DISCHARGE LIFT HEIGHT UPGRADE OF A LARGE ARCHIMEDES SCREW PUMP STATION

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ABSTRACT

Pump Station PS205 is Christchurch's largest storm water pump station with a capacity of 13 m^3/s, lifting water from Horseshoe Lake to the Avon River by 3 Archimedes screws. During the Christchurch earthquakes the pump station settled approximately 150 mm, significantly reducing the return period flood event against which the pump station could pump at full capacity and consequently increasing the risk of flooding in the catchment it protects.

Assessing the feasibility of restoring or increasing lift height was challenging due to the hydraulic complexity of a screw pump, old age of equipment and difficulty in sourcing design specifications. Additional challenges in determining a preferred approach include the uncertainty around sea level rise and the future use of the Residential Red Zone surrounding the pump station.

In response to this complexity the study adopted a multi-layered approach utilizing a range of information sources and evaluation methods including:

- computation fluid dynamics modelling (CFD) to assess the hydraulic limitations and determine increase in loading with screw extension
- specialist market suppliers and Contractors to draw upon specialist industry experience and to validate CFD modelling outputs
- data research to source historical drive train component specifications
- Council operatives to gain historical knowledge

The study confirmed a lift upgrade of 0.45 m (0.3 m above pre-earthquake levels) was technically feasible. This upgrade would enable pumping at full capacity during flooding up to a 50-year return period event. It further identified that additional lift, possibly as much as 0.6 m (0.45 m above pre-earthquake levels) is likely to be feasible.

The paper outlines the assessment method, outputs, value gained from the study process and the resulting confidence gained by Council to make an informed decision on the retention and upgrading of this asset.

KEYWORDS

PS205, Archimedes Screw Pump, Computational Fluid Dynamics, Pumping Station, Capacity Increase, Earthquake Recovery

PRESENTER PROFILE

Matthew Sheppard is a Principal Water Engineer working in Jacobs Christchurch office. He has 26-years experience in hydraulic assessment and design for pump stations and reticulation assets.

Bas van Lammeren is a Christchurch City Council project manager in the Land Drainage Recovery Programme with more than 10 years' experience in technical and asset management of coastal and rivers projects, including design and maintenance of hydraulic structures.

1 INTRODUCTION

Christchurch City Council's (Council) storm water pump station PS205, located between Horse Shoe Lake and the Avon River, settled approximately 150mm in the Christchurch earthquakes, retaining its discharge capacity but reducing its lift and discharge height. The impact of this settlement is that the pump station is less effective than pre-earthquake with respect to its ability to discharge to the Avon River during flood conditions.

PS205 is Christchurch's largest storm water pump station with a maximum capacity of 13 m^3/s. It has two 5.0 m^3/s screws powered by diesel motors that are approximately 70-years old and one 3.0 m^3/s screw powered by electric motor. The pump station was constructed in 1977 and designed to enable pumping from Horse Shoe Lake into the Avon River during a 50-year return period flood level of RL10.81 m.

Advances in the reliability of flood modelling and the adoption of allowances for sea level rise have resulted in the current design 50-year return period flood level in the Avon River increasing to RL11.20 m.

Settlement resulting from the earthquake has reduced the level at which full pump flow is achievable, from RL10.90 m to RL10.75 m.

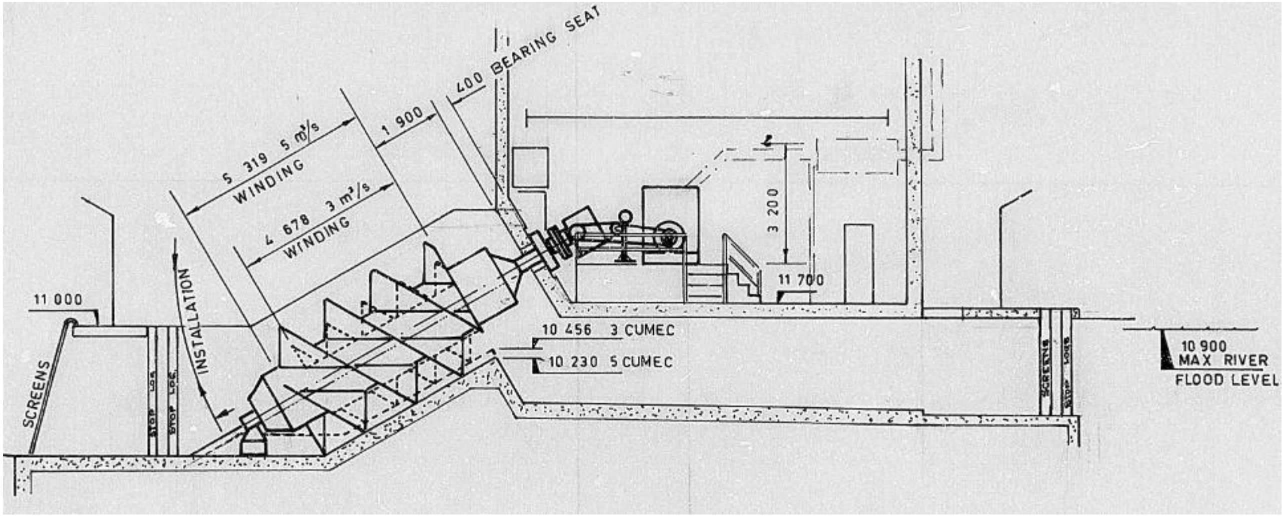
The combination of these factors is that PS205 can now only discharge at full flow when the Avon water level is below RL10.75 m, a level which is close to the 10-year return period tide or a flood event with return period between 10-years and 20-years.

As there remains a need for PS205 to remain operational and effective, Council engaged Jacobs to determine whether upgrading to enable full pump capacity in a 50-year return period flood was feasible and how this could be achieved.

2 PS205 GENERAL ARRANGEMENT

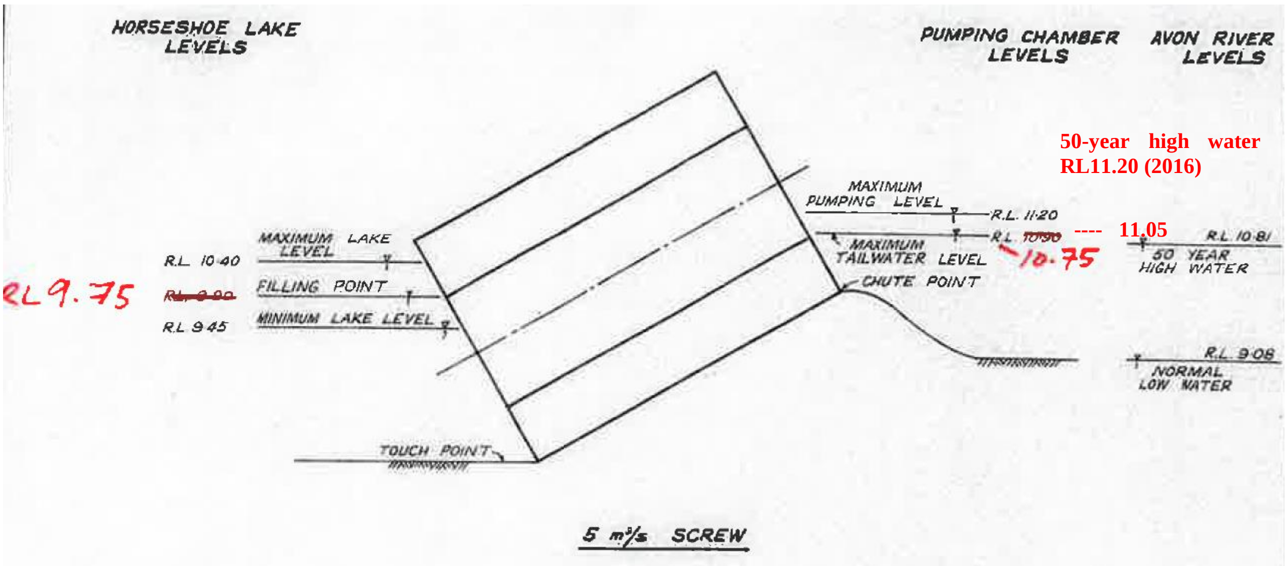
A general arrangement of the one of the 5.0 m^3/s screws, including gearbox and drive unit is presented in Figure 1.

Figure 1 : General arrangement of 5.0 m³/s screw



A schematic showing the original design operational levels, current (post-earthquake) operational levels in red and the current 50-year Avon River water level is presented in Figure 2.

Figure 2 : PS205 design water levels post-earthquake



Note:

1. **Maximum tail water level** is the highest Avon River water level at which the pump station can pump at full capacity. This reduced from RL 10.90 m to RL 10.75 m as a result of the earthquakes.

2. **Maximum pumping level** is the Avon River water level at which pump discharge rate reduces to zero. Above this level water will overflow the screw. This reduced from RL 11.20 m to RL 11.05 m as a result of the earthquakes.

3 LIFT HEIGHT UPGRADE FEASIBILITY ASSESSMENT

The lift height of a screw pump is determined by the level of the flights and trough at point of discharge. The most efficient means of increasing the lift height is to extend the flights along the screw shaft.

Extending the screw length results in an increase in the mass of water within the screw pump and an increase in the height it is lifted, which increases loads on the shaft, bearings and drive train. It also reduces the available "throat" area between the top of the screw and the inlet headwall through which the water discharges which at some point would pose a hydraulic constraint.

There is complexity in determining the feasibility of an extension for reasons including:

- age of mechanical equipment, which is in the order of 40-years for the pump station and 70-years for diesel motors

- lack of knowledge of original design basis and factors of safety applied

- complex hydraulics of the screw pump and discharge into the outlet structure

Recognizing the assessment complexity, importance of the asset and need for Council to have sufficient confidence in the assessment to make asset upgrade decisions, a multi-layered assessment method was adopted, including complex technical assessment, industry liaison to access mechanical experience and specialist screw pump supplier input to validate the technical assessment outputs. The following feasibility assessment activities were undertaken:

- Development of a computational fluid dynamics (CFD) model of the 5.0 m^3/s screw and discharge structure to develop shaft loads and model the flow of water into the discharge structure

- Identifying suppliers of original equipment to source specifications for gearboxes and to seek specialist screw pump designer / supplier input

- Interviewing of operators to gain their experience and undertaking site visits to observe pump operation

- Establish the relationship between hydraulic limits, screw extension and drive train upgrade requirements and visually to demonstrate this

4 ASSESSMENT OF FLOWS AND LOADS

A CFD model was developed for the 5.0 m^3/s screw and intake structure based on the as-built dimensions, post-earthquake building levels and current screw rotational speeds. Critical upstream and downstream water levels and several screw extension lengths were applied to progressively assess loads and discharge hydraulics to enable assessment of the feasibility of increasing screw extensions.

The operational conditions representative of discharging at full capacity into the Avon River during a 50-year return period flood event are as follows:

- **Inlet water level = RL 9.75 m**, being the post-earthquake **filling point** for the screw, the point at which the maximum flow enters the screw and that results in the greatest physical load on the screw (*lower water level results in the screw not being full and therefore lighter, higher water level means that the height being pumped is reduced, both of which reduce the work effort seen by the screw pump*)

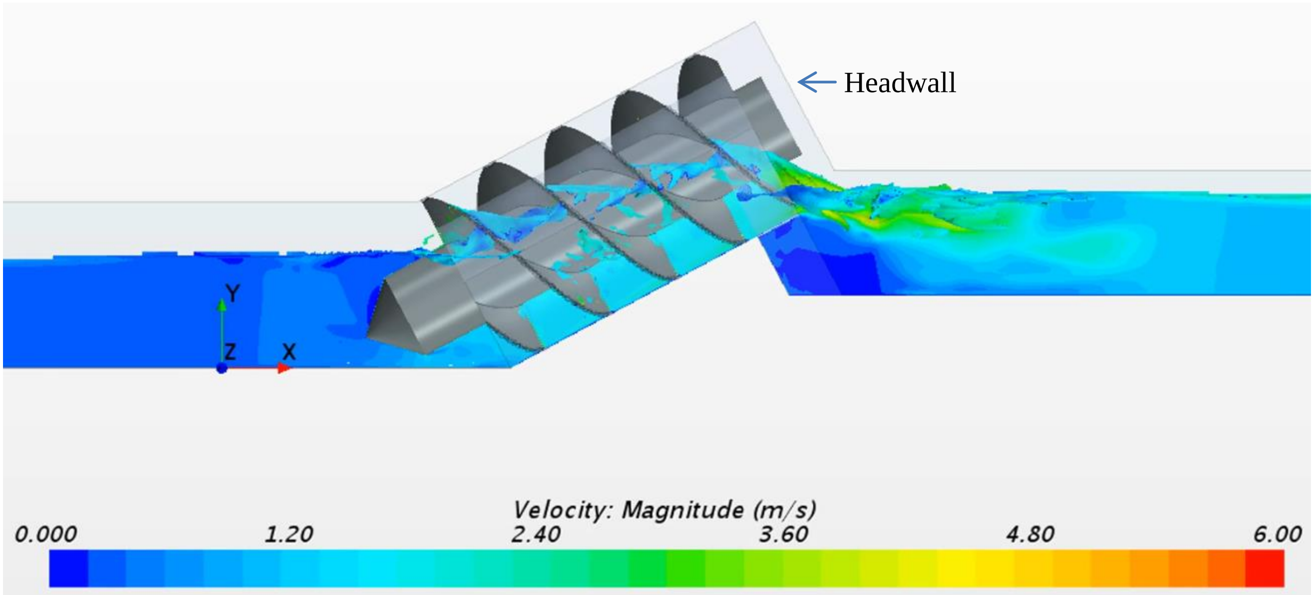
- **Outlet water level = RL 11.20 m**, being the modelled Avon water level in a 50-year return period flood
- **Screw extension = 0.9 m**, the screw extension length required to increase vertical lift by 0.45 m as required to achieve the desired RL 11.20 m discharge height (*raising the maximum tail water level of the screw*)

The CFD model was then run, requiring approximately 2-weeks run time to represent 16-seconds of operational run time. From this analysis, several outputs were generated including a dynamic model output video showing hydraulic profile and flow velocities, flow rate and screw shaft input torque.

Hydraulic profile and flow velocities

A cross section of the CFD model output for the 0.9 m extension showing hydraulic profile and flow velocities is presented in Figure 3.

Figure 3 : Cross section of operation of the 5 m^3/s screw with a 0.9 m extension



Visual assessment of the cross section presented in Figure 3 demonstrates that there is still space between the discharged flow and the concrete headwall, confirming that discharge from a 0.9 m extension is feasible and suggesting further extension is possible before a hydraulic constraint is incurred.

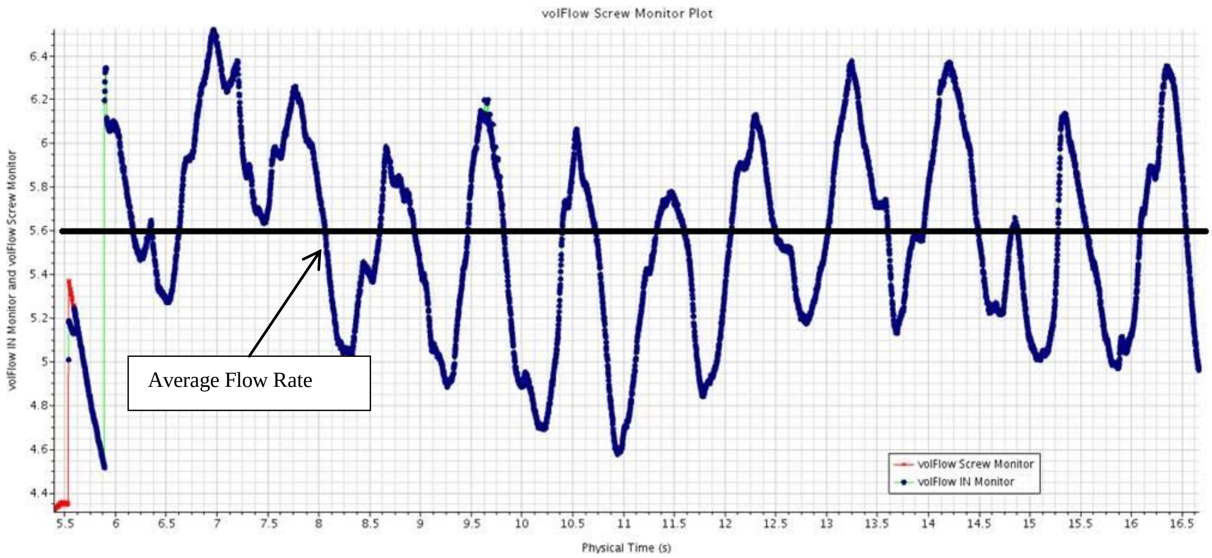
Observation of the pumps running in the field demonstrated for the current situation (without extension), there was more than 1.5 m remaining between the discharged water and the headwall, giving confidence that a 0.9 m extension is likely to be feasible and suggesting that an even longer extension may be feasible.

The overall outcome determined was that outlet hydraulics would not impose a feasibility constraint for a 0.9 m extension.

Flow rate

Flow rate outputs from the CFD model for the 0.9 m extension are presented in Figure 4.

Figure 4 : Flow performance predicted by CFD modelling with 0.9 m extension



The modelled flow rate in Figure 4 indicates the hydraulic capacity of the 5 m^3/s screw is actually closer to 5.6 m^3/s and that there is pulsing of the delivered flow rate, coincident with the passing of each flight.

To assess confidence of the CFD model outputs, original screw designers Landustrie were approached to assess expected pump performance using current screw pump design software for the current installation arrangement with proposed extensions. This yielded a predicted design flow of 5.5 m^3/s. Discussions with Landustrie indicate this is mainly due to the advancement of screw pump flow prediction over the past 40-years, with the result providing confidence in the CFD model outputs.

Further confidence in the outputs was gained through observation in the field as the flow pulses with the passing of each of the three flights.

The overall outcome determined was that the discharge flow is likely to be greater than the rated flow and that confidence should be applied to CFD modelling outputs.

Screw shaft input torque

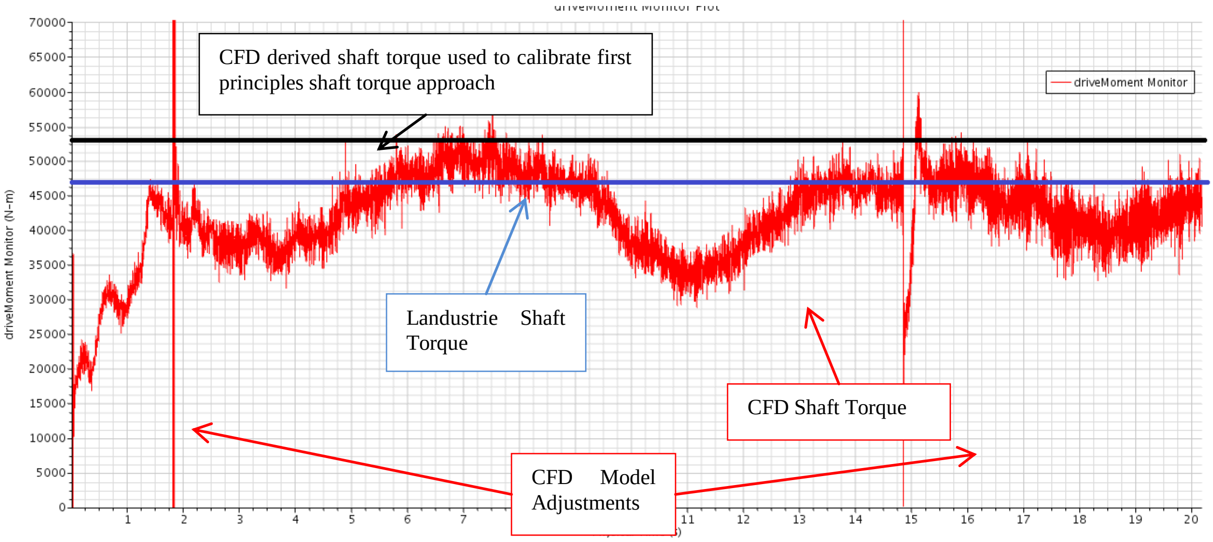
Due to the technical complexity of assessing the input torque required of a screw pump, a combination of approaches were used to derive shaft input torques for the various extension lengths considered.

CFD modelling for the 5.0 m^3/s screw with a 0.3 m extension was trialled initially to establish predicted shaft input torque. This was validated by seeking a parallel design review by Landustrie, which confirmed predicted required shaft input torques approximately 13% lower than the modelled peak shaft input torque. Acknowledging that the Landustrie design assumed a free outfall rather than a flooded outfall (*which increases the discharge height slightly*), the CFD results were used to determine the screw shaft input torque.

A first principles approach was then used to derive the work effort required to lift the designated flow the design lift, i.e. lifting 5.0 m^3 of water every second the height from the **filling point** to the **maximum tail water** level. An adjustment factor was then developed to calibrate with the CFD model outputs for the 0.3 m extension. This factor takes account of uncertainties including inefficiencies at entry and exit of the screw, shear and friction. The derived relationship including calibration factor was then used to assess the increasing torque requirements with increasing extension length.

The CFD derived shaft torque for the 0.3 m extension used to calibrate the first principles design approach is shown in Figure 5.

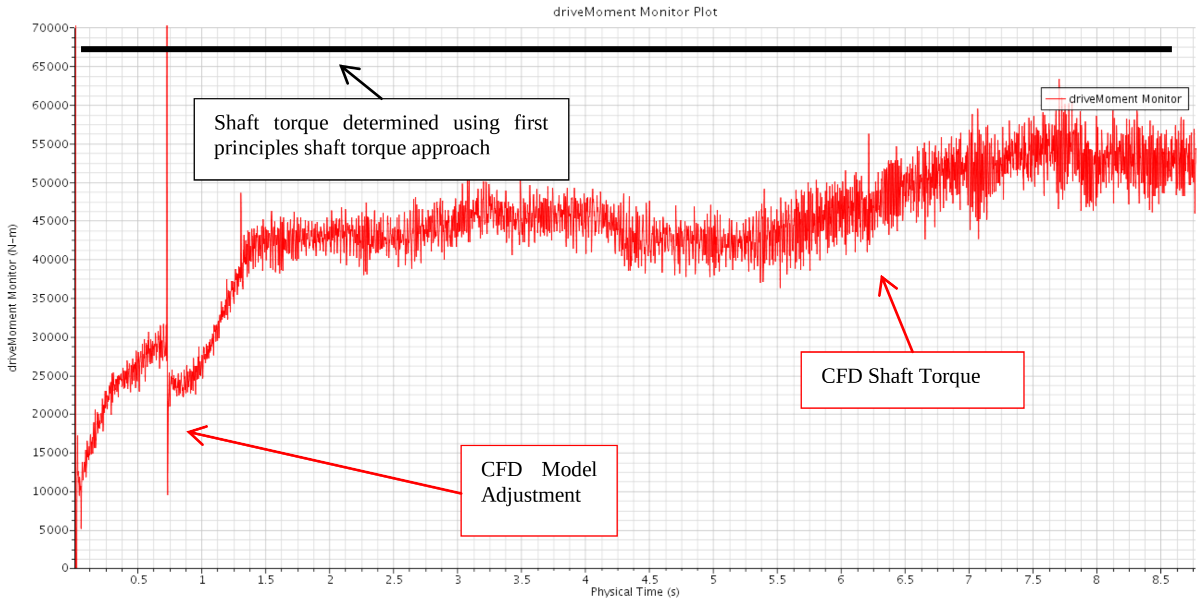
Figure 5 : Shaft input torque for 5.0 m^3/s screw with 0.3 m extension



In Figure 5 it is evident that the CFD torque used to calibrate the first principle design approach (black line) approaches the peak torque observed in the CFD model outputs.

The CFD derived shaft torque and the shaft torque determined using the first principles design approach for the 0.9 m extension is shown in Figure 6.

Figure 6 : Shaft input torque for 5.0 m^3/s screw with 0.9 m extension



In Figure 6 it is evident that the maximum shaft torque determined using first principles (black line) is slightly greater than determined by CFD modelling, however the CFD model run is only 9-seconds of operational run time and the torque load is increasing, so selection of a slightly conservative maximum torque was considered appropriate.

The overall outcome is that the calibrated first principles shaft torque assessment method is considered slightly conservative and therefore appropriate for determination of likely shaft torque when the screw length is extended.

5 EXISTING DRIVE TRAIN CAPACITY ASSESSMENT

Drive train torque loads for extended screw

Development of drive train loads for the range of extensions considered required assessment of both mechanical engineering efficiency factors to account for the minor losses incurred through the gearbox and the belt drive as well as application of a service factor to the design inputs. Service factors are typically applied to mechanical and electrical equipment to provide longevity and are dependent on the impulse loading of the prime mover and hours of continuous operation, in addition to applying a level of conservatism based upon the significance of the application.

The resulting design shaft input torques for the 5.0 m^3/s screw, drive train component efficiencies and recommended services factors are presented in Table 1.

Table 1 : Shaft torque inputs for gearbox, belt drive and drive unit for 5.0 m^3/s screw

Power Requirements for 5.5 m3/s Screw

Option	Screw Shaft Power [2]	Gearbox Efficiency [3]	Gearbox Service Factor [4]	Gearbox Selection Power [5]	Belt/Clutch Drive Efficiency [6]	Engine Service Factor [7]	Engine Selection Power [8]
Existing , no change	111 kW	97%	1.2	138 kW	90%	1.1	140 kW
300mm extension	124 kW	97%	1.6	205 kW	90%	1.1	157 kW
900mm extension - Diesel [1]	149 kW	97%	1.6	246 kW	90%	1.1	188 kW
900mm extension - Electric [1]	149 kW	97%	1.25	192 kW	90%	1.1	188 kW
Method	a	b	c	d = a*c/b	e	f	g=a*f/b/e

Notes

[1] Assumes no removal of flights at base of screw
[2] Uses energy calculation on lift, calibrated using CFD outputs and Landustrie software
[3] Supplied by Sumitomo-Hansens
[4] 1.2 = existing SF, 1.25 = SF electric. 1.6 = SF for diesel. Numbers based off supplier recommendations for load type/frequency
[5] Selection power for gearbox, existing = 138kW nominal
[6] 95% efficiency typical, but have deep belts at high load, so higher losses
[7] Service factor to ensure motor has sufficient capacity long term
[8] Selection power for engine, existing diesel = 153kW nominal

Existing gearbox capacity

To assess the capacity of existing gearboxes, technical specifications were tracked down for the current (original) gearboxes from their New Zealand agents, which coupled with stamped name plates enabled identification of the original design service factors and resulting rated capacity at that service factor. These are presented in Table 2.

Table 2 : Existing Gearbox Capacity

Gearbox	Model	RPM Ratio	Nominal Capacity	Service Factor	Rated Capacity
Drive #1 5.0 m^3/s	NK33-ARNY-31.5	700/22	138 kW	1.2	115 kW

Existing belt drive capacity

No formal assessment of the capacity of existing belt drives was undertaken for the reason that if upgrading of gearbox or drive unit were required then the belt drive would also require upgrading to match the gearbox and/or drive unit.

Existing diesel drive units capacity

The diesel drive units for the 5.0 m^3/s screws are approximately 70-years old and while they have stamped name plates, there is uncertainty on the output torque they are capable of reliably delivering due to their age. Information that could be gained from name plates and interviews with Council operational staff are summarized in Table 3.

Table 3 : Diesel drive unit information

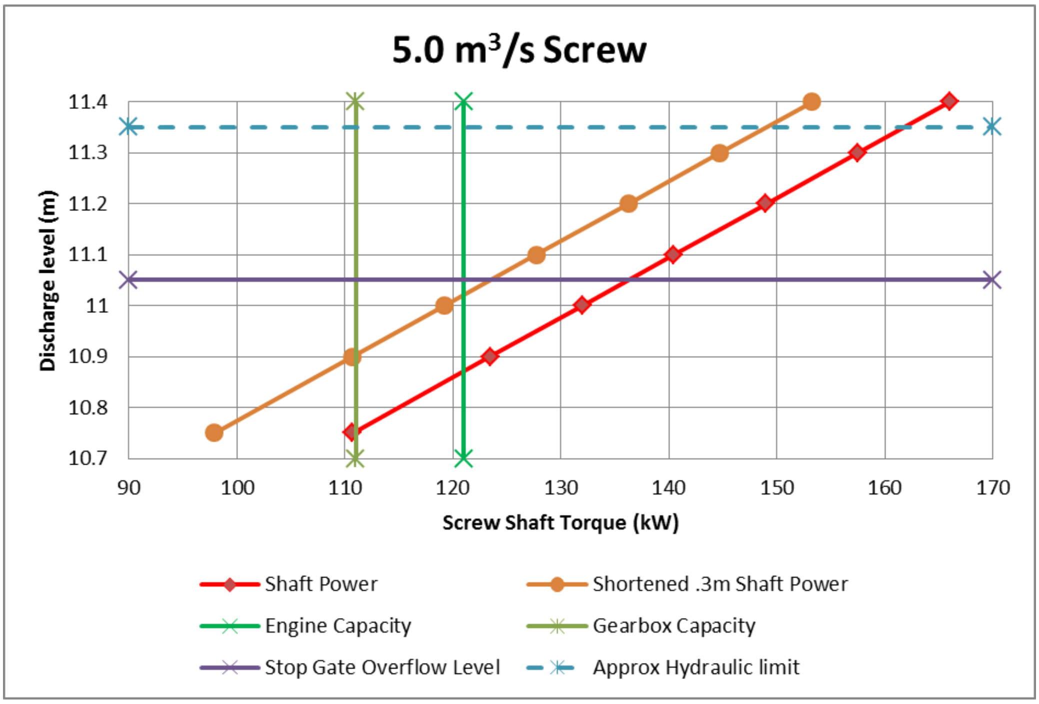
Diesel Motor	Rated RPM	Nominal Rated Capacity	Service Factor	Proposed Rated Capacity
5.0 m^3/s Screw	680	153 kW	1.1	139 kW

We note that the service factor used in Table 3 has been applied based on judgement to account for the uncertainty of the output capacity of the old diesel units.

6 FEASIBILITY ASSESSMENT

To assist determining the equipment upgrading required for increasing lengths of screw extension and to show the established hydraulic constraint, the relationship plot presented in Figure 7 was established.

Figure 7 : Pump lift height / torque load relationship for 5.0 m^3/s screw



Notes:

1. The gearbox and engine capacities shown are the available torque at the screw shaft, after taking into account their rated capacity and the efficiency of the drive train components between them and the screw.

2. The hydraulic limit noted above is the maximum tail water level that would be achieved with a 1.2 m screw extension, if that were confirmed feasible.

Interpretation of Figure 7 identifies the following:

- There is no hydraulic constraint anticipated at the pump discharge for the extension lengths being considered

- Extending the screw to restore pre-earthquake lift of RL 10.90 (0.3 m screw extension) increases torque loads (red line) sufficiently above capacity of gearbox (blue line) and diesel motor (green line) to require upgrading of these items

- Any screw extension longer than 0.3 m requires upgrading of gearbox, belt drive and diesel drive unit, with increasing extension length requiring increasing capacity of all drive train components

- Extending the screw to achieve lift capacity of RL 11.35 m (1.2 m screw extension) is within the nominal hydraulic limit (yellow line) and is expected to be feasible, subject to further CFD assessment

- If the lower 0.3 m of screw is removed and added to the discharge end of the screw to achieve the pre-earthquake lift capacity of RL 10.90 m, then there is no increase in load so this can be achieved without upgrade of existing drive train equipment

Overall the assessment has demonstrated that Councils objectives of restoring pre-earthquake lift height or achieving a greater lift height are feasible and the extent of possible lift increase achievable and drive train upgrading required has been established.

7 COUNCIL DECISION MAKING CONTEXT

The discussion in the sections above has focused on the technical investigations and modelling of the Pump Station lift capacity and options for restoring the capacity that has been lost in the earthquakes. The decision on how, when and to what extent the capacity of the station will be restored, is still to be made. This is not merely an analysis of technical requirements and related cost, but requires a balanced informed decision, taking into account multiple aspects that are set out below, to provide a complete picture of the context that this investigation is taking place in.

Use of Residential Red Zone

PS205 is located in the Residential Red Zone which has been (nearly) fully vacated following the earthquakes. The options for future use of this area are currently being assessed, ranging from re-establishing residential zones to providing green spaces, lakes and flood plains. The uncertainty of the future use of the area, including a growing population that depends on the PS to control their flood risk impacts on the cost/benefit analysis and functional requirements of the upgrade.

Climate Change

The effects of climate change which impact the decision making around the capacity restoration are sea level rise and changes in rainfall intensity and duration.

As discussed in earlier sections, ongoing sea level rise will limit the ability of the PS to discharge water from Horseshoe Lake to the Avon. At the same time, changes in rainfall intensity and duration will increase the inflow of water in Horseshoe Lake from upstream catchments. These two effects impact on the required lift height and flow capacity of the pump station in the future.

Asset condition and operation

Following the earthquakes, an assessment has been carried out into the condition of the pump station. This assessment has identified a number of issues, which are largely a result of the age of the station. These issues are:

- Reduced availability of spare parts for aging critical equipment
- Replacement required for wooden flap gates
- Startup of the diesel motors requires specific skills and experience on site, which currently only a small number of trained staff can do.

Opportunities for improvement

Planning for and designing of a required functional upgrade of the pump station provides an opportunity to improve on multiple aspects of the station. When designing repairs, renewals or delivering new storm water infrastructure, Council adopts a 6-value approach, balancing Drainage, Landscaping, Ecology, Recreation, Cultural and Heritage values.

The pump station has 5 wooden flap gates which provide for gravity discharge of water from Horseshoe Lake into the Avon River. These gates require replacement, which creates an opportunity to install fish friendly gates. This will enable several fish species, particularly Inanga, to migrate between the Avon and Horseshoe Lake, improving on the ecological value of the area.

The required upgrade will also provide an opportunity to increase the reliability of operating the pump station, by enabling remote control (SCADA). Operating the pump station currently requires trained staff to access the station to manually start the diesel engines.

New equipment, both electrical and mechanical, will reduce maintenance needs and will likely be more energy efficient, reducing operational costs and reducing the environmental footprint.

8 CONCLUSIONS

This paper demonstrates how a multi-layered assessment process can be developed to offset the uncertainty that is present in projects that are technically complex and faced with limited information.

Specifically on this project, the use of complex technical assessment methods (CFD analysis) combined with industry knowledge (screw pump designers, gearbox suppliers, Council operators) and field validation have enabled Council to gain confidence that the study outcomes are suitable for making investment decisions for PS205.

ACKNOWLEDGEMENTS

- Landustrie– screw pump designers constructors
- Maude Kirk – gear box suppliers
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- Lyttelton Engineering – heavy industrial contractors
- City Care Limited – Council's PS205 operators