Pipe Deformation Survey Using 3D Laser Scanning

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ABSTRACT

The SKM spatial team, in association with the Roads and Traffic Authority - Southern Region (now Roads and Maritime Services, RMS) found a unique solution to measuring the deformation of a water drainage pipe along Kelly’s Creek under the Princess Highway (located around 65 km south of Sydney), incorporating innovative field collection techniques combined with innovative calculation and presentation methods. The 140-metre long and 1.46-metre diameter stormwater pipe is being deformed by a combination of the pressure exerted on it by highway fill above and subsidence from underground mining below. A custom-built tripod and specialised target supports were constructed to overcome the tight space conditions in the pipe and 3D laser scanning was used to give the most comprehensive result. Ingenious methods were developed to process and present the data to clients in a simple and easily comprehensible format, in addition to highly detailed production plans for design.

KEYWORDS: Static, scanning, deformation, pipe, subsidence, modelling.

1 INTRODUCTION

Subsidence and the monitoring of subsidence due to mining is a big issue in the New South Wales. Many thousands of dollars are spent monitoring and repairing infrastructure damaged by subsidence from both coal and mineral underground mines.

The discipline of surveying contributes in a major way to the monitoring of subsidence, and it has been an area of innovation where traditional surveying technologies may not always be the appropriate tool for the job. While most subsidence monitoring is based on the absolute change in a structure, e.g. the change in height of a bridge or building, a previously unexplored field of subsidence is the deformation of structures relative to themselves.

The SKM spatial team, in association with the NSW Roads and Traffic Authority - Southern Region found a unique solution to measuring the deformation of a water drainage pipe along Kelly’s Creek under the Princess Highway, incorporating innovative field collection techniques combined with ingenious calculation and presentation methods.

2 HISTORY

The NSW Roads and Maritime Services (RMS), formally the Roads and Traffic Authority (RTA), has a firm commitment to monitoring its assets including all culverts and drainage structures across the state. After the collapse of a culvert structure near Bega and another collapse near Gosford claimed the lives of 5 people, RMS put in place procedures to monitor
and asses the condition of its culverts and drainage assets. One of the issues arising from this monitoring process is how best to determine the condition of these assets in both a quantitative and qualitative manner.

In this instance, the asset manager required information on the extent of damage to the pipe to support the claim the damage was caused by mine subsidence as well as to provide a precise measure/assessment of the smallest pipe that could be used to replace the existing pipe. This would in turn determine the method of replacing the pipe. Given the need to locate small transverse cracks, changes in shape, grade and extents of damage, ground survey was deemed the most appropriate solution. Issues associated with access, occupational health and safety, time and cost lead to the use of laser scanning technology.

3 LOCATION

Located around 65 km south of Sydney in the district of Stanwell Park, the crossing of the Kelly Creek by the F6 Motorway (Princes Highway) was completed in 1975 as part of the Waterfall to Bulli Tops upgrade. Kelly Creek runs from the Old Princes Highway to Stanwell Park where it runs into the ocean. Approximately 1.5 km from the project site the creek runs over the escarpment and creates a waterfall known as Kelly’s Waterfall, which is a feature of an old walking trail, established in the 1930s.

The 1.46 m diameter pipe runs from west to east for approximately 140 m, and is 25 m below the F6 carriageways. It is surrounded by heavy bush and is in a steep valley, which creates logistical problems in access and egress. It is around a 1-hour round trip by foot to get to the pipe.

![Figure 1: Location of the Pipe in Kelly Creek Valley.](image)
4 SCOPE

The scope given to the RMS by the Mine Subsidence Board included the requirement for the presentation of:

a) Dimensional changes to the pipe diameter – measured at regular intervals along the pipe (e.g. vertical and horizontal axis).
b) The horizontal angle where the pipe diameter is narrowest – measured at regular intervals along the pipe.
c) Any changes to the pipe joints – provide description / sketches.
d) Any evidence of shear failure at the pipe joints or lateral movement – measured at intervals along the pipe.

Based on this and on consultation with RMS, SKM surveyors decided that the best course of action would be to complete a laser scan of the pipe, to ensure that the deformation of the pipe could be measured over its entire length, leaving no possibility of important information being missed.

The pipe is being deformed by a combination of the pressure exerted on it by the highway fill above and the subsidence from the underground mining below (Figure 2). At the time of building, the pipes were covered with straw bales to allow for the compaction soil not to have an effect on the pipe, but this straw has since been fully compacted.

![Figure 2: Profile showing pressures exerted on pipe.](image)

5 METHODOLOGY

Based on correspondence with RMS, a proposal and techniques were formulated for the project, and after tender agreement, surveyors were dispatched from the SKM offices in St Leonards, Sydney.
5.1 Safety

The number one priority on any project is safety. A full examination of the possible risks for the project were identified before heading out into the field, and control measures were formulated and put in place. Some of the risks on this job included:

- Confined spaces. Gas detecting gear was used inside the pipe, with a spotter and extraction plan drawn up, and all personnel were confined space trained.
- Wildlife, snakes and spiders were a real risk on this job, as dark pipes and bush land are common habitats of these creatures. Controls such as snakebite kits and full length clothing were used.
- Slips Trips and Falls (STF) were also another major source of potential harm on this site. Due to its location and structural type, water, rocks and steep banks all made this a high risk site. Controlling STF involves instructing personnel on steady walking techniques, keeping eyes on the path, and maintaining three points of contact where possible.

5.2 Control

While the main areas of measurement are relative in nature, as with all RMS projects, a state based datum was used. In this case, the Map Grid of Australia (MGA94) and Australian Height Datum (AHD71) were adopted. Three marks were placed at the bottom of the creek using static Global Navigation Satellite System (GNSS) positioning methods, with extended duration times due to canopy and elevation constraints. These three marks were then connected through the pipe using a closed traverse and reciprocal trigonometric heighting (Figure 3).

![Figure 3: Running control through the pipe.](image-url)
5.3 Laser Scanning

Laser scanning is an established survey methodology which has been in use for around ten years. The basic concept of a laser scanner is to take reflectorless measurements, similar to a reflectorless total station, but with large amounts of measurements in a very short timeframe. For example, a Leica 1200 series total station can take a reflectorless measurement once every 1-2 seconds, where a phase-based laser scanner can take 500,000 measurements in one second.

The laser scanner used on this job was a Leica HDS6000, which is a phase-based measuring system. The difference between “phase” and a “time of flight” scanner is that the measurements are taken based on a change in wavelength, instead of measuring how long it takes a signal to return.

At each scanner location, the laser scanner will pick up measurements in a 360° horizontal and 270° vertical field of view. However, the distance between each location is limited by what is visible and the angle of incidence of the laser. The angle of incidence is the angle with which a laser hits a surface. The more acute the angle, the less chance there is of getting a return signal. In a road-based situation the angle of incidence is increased by setting the instrument up higher, which increases the setup spacing to 20-30 metres. Inside a pipe there is no way to increase the angle of incidence (Figure 4), so the scanner was required to be setup at 5-metre intervals to collect the necessary amount of data.

Figure 4: Angle of incidence inside a pipe.

The normal process of scanning involves placing targets around the area to be scanned, coordinating the targets using a total station and using the scanner to collect a point cloud that includes the targets (Figure 5).
Working inside a pipe with restricted headroom creates and number of equipment based problems. A standard survey tripod has a minimum height of approximately 1.3 m, which when the scanner was placed on top of the tripod would have been projecting up through the top of the pipe. To overcome this problem, two methods were used to set the scanner up at the lower height:

1) The “spider” – The “spider” is a purpose built mini tripod, based on a pillar plate, with the legs replaced by threaded rods, allowing for levelling (Figure 6).
2) The “trolley” – The “trolley” is a piece of ply board, with a 5/8th thread coming up through the centre. The board is placed in the pipe creating a bridge across the bottom (Figure 7).

To speed up scanning time the spider and trolley were alternated, so while one tripod was used for scanning the other was being setup for the next scan.
The next problem was the targets. The HDS6000 laser scanner uses black and white swivel targets, which are acquired in the scan data due to the cross formed by the alternating colours (Figure 8). These can be either stuck to metal objects using magnetic bases or mounted on tripods. Inside a concrete pipe neither of these methods could be used, so an alternative was found.

![Magnetic black-and-white swivel target.](image)

Holes were drilled in either end of a 1.3-metre wooden beam, and through these was inserted a 5/8th bolt. The black and white targets were then affixed to these bolts. Three of these beams were constructed, creating the six required targets to register the scans together. The beams were then wedged into the pipe until stable, and the scanning and target acquisition could begin (Figure 9).

![Scanning field procedure.](image)

A total of 28 scans were competed along the length of the tunnel (Figure 10). At each scan the scanner acquired six targets which were then coordinated using a total station located at the ends of the tunnel. While the minimum number of targets required to control each scan is 3, SKM surveyors use 6 to ensure there is redundancy even if targets are obscured or bumped. The scan data was stored on board the scanner and downloaded and uncompressed in the office.
5.4 Registration of the Point Clouds

Each cloud is an independent setup, and straight from the raw data, has no absolute orientation or position values. In order to transfer each cloud into real world coordinates, the black-and-white targets are identified within the cloud using an advanced detection algorithm. These black-and-white targets were surveyed in the field using a traditional total station, so their coordinates were known.

Once all the targets have been identified in the scan data they were registered together using least squares techniques. The diagnostics from this registration give an indication of targets that may have been bumped in the field, or improperly fitted in the cloud acquisition process. They can then be corrected or removed from the calculations.

Once the registration is complete, the separate scans are unified into a single point cloud. The unification process ties all the scans together into one big cloud, while at the same time reducing the density of the cloud. This density reduction is required due to the fact that more information is recorded close to the scanner, due to the angle of acquirement (Figure 11). For the Kelly Creek project a reduction to the cloud of 3 mm was used.
5.5 Quality Control Checking

For this particular project it was difficult to find a method of quality control based on RMS’s G73 specification, which outlines standard methods for quality checking work. The calibration of the scanner and instruments were up to date, but to ensure the results obtained were accurate, a number of methods were used to check the work performed in the field:

1) Control checking and traverse closing. This involves examining the results of the closed traverse and ensuring they meet the minimum requirements.
2) While scanning. Each scan covers a horizontal rotation of 182°, capturing data in the overlap on both faces. The extra 2° is to ensure that the scanner’s vertical circle is in calibration. If this was out of calibration, there would be a step and overlap in the data inside this 2° overlap.
3) Scanner Registration. Each time a scan is registered, it is also performing a simple calibration check on itself. If the scanner was out of calibration, there would either be abnormalities in the registration, due to either a scale factor in the distance measurement, or errors in the horizontal and vertical circle. The 3 redundant control points from each scan ensure that this is not the case.
4) Quality control string. A quality control string down the middle of the pipe, commonly known as a QQ string, was acquired using a total station. These points were then compared with results from the scan data to ensure conformity.

5.6 Processing and Calibration

The processing of the cloud to a deliverable was perhaps the most important section of project. Not many clients have the ability to use a point cloud directly from the registration software, so it is the job of spatial professionals to extract the required data from the cloud. Since no project like this had ever been completed before, the processes to present the data needed to be developed from scratch:

1) The first step was to find the nominal size of pipe. The pipe segments are a precast concrete, but due to concrete mould wearing they may not be the exact size as specified by the drainage specifications. By taking a segment of pipe and using the ‘fit to cloud’ algorithm, a least-squares fit of the pipe was executed over a single segment of pipe, using in excess of 40,000 points to find the nominal size of the pipe. The nominal pipe size was found to be 1.46 m with a standard deviation to the cloud of 3 mm.

2) Using this size, a series of sections were taken along the pipe, the ends and midsection of each segment, using a fit of the nominal pipe diameter.

3) The end segments gave a good indication of the deflection of the pipe along its length, and an alignment was formed from the centres of these sections. From there a long section of the pipe was generated. This showed a dip in the middle of the pipe (Figure 12).
4) The next stage was to extract a contour map from the cloud that would show the pipe’s deviation from its nominal shape. To do this, a technique used for doing as-builds of tank structures was employed. Special software known as ‘Unfurl’ was developed in-house by the SKM spatial team. Unfurl is typically used to show deviations from design inside tank structures. Circular structures are always difficult to present on paper, so to simplify the presentation, the tank is unrolled based on the design radius into a flat surface (Figure 13). The difference in the distance along the centre of the pipe is used as the new y coordinate, the arc distance around the circle becomes the x coordinate and the z coordinate reflects the radius. By then turning the new plane on its side and contouring the results, a contour map of the deviations can be shown.

The problem in this case was the pipe was not suitable for using the tank method, as the axis of the pipe was changing along each segment. The unfurl program was re-written to use the alignment developed in step 3, and each point was calculated to the nearest segment on the alignment. As a result the pipe was unfurled segment by segment (Figure 14).

This flattened section also became useful for the mapping of the cracking along the pipe. The cracks became visible when the laser return intensity values were plotted in grey scale (Figure 15).
5) The next step was to find the maximum and minimum cross sectional distance inside each segment of pipe. After a number of attempts to do this by eye and trial and error, the SKM spatial team came up with the solution of using the point cloud processing package to create a cross sectional polyline, and then analysing the polyline to find the maximum and minimum deviations from the centre. On the first attempt it was found that overspray and outliers, that are common in laser scan data, were giving false readings, and the routine was rewritten to take an average of the vertexes over a $6^\circ$ slice of the section. This also allowed for deviation calculations, in the form of a numerical value to be show in a series of sections (Figure 16).
6) The final processing step was to calculate the maximum deviation of the pipe along the alignment. This was required because the next step in the project may involve the insertion of a liner inside the pipe. The different types of liners available on the market have different amounts that they can distort before they will stop feeding into the pipe. This maximum value is a combination of the vertical and horizontal deviation of the alignment (Figure 17). A routine was written to transform the segment lines to a horizontal plane and then calculate the deviation from these values. This was done using a z-axis transformation. These values were then added to the long section for clarity purposes.

Although crack mapping was performed, only the most significant cracks were plotted from the point intensity values. This gives an overview of the cracks, but the scope specified that the client wished to identify areas where the cracking was extensive, especially at joints.

As a by-product of the scanning process, panoramic images known as Truviews are created (Figure 18). From these Truviews engineers, project managers and other stakeholders can carry out a ‘virtual visit’ of the pipe from the office, without the need for extensive safety procedures, and examine parts of the pipe that may not have been visible, even with the use of artificial lighting. The other additional benefit of the Truviews is that as well as being able to view the inside of the pipe, they can also take measurements and positions at any stage, giving the panoramic photos a fourth dimension.

Figure 17: Deviation of the alignment.
6 RESULTS

A meeting between the SKM survey team and RMS mechanical engineers was organised to present the results of the survey. The results were primarily supplied as a series of sections and contours maps. These were analysed by the mechanical engineers to interpret the structural deformities of the pipe. The analysis determined that the bottom of the pipe appeared to have no or minimal deflection, while the top of the pipe had visibly split at 45° and 315° (Figure 19). This is consistent with the stresses being placed on the pipe based on theoretical forces.

7 CONCLUDING REMARKS

Deformation of structures due to mining remains a real threat to infrastructure in New South Wales, and the monitoring of these structures will continue to be required over the coming decades. This project has seen a new way of monitoring these structures, by not using the
conventional single point observation, but by looking at the entire structure, to deliver a more comprehensive deformation analysis. There are hundreds of pipes that are affected by mine deformation and other stress factors across NSW, giving this new process the potential to be adopted throughout the spatial industry on multiple projects.

The project delivered above and beyond the original scope, conveying information that may not have been realised using traditional methods. Although the project may not have been large in terms of expenditure, the potential ramifications of this technique could contribute huge benefits to the surveying industry as a whole.

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