the pedestal and turbine hall are structurally separated as shown in Figure 14. This structural separation is carried all the way through to the foundations, and so the whole pedestal structure is nested within the turbine hall. This must be considered at all interfaces between the pedestal and the turbine hall [8].

Figure 14: Photograph showing the separation gap between the pedestal and the turbine hall building.
CONCLUSIONS

The design of a turbine-generator pedestal is an involved analysis and design problem that integrates a broad range of engineering disciplines. The nature of the geothermal environment, the massive size of the pedestal parts, and the special demands of power plant operation means that the design and construction of these structures is technically challenging.

Geothermal environments are typically highly seismic areas, and the exposure environment is severe for most materials.

The concrete mix designs for the pedestal were driven primarily by the durability requirements, and fly-ash was used as a supplementary cementitious material in the concrete.

For pedestal structures the turbine manufacturer imposes strict limits for deflections and vibration. These limits reflect the sensitivity of the machinery to differential deflections and excessive vibrations in the supporting structure.

Support structures for any rotating or reciprocating machinery require special consideration of operating loads and dynamic effects, so specific vibration analysis needs to be carried out as part of the pedestal design.

The turbine and generator at NAP will be commissioned in early 2010. Following on from the construction phase, we trust that the commissioning phase will go equally well.

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REFERENCES

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