TE MIHI GEOTHERMAL POWER STATION – STEAM TURBINE GENERATOR PEDESTAL DEFLECTION

Dugald Morrison[1]

[1]Contact Energy Geothermal Resources and Development, Brandon Street Wellington, New Zealand

dugald.morrison@contactenergy.co.nz

Keywords: *Pedestal Deflection.*

ABSTRACT

The Te Mihi geothermal power station steam turbine generator (STG) is supported on a concrete pedestal structure that supports the STG over an underslung direct contact condenser. Following commissioning, both Units had experienced significant ongoing deflection of the pedestal table due to both permanent plastic deflection from concrete creep shrinkage and elastic deflection from vacuum loading. These ongoing deflections have exceeded the turbine manufacturer's design criteria and required remedial works for STG rubs with multiple STG alignments and shimming of the STG casing.

Following an extensive investigation, a mitigation program was developed to address risk of STG rubs, potential coupling failure and future unplanned additional maintenance overhauls and alignments. A two stage implementation was used to initially relocate existing services, with a subsequent in-service installation of wide trussed columns. These works have been successfully implemented and pedestal deflection arrested.

Adequacy of support of the STG and the need for post commissioning monitoring of pedestal deflection is often not well understood by either the designer of the pedestal structure nor the operator.

This case study reviews the engineering investigations and mitigations developed for the excessive elastic deflection of the STG pedestal structure.

1. THE CASE STUDY ENVIRONMENT

The Te Mihi power station STG exhausts steam with a bottom discharge into an underslung condenser mounted beneath the STG. The condenser is bottom supported in the hotwell basement with a flexible bellow to the STG casing to accommodate thermal expansion.

The STG is mounted on a concrete pedestal with the turbine operating floor 15m above the basement floor. The STG has two cylinders comprising a single flow low pressure (LP) cylinder and a double flow intermediate pressure (IP) cylinder. The pedestal design uses 6 columns to support the STG such that the STG span is 14m between supports. This configuration resulted in the IP/LP coupling and the #2 & #3 bearings being mid span.

Following Unit hand over and commercial operation, excessive deflection of the STG pedestal was initially identified at the first major Unit outage within the first 5 months of commercial operation. STG realignment was required at each outage period until the pedestal strengthening works were completed. STG realignment requires a 25 day outage period. Maintenance planning for major outages was intended to have an initial 2 year period then stepping up to a routine 4 year period. Contact Energy (CE) had no expectation that frequent STG realignment would be required and the primary objective of the pedestal strengthening mitigation has been to minimize ongoing maintenance cost and operating risks.

1.1 Chronology

The following are the major dates over the duration of the Te Mihi power station development and operation:

- May 2014 – Unit completion
- Oct 2014 – Major Unit outage. STG required realignment to reinstate the IP / LP coupling top face gap to design condition. This alignment used all available bearing adjustment tolerance within the STG casing
- Sept 2015 – Major Unit outage. As found IP / LP coupling had an increased bottom gap. The STG casing required shimming to correct permanent deformation so as to enable the STG realignment to be performed. Soft rubs on blade tips and rotor inter-stage and gland areas were observed during the outages
- Oct 2016 – Major Unit outage. As found IP/LP coupling had a bottom gap indicating ongoing permanent deflection due to continued concrete creep / shrinkage. STG realigned with the No.2 & the No.3 bearings lifted. No significant additional new soft rubs were identified. Light rubs were identified on U1 LP rotor and U2 IP and LP rotors

  Stage 1 services relocation were performed to create a spatial void for future Stage 2 construction and transverse beam reinforcement was installed during that outage
- Aug 2017 – Planned outage for Sep 2017 for statutory inspection deferred by 3 months to allow for Stage 2 fabrication following review of ongoing deflection
- Jan 2018 – Stage 2 STG rectangular hollow section (RHS) and wide trussed columns installed and pedestal jacked

2. PEDESTAL DEFLECTION

2.1 Deflection Mechanism

Deflection of the STG pedestal since construction occurred as a result of two mechanisms :

- Permanent (plastic) displacement due to concrete creep and shrinkage

- Elastic deflection from vacuum drawdown and STG casing self-weight

The LP turbine is supported at the No 2 bearing and the IP turbine is supported at the No 3 bearing. (Refer Figure 1) The No 2 and No 3 bearings are supported on a transverse beam (east – west with 8m span). The transverse beam is supported by 14m longitudinal beams between the column supports. Each of these beams contribute to the overall mid span STG deflection.

Deflection of the STG foundation support will affect the position of each bearing and cause rotor misalignment. A conceptual image of the change of the bearing position due to elastic deflection from vacuum loading only is shown in Figure 1. Plastic deflection from concrete creep shrinkage has contributed an additional 3.6mm.

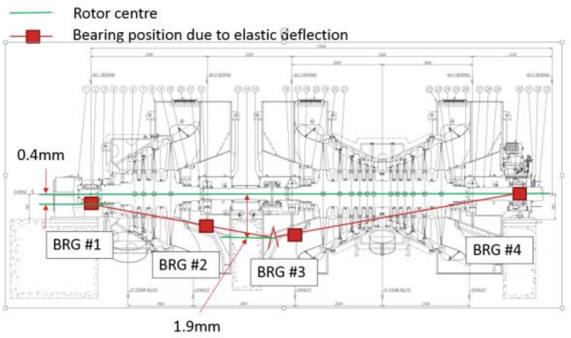


Figure 1: Modelled bearing position change due to elastic deflection from vacuum loading.

The Original Equipment Manufacturer (OEM) "Design Criteria for Turbine-Generator Foundation" required the maximum allowable vertical deflection for the foundation support, regardless of whether it is plastic (permanent) or elastic deflection, to be no more that 0.5mm.

2.2 Operational Effects of Excessive Deflection

The deflection of the STG foundation structure had resulted in the following over the first 4 years of operation :

- Soft rubs of the diaphragm seals and rotor castellations
- As-found LP/IP coupling bottom joint gaps approaching the OEM design tolerance for the accumulation of fatigue damage to the rotor coupling and coupling bolts
- Additional outage time incurred at each outage for STG realignment
- Additional outage time for shimming the IP and LP casings to relevel and compensate for permanent deflection from creep shrinkage
- Increased outage frequency

2.3 Risk Assessment

Contact Energy risk assessment considered the following as having life limiting consequence;

- Misalignment bending stresses on the rotor coupling and coupling bolts incurring fatigue damage. OEM identified an IP/LP coupling face bottom gap whereby cyclic bending stresses will result in a cumulative fatigue damage accumulation mechanism that could eventually result in failure of coupling bolts and rotor coupling. Progression beyond the elastic limit of the bolts would be expected to lead to catastrophic failure within a few seconds
- STG rotating component rubs. The shaft catenary, bearing support and casing support do not deform uniformly, potentially leading to ongoing rubbing which may deteriorate during the life of the assets

There are a range of risk / consequences for STG rubs. Soft rubs will result in increased maintenance costs to remediate and reduced operational life. There is potential for escalation to a low likelihood / high consequence event to occur.

CE concerns for long term mitigation of STG risk from inadequate clearances are :

- There will always be some rub/contact between fixed and rotating turbine components
- Rubs on both the shaft and on the tip seals will gouge out metal on the shaft or the seal faces on the diaphragms
- Possibility of micro-welding on the blade tip seals resulting in blade failure (worst case, low probability scenario)
- Rubs on the gland seals on the turbine shaft can cause hot spots which result in a bend or deformation in the shaft (worst case probability scenario)
- Rubs on the gland seals on the turbine shaft provide a path for steam erosion requiring extensive repair
- Constrained shaft from rubbing can stiffen the shaft and alter the critical speed so that it becomes a potential vibration source under normal operating conditions

2.4 STG Alignment

Alignment of the STG is performed with the Unit out of service by setting a coupling top gap so that in the operating condition, with vacuum draw down, the coupling faces are parallel. Excessive elastic deflection of the pedestal table and ongoing permanent deflection results in deflection of the STG rotor and applies bending stresses to the coupling bolts.

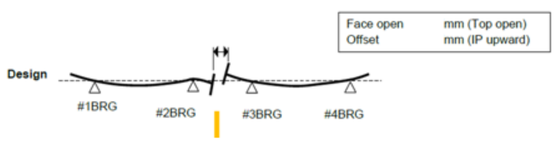


Figure 2: OEM design coupling alignment setting.

To counteract the effect of deflection from vacuum loading, the STG alignment is set with a LP /IP coupling face top gap so that in the operating condition the coupling faces will be parallel. The design coupling face top gap shown in Figure 2 is based on the foundation being level and that the STG pedestal elastic deflection will be within the OEM design criteria.

STG alignment has been over built from the OEM recommendation for the top gap to allow for greater elastic deflection from vacuum drawdown.

3. INVESTIGATION

3.1 Pedestal Beam Crack Survey

Following the first outage STG realignment, an inspection of the underside pedestal longitudinal beam identified similar cracking on both Units. A symetrical pattern of crack spacing was observed indicative of beam deflection with a crack spacing of approx 400mm adjacent to the columns increasing to approximately 200mm mid span.

Dial gauge monitoring of crack width (Figure 3) before and after outage showed that these cracks closed when the Unit was removed from service (vacuum released) and opened again on return to service, i.e. cracking is related to beam deflection from vacuum loading and not a result of concrete creep shrinkage.

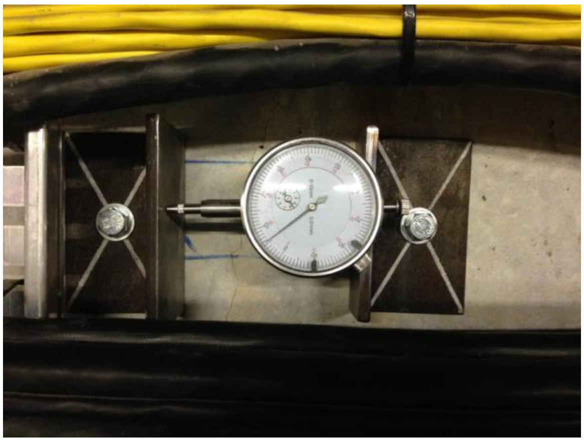


Figure 3: Unit 1 longitudinal beam crack monitoring.

3.2 STG Pedestal Modelling

BECA was engaged by CE in 2015 for the initial assessment of long term creep and shrinkage of the STG pedestal (Figure 4). The predicted permanent displacement due to creep and shrinkage properties at the No.3 bearing benchmark. The operational rate of displacement rate was estimated to be approximately 0.17mm/year, becoming asymptotic over time. Observed displacements were slightly greater than the predicted displacement.

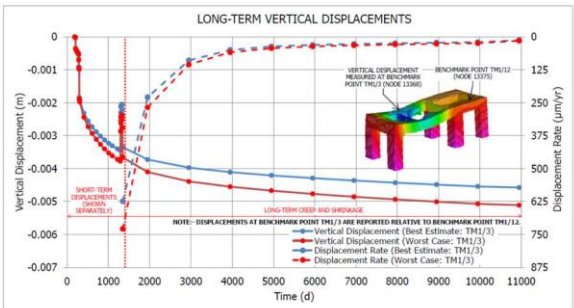


Figure 4: Initial assessment of long term displacements from concrete creep shrinkage.

The initial model of the in-service deflection included both plastic deflection due to concrete creep / shrinkage and elastic deflection from vacuum loading. This used "expected" standard concrete properties and the OEM sole plate loadings, which are based on full vacuum loading. Concrete properties are inherently uncertain in the material. Variation in geometric property estimates is mainly attributed to its highly non-homogenous and micro/macro discontinuous nature.

Discrepancies over a period of time with observed deflection resulted in revision of the modelled flexural rigidity identified from the dynamic response testing of the STG pedestal.

Modelling of the existing pedestal estimated that deflection of the longitudinal beam would be approx. 1.0mm at BM3 using standard concrete properties. Following the pedestal dynamic testing, the model was revised for coefficients of stiffness of 40% of the gross stiffness. This increased the analytical estimate of deflection at BM3 to 1.5mm

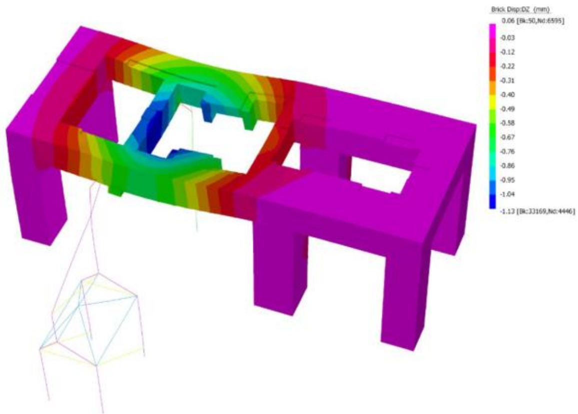


Figure 5: Elastic deflection under vacuum load with new RHS and wide trussed column supports.

3.3 Dynamic Analysis

Stiffening the STG pedestal will change the dynamic response of the STG pedestal and assessment was required to have confidence that no deleterious effects will occur.

The vibration monitoring provided accurate estimates of the existing un-stiffened STG pedestal structure's dynamic properties. This data was used to verify the analytical models of the pedestal. Understanding the dynamic characteristics of the pedestal is essential in preventing a structural dynamic issue when strengthening and stiffening the structure.

The assessment used an array of 47 temporary stand-alone tri-axis accelerometers and 18 single axis accelerometers mounted to the pedestal columns and underside of STG table. These were used to measure and record the natural frequencies during steady-state operation, turbine run-down and subsequent run-up sequences (Figure 7). The purpose of the run-down / run-up was to use the STG as a "shaker" so as to provide excitation to the STG pedestal structure over the range of 0-50Hz.

The analysis identified 5 global modes and provided estimates for the dominant natural frequencies, corresponding mode shapes and dampening ratios shown in Figure 6.

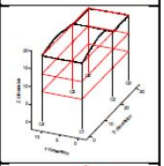
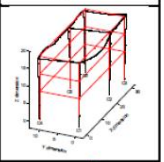
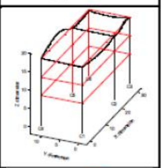
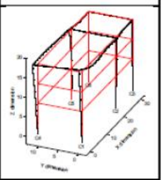
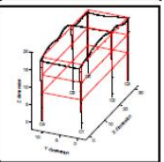
Mode	Frequency (Hz)	Damping (%)	Comment	Illustrative mode shape
1	15.6	6.2	Vertical bending mode, beam 1 (C1-C2) and beam 2 (C4-C5) move in-phase. This mode was not excited while the turbine was turned off (sequence 3).	
2	21.2	3.7	Lateral torsional mode. The modal participation for this mode is very weak.	
3	25.6	3.7	Vertical bending mode, beam 1 and beam 2 move out-of-phase, with small translational movement in the X-direction. This mode has the highest modal participation ratio. It was also very well excited during various operation stages.	
4	26.6	3.7	Vertical bending mode, beam 1 and beam 2 move out-of-phase, with translational movement in the X-direction (similar to mode 3). This mode was not detected by the frequency domain techniques.	
5	34.6	3.6	Vertical bending mode, beam 1 and beam 2 exhibits double curvature bending and they vibrate out-of-phase.	

Figure 6: STG dominant global modal shapes.

The observed dynamic response in the vertical direction is significantly larger than that in the horizontal directions. The 15.6 Hz mode was not excited during the off sequence and was likely a spurious mode. The mode at 21.2 Hz was a lateral torsional mode with a low modal participation ratio. The next three modes at 25.6 Hz, 26.6 Hz and 34.6 Hz were all vertical bending modes. The identified mode at 25.6 Hz had the highest modal participation ratio. The mode shape at 25.6 Hz consisted of out-of-phase vertical bending of the two longitudinal beams on the top level of the pedestal. This mode was strongly excited when the turbine was turned off which was a clear indication that this mode is purely structural and was not affected by the turbine vibrations.

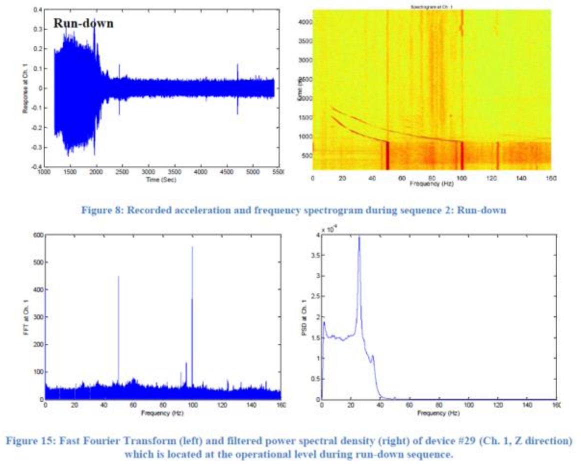


Figure 7: Structural dynamic assessment.

3.4 Dynamic Analysis

The dynamic analysis allowed validation of the theoretical model using the measured structural resonance modes, actual stiffening and damping coefficients. This provided confidence that modifications for stiffening the STG structure would not significantly modify the dynamic response nor inadvertently lead to resonance effects from in-service vibration of the STG. Model inputs for concrete properties for stiffness parameters and dampening coefficients were modified so as to match the analytically derived mode shapes (refer Figure 8) and frequencies of the theoretical model dynamic response with the actual observed result.

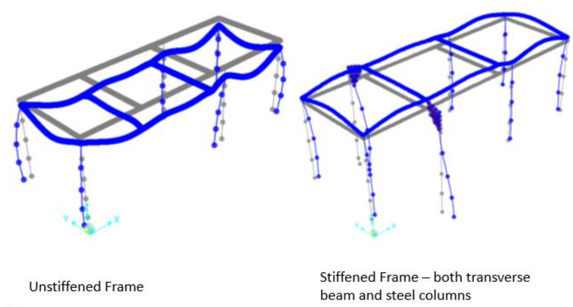


Figure 8: Dynamic response – 1st modal shape.

The initial theoretical model, using expected concrete properties, required the gross flexural stiffness to be reduced to 20 – 30% of their initial value (original assessment using standard concrete properties) to obtain a close match for the dominant frequencies derived from the vibration analysis. The revised displacement assessment is shown in Table 1.

With the theoretical model calibrated to the actual STG structure performance, the modification for the stiffened structure for both transverse beam stiffening and RHS column and wide trussed column modification was assessed. There was a 4% difference for increased vertical natural frequencies. It was concluded that the stiffened STG pedestal was compliant with the OEM design criteria as the natural frequency of the structure was not within 20% of the STG running speed.

Pedestal Condition	Load Case	Original Assessment		Final Assessment	
		Point A	Point B	Point A	Point B
Existing (unstrengthened)	Vacuum load	1.6mm	1.0mm	2.6mm	1.5mm
	Thermal change (-15°C) (displacement is relative to top of the end columns)	0.4mm	0.3mm	0.6mm	0.5mm
Transverse beam strengthened	Vacuum Load	1.2mm	1.0mm	1.9mm	1.5mm
Beam and column strengthening	Vacuum Load	0.75mm	0.4mm	1.1mm	0.5mm
	Column Preload (50 Ton)	0.3mm	0.3mm	0.5mm	0.5mm
	Thermal change (-15°C) (displacement is relative to top of the end columns)	0.5mm	0.4mm	0.7mm	0.6mm

Table 1: Assessment of STG pedestal table displacements.

3.5 Temperature monitoring

Modelling indicated that thermal effects had a significant impact on the unmodified STG pedestal platform level of 0.6mm for a 15°C temperature change of the structure.

The effect of temperature variation on the structure was also observed with multiple laser survey flatness data over outage periods.

Monitoring of actual annual temperature variation for the Unit 2 STG pedestal structure has been performed since Nov 2016 using TinyTag data loggers and temperature probes. (Refer Figure 9) Concrete column measurements were taken from thermocouples embedded 120mm into the column at the mezzanine level approximately 1.2m below the STG table. Surface mounted thermocouples are mounted on adjacent steel columns.

The modelled 15°C concrete structural temperature variation has been validated as a conservative assessment.

Figure 9: Thermocouple monitoring installation of Concrete and steel columns.

Temperature monitoring (Figure 10) indicated that both steel and concrete columns are sensitive to ambient temperature variation.

- The concrete column follows the daily ambient max / min with a typical 6.5 hour offset and temperature range is typically 10% of the daily ambient temperature variation
- The steel column follows the daily ambient max / min with a typical 3.5 hour offset and temperature range is typically 54% of the daily ambient temperature variation

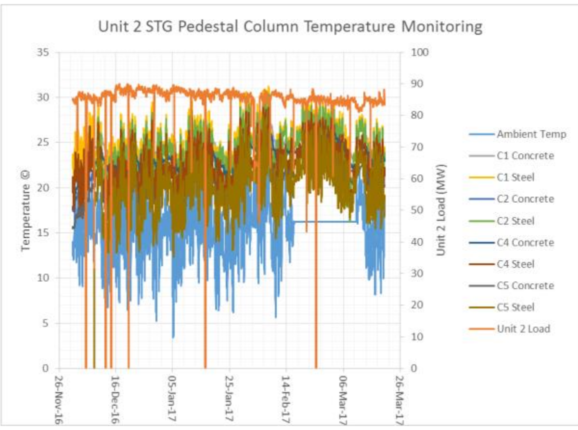


Figure 10: STG pedestal temperature monitoring.

3.6 Deflection Monitoring

Benchmarks were installed in the pedestal table during construction adjacent to each STG pedestal. Initially optical survey levels (Figure 11) were used to monitor bearing benchmarks using the #6 bearing (northeast generator outboard) benchmark as the reference point.

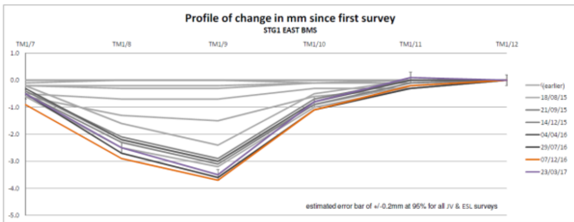


Figure 11: Optical deflection survey monitoring.

Multiple laser surveys have been used for high definition measurement of bench mark deflections prior to outages, monitoring run down and run up and during the outage strip downs.

Additional reference benchmarks were installed outboard of the STG when it became apparent that the #1 bearing benchmark was subject to deflection. These have verified the modelled pedestal deflections.

3.7 Vibration Monitoring

Independent assessment of Bentley Nevada 408ADRE data for Unit run-up and run-downs was performed by SVT.

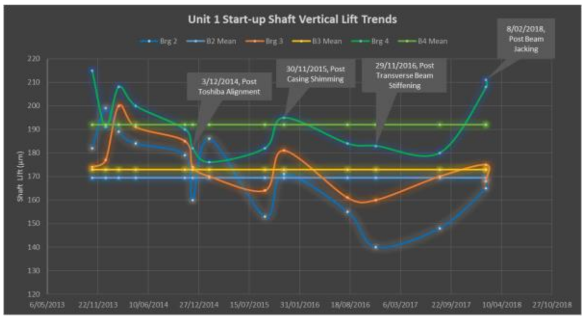


Figure 12: Historical Unit 1 start-up shaft vertical lifts trends (bearings 2,3 & 4 with mean values).

The vibration assessment has shown increasing constraint in the vertical plane over time due to increasing plastic deflection, in the form of reduced shaft lifts and vibration amplitudes. Following each outage, STG realignment, and the casing shimming works in 2015, there was reduced constraint in the form of increased shaft lifts and vibration amplitudes. These degraded over time with the ongoing plastic deflection indicating light rubbing present in vibration data; with evidence in the form of variability in amplitudes, orbit position, and orbit shapes.

4. MITIGATION OPTIONS

BECA were engaged to perform detailed analytical modelling of the pedestal and structures for strengthening options to reduce displacement of the STG table due to vacuum loading.

Five preliminary concepts were developed by BECA for stiffening the longitudinal beams. These were:

- Truss depth to Mezzanine Level

- Truss depth to Ground Level
- Fabricated Steel I-Beam to Mezzanine Level
- Single vertical column
- Double vertical column

Assessment of viable options for stiffening the longitudinal members identified vertical column supports as the most viable construction / installation option for minimising modification of existing infrastructure and consideration of the outage periods required for installation.

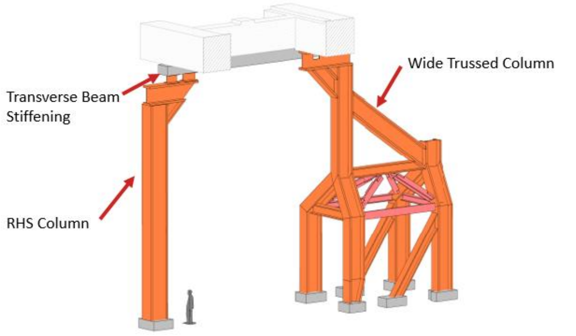


Figure 13: STG pedestal stiffening structural elements.

Assessment of strengthening options were designed to achieve a 55% reduction in deflection. Larger reductions in deflection are technically possible but are into the regime of diminishing rate of improvement.

Transverse beam stiffening design was configured to use the maximum available remaining space above the condenser

Two vertical columns were designed (Figure 13). The west side allows for a single fabricated RHS box section column to be installed by relocating lubricating oil and other service pipework to provide a void. The east side was achieved by use of a wide trussed column so as to bridge the CW pipe work (Figure 14). Multiple iterations were required to finalise the design.

The columns were fabricated from 100mm thick plate and require approximately 227 t of steel per Unit.

The structural steel frames were modelled with base spring supports to take into account the resultant displacements of existing piled raft foundation resulting from the frame base reactions. The spring stiffness was determined by modelling the proposed frames on the existing raft foundation.

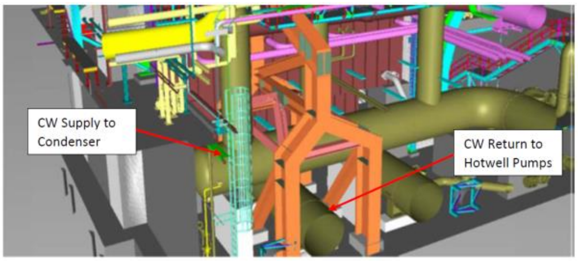


Figure 14: Wide Trussed Column Straddling CW Pipework.

5. IMPLEMENTATION

A staged implementation was used to manage risk and cost as the engineering assessment proceeded :

- Stage 1 – Enabling Works; Transverse beam and services relocation installed in 2016 outage to provide clear void for the subsequent (in service) installation of Stage 2.
- Stage 2 – Procurement of bulk materials, off site fabrication, and in- service installation of RHS column (west side) and wide trussed column (east side). Jacking of the STG pedestal performed during the Jan 2018 statutory inspection outage.

An early decision was made in 2016 to split the strengthening works into two stages when lead time for large plate material procurement and fabrication of columns was not viable to meet the scheduled outage. The Stage 2 works were committed in August 2017 when assessment of ongoing deflection indicated a high risk of an additional outage for STG realignment would be required prior to the next scheduled major outage in 2020, with potential STG damage occuring if no action was taken.

5.1 Stage 1 Enabling Works

The following services were relocated so as to provide construction space for the subsequent in-service Stage 2 column installation:

- Lube oil supply, vent and drain lines
- Component cooling water, raw water, domestic water, fire water and auxiliary cooling water
- Instrument air and distributed service air
- IP steam condensate, gland steam and condenser drains
- Gland steam supply and IP bleed steam
- Hydraulic oil lines to IP steam valves, Condenser CW inlet valve actuators condenser LP spray manifold
- Access ladders and handrail modifications
- Miscellaneous control, small power and lighting cables
- STG Pedestal No 2/3 bearing transverse beam installation

The following Figures 15 & 16 illustrate clash / interference and the relocation of the gland steam pipework were required on the east side to provide the construction space for the wide trussed column installation.

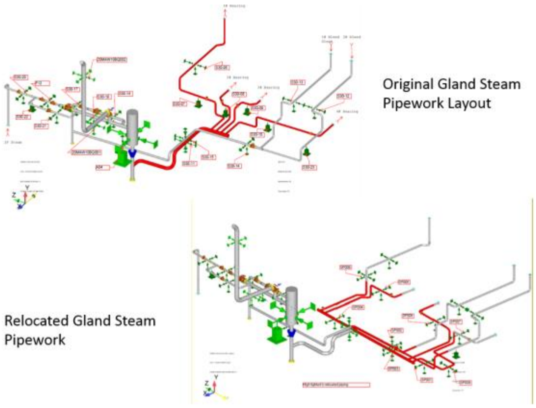


Figure 15: Gland steam pipework modification.

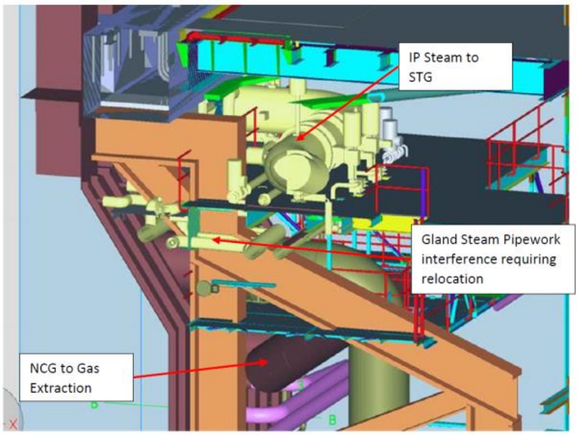


Figure 16: Wide trussed column showing interference with the original gland steam pipework.

The use of point cloud survey of the original equipment installation (Figure 17) provided a high degree of confidence for the design and installation of the both services and structure.

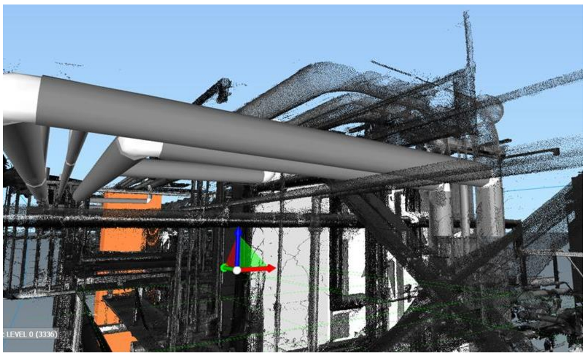


Figure 17: Relocated lube oil pipework with point cloud location of original services.

Extensive prefabrication of pipework spooling minimised installation time and enabled the Stage 1 services relocation to be performed within the scheduled Unit outage.

5.2 Stage 2 Column Installation and Jacking

In-service installation of the RHS (Figure 18) and wide trussed columns was completed prior to the 7-day statutory inspection outages. Once the structures were complete, the jacking process was able to be undertaken. This involved placement of large hydraulic rams between the top of the installed structures and the underside of the STG pedestal table; incrementally lifting the table; placing thin metal 'shims' in the created gap; and then lowering the STG pedestal table onto the shims/columns. Checks were made to ensure that the STG pedestal table was still level, before making the final bolted connection.

Figure 18: RHS column installation Unit 1.

Strain gauges (Figure 19) were also installed at critical locations on the structures to provide real time information about internal material stresses and movement during the jacking process. These strain gauges will be used for monitoring ongoing operation.

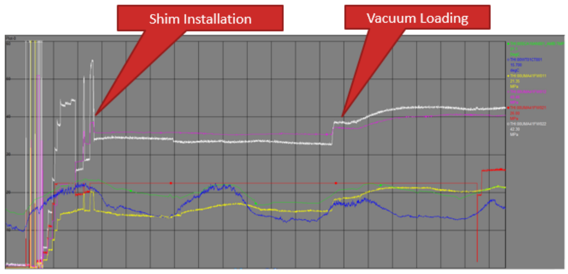


Figure 19: Strain Gauge Monitoring Of Pedestal Jacking.

Surveys of the STG pedestal table were undertaken prior to jacking, during jacking, immediately after completion of the shimming works, and at regular intervals since.

The magnitude of the lift achieved by the jacking process was within the expected range (1.2 – 1.5mm) for both units, and no further unexpected movement has been measured on either foundation since the completion of the works.

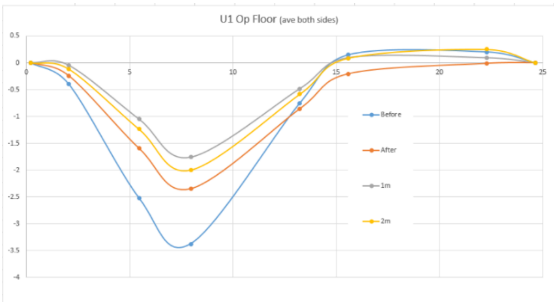


Figure 20: STG Pedestal Deflection Pre & Post Jacking

Post-works measurements to date (Figure 20) have confirmed that deflection of the foundation has been halted, with only minor movements due to changes in ambient temperature and operational loading now evident.

Following the completion of the Stage 2 works and the observed stability of the turbine foundation slab, the risks of turbine damage due to ongoing deflection of the foundation slab have now been mitigated.

6. LESSONS LEARNED

While the Te Mihi STG design with a mid-span IP/LP coupling highlighted deflection issues, conventional STG design for under slung condensers being supported by bearings at column locations will also be susceptible to rubs as STG cylinder cases are not rigid. Casings will deflect with the foundation support and this has the potential to reduce top gap clearances mid span and result in rubs. Midspan casing shimming has been performed on a number of plants to remediate foundation deflection.

The following items address concerns that are specific to how the Te Mihi STG pedestal issues progressed. Understanding the context of the Te Mihi STG pedestal can assist with ensuring that these are not repeated. Installation of adequate bench marks during construction will provide the operator / maintainer with the means to monitor deflection.

6.1 Implementation / Execution

- Stage 1 Transverse beam strengthening was the most time critical component so as to achieve an adequate cure before significant deflection loading from the turbine rebuild
- Preplanning / coordination contributed to successful implementation for staging of works and completion within planned outages. Timely application of safety isolations enabled as early as practical commencement of works
- Constructability reviews with designer and Contractor in final design iterations contributed to prefabrication and minimized site field installation and time slippage
- The lube oil cut-ins and relocation were a high-risk activity for potential contamination and outage delay for achieving oil flush. This was addressed with contract requirements for cleanliness. Contractor implementation and compliance with best practice installation (including water blasting and independent borescope inspection) provided high assurance of cleanliness prior to boxing up
- Installation of large column sections required design modification for additional flanged connections due to restricted access within lifting corridors
- Laser level surveys from outboard bench marks have provided consistent high definition measurement of pedestal deflection
- The balance condition of the STG remains very good and low vibration levels resulted in subtle indications of rubs

6.2 Future Design / Specification

- Benchmarks to be installed along length of pedestal table on either side of the STG at bearing supports and include mid span of casings and beams
- Reference benchmarks to be installed outboard of the STG on the pedestal at locations least likely affected by structure deflection
- Structural design reports to expressly require forecast of long term displacements over the initial 10-year operation
- Contractor / STG OEM to provide outage schedule program on when SGT realignment expected to be required based on pedestal deflection (no surprises outage planning)
- STG OEM sign off of structural design report to ensure compliance with STG deflection criteria
- Construction scheduling for early STG pedestal construction and as late as possible erection of the STG to provide the longest cure time to reduce the creep shrinkage post STG installation

ACKNOWLEDGEMENTS

Thanks to my CE colleagues, Bernd Pummer, Chris Morris and Peter Moffat, for their comments and review of this paper.

REFERENCES

BECA: Assessment of Long Term Displacements for the Te Mihi STG Pedestals (2015). Confidential client report

BECA: Te Mihi Turbine Generator Pedestal Strengthening (2016). Confidential report. Confidential client report

BECA: Te Mihi GPP Investigation of Possible Impact of Stiffening the STG Pedestal (2016). Confidential client report

Building Sensory Systems Limited: Vibration Monitoring and System Identification – Turbine Generator Pedestal Te Mihi Power Station (2016). Confidential client report

Contact Energy: Evaluation of Stage 1 Te Mihi STG Pedestal Stiffening Work (2017). Confidential client report

Progen: Laser Survey – multiple reports (2016 – 2018). Confidential client reports

M Robinson, H Houston: Flatness Survey and Correction of Turbine-Generator Alignment Using Laser Measurement Techniques, NZGW (2016)

SVT: Te Mihi Steam Turbine Generator 1&2 ADRE Data History Review – multiple reports (2016 – 2018). Confidential client reports