SMALL BRIDGES CONFERENCE 2015

TOPIC TITLE: 'Synchronous Lifting Case Study' Bridge St Bridge. Christchurch

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Synopsis:

This paper reports the technical aspects of the Computer Controlled Synchronous Lifting involved in the Bridge St bridge correction in Christchurch, New Zealand, with valuable insights into areas of project planning, lift design and equipment capability. The work was contracted by SCIRT (Stronger Christchurch Infrastructure Rebuild Team) to Fulton Hogan as principal contractors.

The 67m long, 17m wide Bridge St bridge abutments and piers had moved significantly during the Christchurch earthquakes leading to the bridge deck dropping and twisting. Repairs required the installation of temporary abutments and the use of high precision, computer controlled lifting equipment to straighten, level and raise the bridge deck.

An array of five centrally controlled pumps, each capable of controlling up to eight jacking points, was employed with high precision displacement encoders, to control the movement and correction of the 36 support points on the bridge. As a result of limited access and cylinder stroke, load support and cylinder re-packing strategies were also needed.

The bridge was successfully straightened, levelled and raised before being lowered onto temporary supports in its interim position.

1. Introduction

The February 2011 earthquake in Christchurch – New Zealand, damaged and destroyed many buildings and much infrastructure. Of the approximately 225 bridges in the Christchurch region, 140 needed repairs.

Over the months that followed the earthquakes and aftershocks, many buildings and structures were assessed, and some were identified as being economically and technically viable for repair and remediation works. Bridge St Bridge was one of these.

The additional requirement that the bridge was kept trafficable for the light vehicles for the duration of any works was due to the risk of Tsunami affecting the Lower Brighton area, as the Bridge St bridge is the first access point for residents evacuating.

Figure 1: Bridge St Bridge and Residential Catchment

Figure 2: Pleasant Point Yacht Club beside Bridge St Bridge

Figure 3: Pleasant Point Yacht Club after the Earthquake

Figure 4: Aerial View of Bridge St Bridge and Yacht Club site.

The Pleasant Point Yacht Club sat directly beside the Bridge St bridge. The images above show the extent of ground movement at the yacht club, the access road to which is still visible in Figure 4.

During the earthquake, the bridge deck dropped and twisted as the abutments sunk and rolled.

This led to a relative displacement of up to 200mm, with each bearing point sinking by a different amount.

Figure 5: Rotated western abutment and temporary pile for abutment.

As the piers and bridge deck were declared to be sound, the engineering challenge was to install temporary abutments, then perform a high precision correction lift, jacking off the existing piers and the temporary abutments.

The lift involved 36 control points (one for each bearing point) as the bridge deck was first returned to a flat plane, made level, then lifted to its temporary placement height. After this it was packed at the temporary height, re-opened to traffic, and the correction works continued.

2. Equipment

The lifting of structures by jacking from the ground, as opposed to overhead lifting, is usually achieved through hydraulic or mechanical means i.e. hydraulic cylinders or mechanical screw type jacks.

For reason of cost, capacity and product range selection, hydraulic systems are the most common, with three main types of systems being employed.

Bridge lifting is typically undertaken using hydraulic cylinders, single acting, with or without locking collars, as shown in the images below.

Figure 6: Locking Collar Cylinder

Figure 7: Low Profile Cylinder

These are operated by hand pumps or power pumps (diesel, petrol, electric or pneumatic).

Of the power pumps, there are single outlet and multi outlet, and these outlets are split further using manifolds or flow dividers.

2.1 Manual Systems

The first, simplest and cheapest also has the least control. This is any number of cylinders connected to a manual or powered pump with external measurement in the form of tapes, rules or surveying to monitor the displacement of the load or extension of the cylinder, and analogue or digital pressure gauges to estimate load. Each pump can operate from one up to several cylinders, with the control accuracy typically reducing as the number of cylinders increases.

With this type of system, lead lag variance (the distance between the most advanced and most lagging cylinder) is usually large, ranging from several millimetres through to several centimetres.

This can and does impose significant load transfer between lifting points, which can in turn subject the structural elements to undefined and uncontrolled amounts of bending and shear.

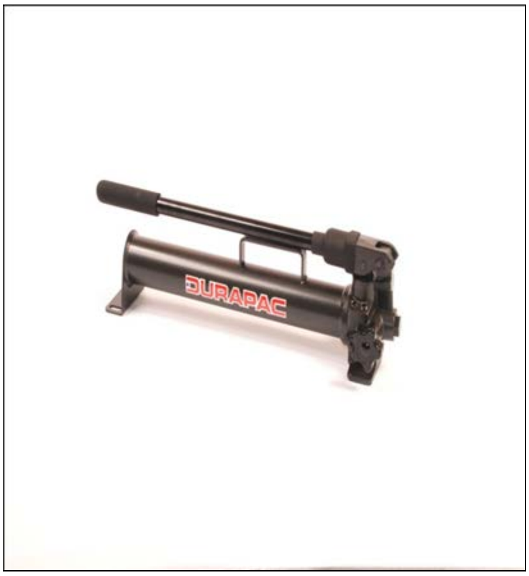


Figure 8: Manual Hand Pump

Figure 9: Single Outlet Electric Pump

2.2 Split Flow System

The second type of lifting system is a split flow pump. These pumps send an equal amount of oil to each outlet, so that with cylinder of equal effective area, the extension per cycle of the pump is the same within a small percentage. These systems are economical for a reduced number of lifting points and are effective of level lifts. They generally have no displacement feedback or data logging and so rely on manual load displacement measurement, manual control of the pump and manual recording of any data.

Figure 10: Four Outlet Manual Split Flow Pump

Figure 11: Manual Manifolds with Pressure Gauges off a Split Flow Pump

The methods shown above are typical of the lifting technology that has been utilised across the industry to date. They are lower cost, and in some applications, are appropriate for the level of control, accuracy and feedback required. They typically rely on having people near or under the structure while it is being lifted, and the control and is by people with rulers or tape measures communicating by radio or other signals

2.3 Synchronous Lifting Systems.

These are the state of the art in hydraulic lifting systems, with the following features being commonly found across various manufacturers.

- Direct measurement of load displacement at each lifting point
- Direct measurement of cylinder displacement at each lifting point
- Measurement and control of pressure and hence load or force at each lifting point
- Systems can control in excess of 100 points
- High levels of accuracy and precision in displacement control (less than 1mm)
- Data logging of displacement and pressure
- Different lift modes, including tilting, uniform displacement, pressure preload
- Measurement and control of Centre of Gravity
- Control of pump speed to suit various cylinders and required lifting speeds
- Ability to employ a wide range of cylinders, even on the same lift, without compromising accuracy or control

In an application such as the Bridge St bridge in Christchurch, where there were 36 lifting points and the structure has dropped and twisted, a synchronous lifting system was the only viable option to correct the plane of the bridge deck (remove the twist), bring the deck to level, then raise it to the required height for placement on temporary supports while the damaged abutments were removed and replaced.

Figure 12: Linked Synchronous Lifting System Pumps placed across the Bridge

Hose burst valves are also useful for safety and environmental reasons and were used on this job due to its complexity and the exposure to environmentally sensitive waterways.

Figure 13: Hose Break Valve and Symbol

In the event of a hose or coupling failure, the valves automatically lock and stay closed until pressure from outside the cylinder opens them. When used with a synchronous system, the cylinder experiencing failure will lag behind the others and will become out of tolerance, causing the lift to stop.

A precautionary note is that sudden flow during lowering can trigger these valves and the load will need to be raised very slightly to open the hose burst valve. For this reason, flow control valves are often used and should be almost closed at the commencement of lowering, and opened carefully to avoid hose burst valve triggering.

3. Lifting Process

3.1 Due to the nature of the damage to the bridge, both abutments needed to be replaced. To support the bridge in a trafficable condition during these works, live load capable temporary abutments, fabricated from 400UC, were installed at each end (see Figure 14 below).

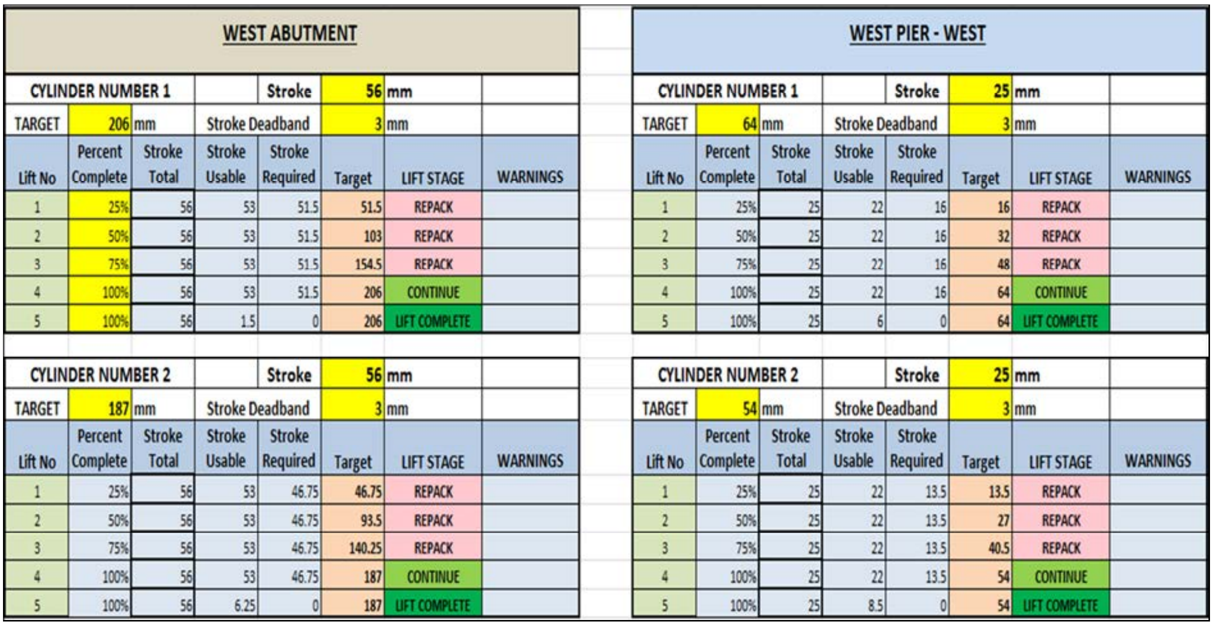
Figure 14: Rolled Abutment and Temporary Abutment prior to lift.

The existing piers were still sound, however the bearings and bearing pads needed replacement from a combination of damage as a result of the bridge movement, and the need to establish new levels for the finished position of the bridge. This meant the whole deck needed to be lifted sufficiently to allow the removal and replacement of these elements.

3.2 At this point, one of the important process learnings was around temporary jacking and support structures placement. The height of the temporary abutment was based around minimum comfortable operating clearances for the jacking cylinders proposed to be used. There were two sizes of cylinder being used; one with 50mm stroke on the abutments where there was more room, and 25mm stroke on the piers where there was less clearance. This meant that the full lift required several re-packings of the cylinders at most points (refer Figure 16 Excel Spreadsheet).

Figure 15: Low Profile Cylinders and Stroke Encoder on Pier

In the case of the piers, this was generally unavoidable, however on the temporary abutments, the height was arbitrary, and longer stroke cylinders could have been used. This was essentially a cost benefit decision, because the cost is always a factor, and the hire company had stock of the 50mm stroke 100 tonne cylinders. However, in the early hours of Saturday morning with two repacks done and two more to do, longer cylinders were looking like a very attractive option!



WEST ABUTMENT

CYLINDER NUMBER 1				Stroke	56	mm	
TARGET	206	mm	Stroke Deadband		3	mm	
Lift No	Percent Complete	Stroke Total	Stroke Usable	Stroke Required	Target	LIFT STAGE	WARNINGS
1	25%	56	53	51.5	51.5	REPACK	
2	50%	56	53	51.5	103	REPACK	
3	75%	56	53	51.5	154.5	REPACK	
4	100%	56	53	51.5	206	CONTINUE	
5	100%	56	1.5	0	206	LIFT COMPLETE	

CYLINDER NUMBER 2				Stroke	56	mm	
TARGET	187	mm	Stroke Deadband		3	mm	
Lift No	Percent Complete	Stroke Total	Stroke Usable	Stroke Required	Target	LIFT STAGE	WARNINGS
1	25%	56	53	46.75	46.75	REPACK	
2	50%	56	53	46.75	93.5	REPACK	
3	75%	56	53	46.75	140.25	REPACK	
4	100%	56	53	46.75	187	CONTINUE	
5	100%	56	6.25	0	187	LIFT COMPLETE	

WEST PIER - WEST

CYLINDER NUMBER 1				Stroke	25	mm	
TARGET	64	mm	Stroke Deadband		3	mm	
Lift No	Percent Complete	Stroke Total	Stroke Usable	Stroke Required	Target	LIFT STAGE	WARNINGS
1	25%	25	22	16	16	REPACK	
2	50%	25	22	16	32	REPACK	
3	75%	25	22	16	48	REPACK	
4	100%	25	22	16	64	CONTINUE	
5	100%	25	6	0	64	LIFT COMPLETE	

CYLINDER NUMBER 2				Stroke	25	mm	
TARGET	54	mm	Stroke Deadband		3	mm	
Lift No	Percent Complete	Stroke Total	Stroke Usable	Stroke Required	Target	LIFT STAGE	WARNINGS
1	25%	25	22	13.5	13.5	REPACK	
2	50%	25	22	13.5	27	REPACK	
3	75%	25	22	13.5	40.5	REPACK	
4	100%	25	22	13.5	54	CONTINUE	
5	100%	25	8.5	0	54	LIFT COMPLETE	

Figure 16: Extract of Excel Lift Stage Calculator Spreadsheet

3.3 To plan and optimise the stroke usage and repacking sequence, a spreadsheet was developed which took into account the total displacement, total cylinder stroke and cylinder ‘deadband’. Cylinder ‘deadband’ is the lost stroke in the lift off and repacking process. So although a cylinder has a stroke of 25mm, because of the need to lower onto packing to re-pack the cylinder, each stage may only achieve a 20mm height increase. This means for a 90mm total lift, four repacks and five lifts will be needed, rather than the theoretical four lifts. Optimising this across a large number of points is best done by spreadsheet.

3.4 There are also operational issues with repacking, as the packing material does not compress evenly and so inevitably, some points carry more load than others where the structure is rigid. This can be minimised with threaded or hydraulic packing, but with blocks and shims it is time consuming and usually heavy and cramped which can present safety as well as effectiveness issues.

Figure 17: Jacking and Packing on Temporary Abutment

Figure 18: Jacking Plate and Cylinders

From a structural perspective, the uneven loading inherent in packing can subject the structure to unplanned and unquantified bending and shear. These loads are reversed as the structural load is taken again by the hydraulic system.

In this lifting case, and doubtless in most applications, there will be maximum loads per lifting point. Regaining the structure on the main lifting rams can be difficult without breaching these limits if the loading is uneven on the support blocks - which it usually is.

3.5 The reason this occurs in a synchronous lifting system is because of a feature called ‘lead lag tolerance’. Different equipment suppliers have their own name for this, but it is the amount of lead of the most advanced cylinder and lag of the most retarded cylinder about the target displacement at any given point in time. For example, if the cylinders are all moving to a target of 40mm and are currently at 23mm with the system set for a lead/lag of 1mm, then the most advanced cylinder should be no more than 23.5mm, and the most retarded cylinder no less than 22.5mm. All cylinders will be in that 1mm tolerance band around the current target value. If the system is required to stop when the ‘lead lag’ limits are broached, then the operator may need to have large tolerances to allow the system to keep running, depending on pump volume, cylinder size and control switching speed. Some Synchronous Lifting products have adjustable flexibility around the ‘lead lag’ setting. This adjustable tolerance allows the system to ‘overshoot’ the lead lag by a set percentage. So although the target ‘lead lag’ remains the same, of say 1mm, the 20% overshoot reduces the number of nuisance trips and lift stop conditions. It is also very useful in allowing lift resumption after the repacking, as the lead lag can remain the same, but the tolerance can be increased to allow the system to start, after which the control works to pull the limits back. As these values can be altered while lifting, the tolerance can be opened up to, say 100%, then quickly reduced down to the previous operation value once the lift starts. Exactly how each system deals with this problem will vary, but the principal will be similar.

When the structure is lowered onto packing (timber, steel or plastic) and the packing flexes or compresses varying amounts, that tolerance is no longer achieved, so the operator either keeps raising and lowering the structure until the packing is adjusted and the structure is lowered onto an ’in tolerance’ set of packings, or it is accepted that there will be uneven loading. Achieving tight tolerance packing is practically impossible unless using infinite adjustment methods such as a threaded or hydraulic type as mentioned above.

Early in the lifting/packing process, hydraulic cylinders were used to re-pack the lifting points one at a time. This was done by placing cylinders adjacent to the lift point and increasing the pressure in these cylinders until the load was seen to reduce at that lifting point and a small amount of movement was measured (0.1 – 0.2mm). At this point, the jacking cylinders could be retracted, repacked and extended to the point of taking the original load.

While this is effective, it is also slow and labour intensive as the cylinders are heavy and access is restricted (see Figure XX). In many applications it would not be possible to use this process as there would not be sufficient room or structurally adequate jacking points to place extra cylinders.

3.6 A note here is the requirement for bridge designers to make provision for cylinder pockets, or other design features, to allow easy placement of standard cylinders with sufficient stroke and tonnage in appropriately strengthened jacking points for the safe and reliable lifting of bridge elements for service and repair work. In the case of the more common task of bridge bearing replacement, the lift height required is generally small, and locking collar cylinders are used which achieve the dual requirement of raising the bridge and then supporting it mechanically.

As the lift proceeded, subsequent repacks were done by lowering the whole bridge deck onto packing, as this was to be the final support state, and then repacking the cylinders. This was faster than the load transfer method as several points could be repacked at one time, but had the disadvantage of potentially inducing bending and shear load in the structure due to the uneven compaction and finite increments in packing thickness inherent in this method.

Although unavailable at the time of this project, a compact threaded mechanical support that could be used as an interface between packing blocks and the structure would have been superior. It must also be remembered that using cylinders of sufficient stroke to complete the lift without repacking is by far the fastest and safest method.

3.7 In the case where longer stroke cylinders are employed and only one end of a span is lifted, there will be an arc of rotation that alters the distance from the pivot point to lifting point. This rotation must be accommodated at the point of contact with a swivel load cap, and depending on the magnitude of this change in length, there will be side loading on the cylinder and potential for slippage of the cylinder at either contact point. An option for addressing and minimising this is the type of swivel load cap. Most swivel load caps have a concave machining in the stationary part attached to the cylinder rod, and convex machining in the part contacting the load. When extending from a level position, this type of load cap moves away from the pivot point during extension, exacerbating the issue of side loading and potential slippage. A swivel load cap with the concave and convex reversed moves toward the pivot point as the angle increases and therefore can be designed to reduce the problem. Basic trigonometry allows calculation of the potential side slip based on pivot length and lift height which for longer spans and small lifts is negligible, but needs to be considered.

3.8 Bearing pressure is not usually a problem on the cylinder base, as even 700 bar cylinders (70mPa) have a base to bore area ratio of around 1.7:1 giving a bearing pressure of around 400 bar (40mPa) at full system pressure. As most cylinders are selected with generous safety margins of at most half rated load, this lowers the bearing pressure to 200bar (20Mpa), so a small pad is sufficient for the cylinder base, and a similar size for the rod, although the rod pad needs to be rigid enough to cope with the smaller load point from the load cap without bending.

The Bridge St bridge weight was approximately 1700 tonne and there were 72 x 100 tonne single acting cylinders employed in pairs, giving a lifting capacity of 7200 tonne. Referring to the bearing pressure mentioned earlier, this arrangement gives low bearing pressures, although jacking plates with intermediate slide plates were also used.

3.9 Because the bridge had suffered earthquake damage, and wedges had been glued in place between the super ‘T’ beams and the abutment to give an adequate area of contact, there was uncertainty as to what stored energy was in the structure and what it would do once it was lifted and could ‘relax’.

This connection between the bridge deck and the abutments also led to larger than expected lift off forces as the adhesion between the deck-wedge-abutment sandwich was broken. These unplanned loads can cause substantial delays or damage in the lifting process. If there is insufficient tonnage available from the cylinders, the lift will not proceed, and certainly in this instance, that was possible. In another lift recently completed in Christchurch, insufficient cylinder capacity was also an issue, not because of the structural mass, but because of suction between the ground and the building. This led to greater than calculated lifting loads, which in turn contributed to jacking pad sinkage and insufficient cylinder stroke. As the pad was the connection and reference point for the encoder, the measured displacement was the increase in distance between the structure and the jacking pad. This was not the distance that the building had moved, so a new set of reference measurements needed to be taken. If dual encoders had been employed and one encoder was used as a ground reference, the sinkage of the jacking pad would have been detected very quickly, and the actual displacement of the load would also have been measured.

4. Correction

4.1 The Displacement Plan shown below in Figure XX indicates the range of target displacements across the bridge deck. These values ranged from 200mm at the South West corner, through to 8mm at the Northern end of the Western pier. The target values show how the bridge deck was dropped, bent and twisted, which is also why there was concern regarding the stored energy in the structure and how it would resolve once the deck was lifted.

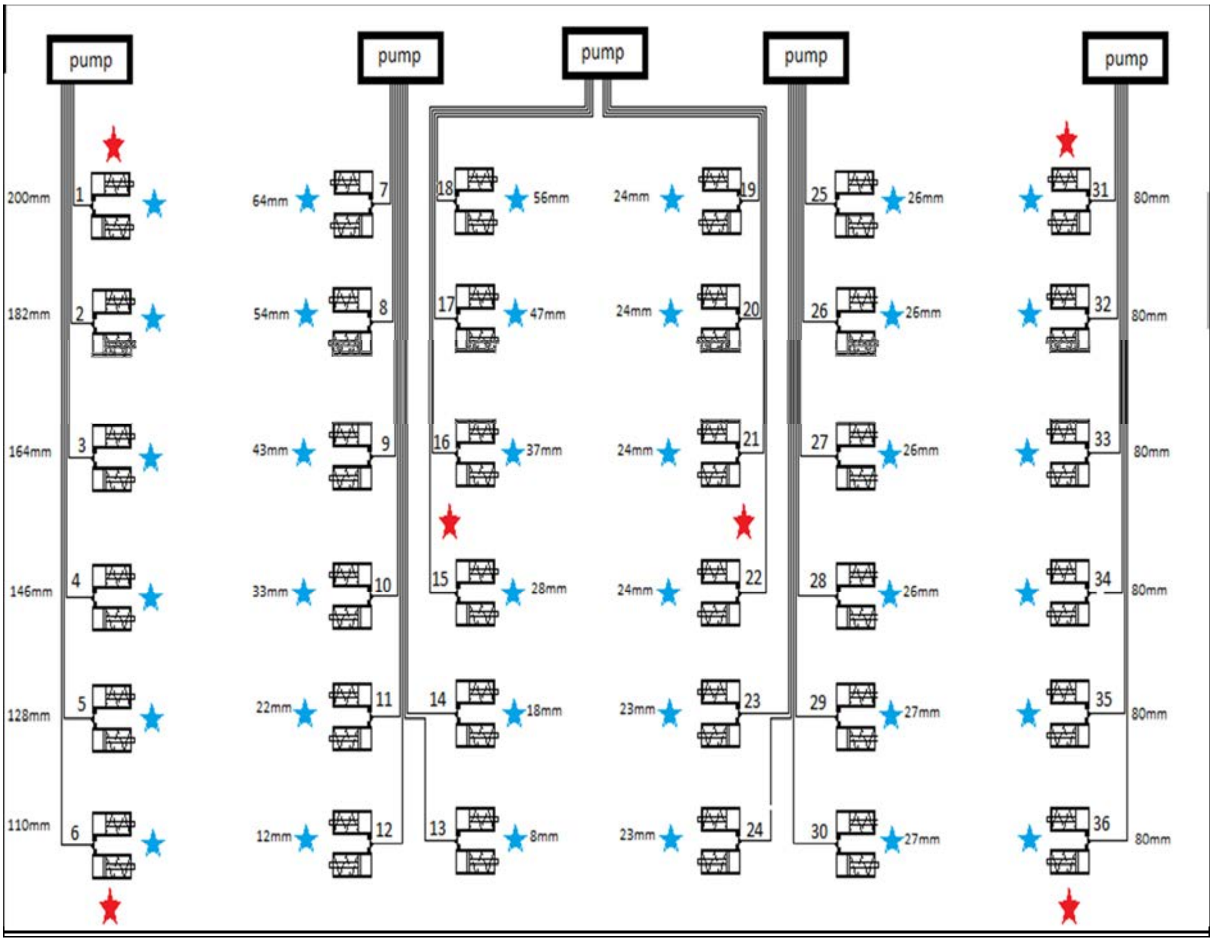


Figure 19: Bridge St Bridge Target Displacement Plan

The layout above shows the placement of single encoders (blue stars) and dual encoders (red stars). The design of any synchronous lifting system is based around having feedback to a central controller of the cylinder extension, or load displacement, and usually cylinder pressure.

The pressure in each cylinder, used with the cylinder effective area, enables calculation of the load at a given point.

4.2 Measurement of the displacement of the cylinder extension, or load displacement allows for calculation of the position of the load. Some systems also permit entering of X and Y co-ordinate data so the system can calculate the line of action of the centre of mass, typically referred to as Centre of Gravity in the brochures.

4.3 At points 1, 6, 15/16, 21/22, 31 and 36, dual encoders were employed to monitor the load displacement and the cylinder stroke. The purpose of this is to look for differential displacement between the amount the cylinder has extended and the distance the load has moved. This is critical in cases where a footing might sink, or the load may be subject to deformation. In many cases, the structure is not designed with designated lifting points, and localised load can lead to failure of the structure. Alternatively, higher than expected ground pressures can lead to jacking point subsidence, and being able to measure these and put a tolerance around them enhances safety.

For this to work, the ‘Load’ encoder must be reading between stable ground and the structure, while the ‘Cylinder’ encoder reads the cylinder extension.

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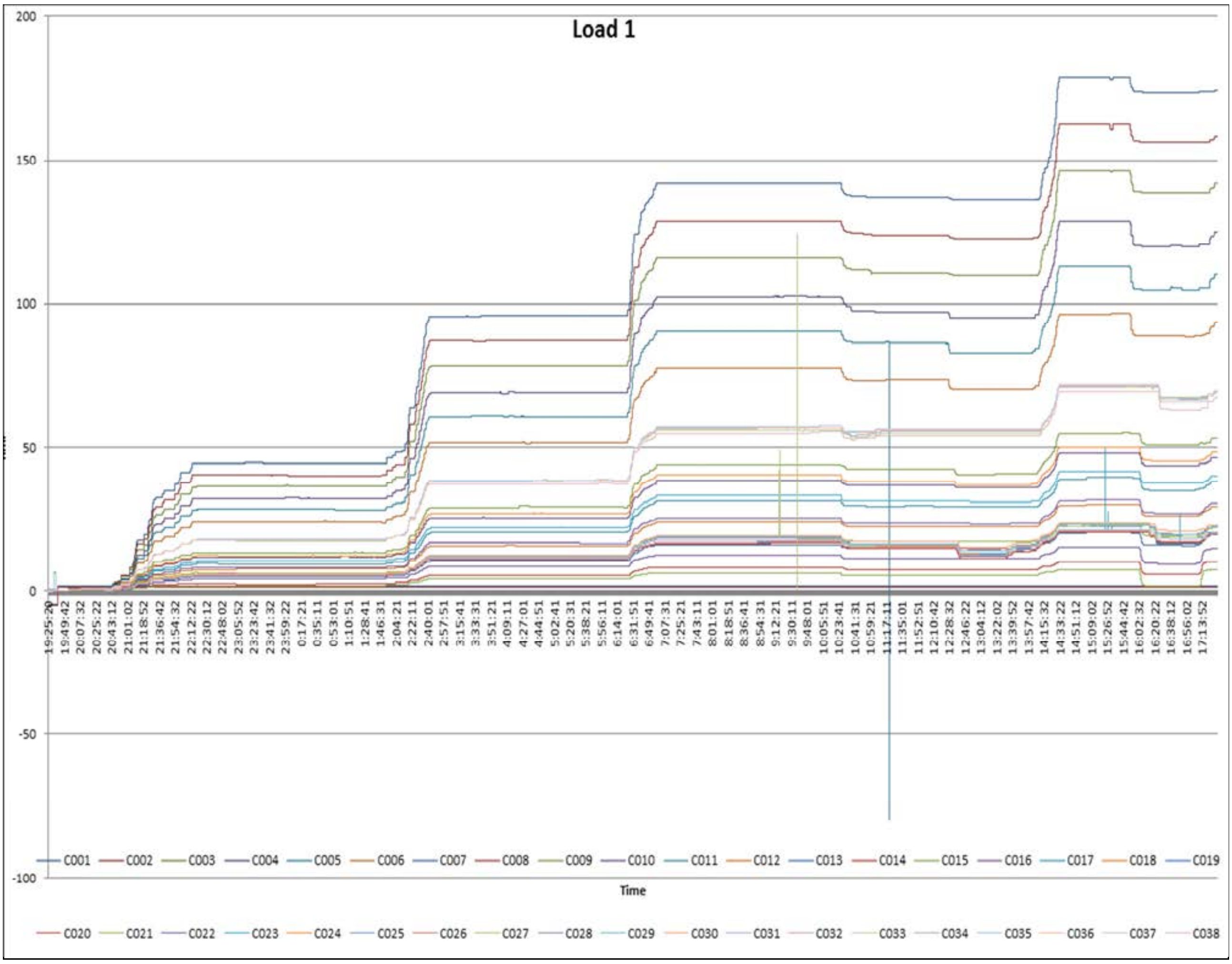

Figure 20: Displacement Data

In the graph above, there are some vertical lines that are a result of an encoder being retracted. During repacking (the flat horizontal lines where nothing is moving) occasionally the encoder needed to be retracted for access to the packing or cylinder. The length of these packing stages shows how much time was spent on this part of the lifting process.

5. <u>Lowering</u>

There were two parts to the lowering process. The first was on to lower the bridge deck onto the temporary supports and abutments. This is similar to the support during the repacking process, only the deck was also clamped down with threaded reinforcing bar as seen in Figure XX.

Later, once the abutments were replaced, the bridge deck was lifted, correct levels set while the bearing blocks were grouted in place, then the deck was lowered onto the new abutments.

6. Conclusions

The unique nature of lifting damaged structures presents many challenges and opportunities.

Although the lifting process was successful, and completed well within the allowed timeframe, this was due to the careful planning and preparation of many contractors and their teams.

The use of Synchronous Lifting equipment was the only viable way to safely lift the structure with full, real time visibility of the loads and displacements, with the ability to limit maximum forces and keep adjacent lifting points within prescribed tolerances to minimise applied stresses within the structure.

Having dual displacement encoders was also important as it enabled the lift controller to monitor movement in the support structures of the temporary abutments as they started to bear load.

Many of the lifts done with this type of equipment are relatively simple, with the lifting of one end of a span for bearing replacement being typical. Even here though, the advantage of full data logging for evidence of displacement and applied load, coupled with tight control of lift precision and the elimination of having people under the structure make synchronous lifting system a superior choice to manual systems.

There is still a place for the split flow and manual pumps where structures have more flex and can cope with the relatively low precision positional control, but for projects with many point lifts and corrections, tilting, weighing and stability issues, Synchronous Lifting systems are often the only viable choice.

7. Acknowledgements

The author would like to thank Fulton Hogan for their permission to use technical drawings and lift data in this presentation.

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