# PHOTOGRAMMETRIC MONITORING OF THE EXCAVATION OF A TRUNK SEWER PUMPING STATION

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## ABSTRACT

The Melbourne and Metropolitan Board of Works is currently replacing the Western Trunk Sewer which services parts of the city of Melbourne. Twenty-three kilometres of four metre diameter tunnel will connect an outer suburban treatment plant with the Hoppers Crossing Pumping Station. Part of this station consists of two interconnected pumpwells which return the treated sewage from the tunnel outfall to the surface for farm distribution. The pumpwells are each fifty metres deep and thirty metres in diameter.

The size of the excavation for the pumpwells necessitates monitoring for safety and economic reasons. However the measurements required to carry out the task must cause a minimum of interruption to the ongoing excavation and construction work, whilst still achieving the desired measurement accuracy. Photogrammetric techniques largely fulfill these requirements, and are being used to monitor

(a) the geology of the excavation,
(b) the volume and shape of the excavated wells, and
(c) deformations of the walls of the wells.

The conflicting requirements of these three tasks has led to the application of the quite different techniques of strips of stereopair photography with Wild P32 cameras and multi-station photography with a Geodetic Services CRC-1 camera. The paper describes the project, the techniques used, the problems encountered and the results obtained.

## 1. INTRODUCTION

The Western Trunk Sewer is being constructed by the Melbourne and Metropolitan Board of Works to replace the existing sewer which has been in operation since 1897. The growth of the metropolis of Melbourne has placed increasing strain on the capacity of the old sewer, and sections of the structure are in poor condition.

The new sewer, scheduled for completion in 1993, extends for 23 kilometres and consists of:

(a) 15.3 kilometres of 4.4 metre internal diameter tunnel from the existing pumping station at Brooklyn to Hoppers Crossing. The tunnel varies in depth from 28 to 40 metres below ground.
(b) Hoppers Crossing pumping station, a complex of a penstock well and two adjacent pumpwells.
(c) 7.3 kilometres of 4.5 metre internal diameter shallow conduit from Hoppers Crossing to the Board's distribution farm at Werribee. The shallow conduit varies in depth from 5.4 to 8.5 metres below ground.

The construction of the three major components is being carried out concurrently, the tunnel by boring machines, the pumping station by "drill and blast" and the conduit by "cut and cover" excavation.

Conventional survey techniques have been and will continue to be involved in all stages of the project, varying in complexity from routine work to innovative solutions to particular measurement problems (Benwell 1985). However, the excavation of the Hoppers Crossing pumping station presents some unique measurement tasks which are better serviced by photogrammetric techniques.

The pumping station consists of three deep interconnected wells. The first of these, the penstock well, controls the incoming flow of sewage and is excavated to 15 metres in diameter and 40 metres deep. The penstock well distributes the flow to two pump wells, each excavated to 30 metres in diameter and 50 metres deep (see Figure 1). When complete, the pump wells will house a total of eight massive pumps which will lift the flow to the shallow conduit for further transport.

The measurement tasks during the excavation and construction of the wells are as follows:

(a) monitoring the geology of the internal wall faces of the wells,
(b) monitoring the volume and shape of the wells,
(c) monitoring deformations of the walls of the wells.

The size of the excavation increases the importance of monitoring for both economic and safety reasons. The geology is relevant, in the initial stages, to confirm the data acquired by core sampling and has an overall influence on both economic and safety factors. The volume and shape of the wells has a direct effect on the economics of the excavation, both in terms of the volume of material removed and the amount of concrete required to obtain the lined diameter. If volume and shape relative to design surfaces can be monitored during excavation significant cost savings may be forthcoming. Monitoring deformations is of primary importance for the safety of the construction site personnel.

Any measurements required to carry out the above tasks must cause a minimum of interruption to the ongoing excavation and construction work, have sufficient density to provide an accurate basis for assessment, and achieve the desired precision and accuracy of measurement. Photogrammetric techniques were adopted as they largely fulfil these requirements, and have the additional advantage of providing an instantaneous and permanent record which can be re-measured and re-assessed.

## 2. INITIAL DEVELOPMENTS

Photogrammetric techniques were first used during the construction of the Hoppers Crossing pumping station to determine the volume of the excavated penstock well (Shortis 1985). Carried out as an experiment to test the suitability of photogrammetric measurements, the project used four vertical strips of Wild P32 stereopair photography. The strips were connected into a consistent whole by a multi-station bundle adjustment solution known as TBO (Earls 1983). Individual stereopairs were then restituted using triangulated control and a vector solution (Shortis 1982) to obtain a digital terrain model of the well with a point accuracy of a few millimetres.

The success of this pilot project led to feasibility investigations for the impending excavation of the pumpwells. Whereas the penstock was not amenable to a continuing program of monitoring, it was envisaged that periodic photogrammetric monitoring of the pumpwells for geology, volume and deformation was economically and practically feasible. Early simulations on the proposed design suggested that acceptable accuracies were achievable and, most importantly, little or no interruption to the contractor would be caused.

While point accuracies of a few millimetres for volumes could be realised using the established method of Wild P32 stereopair photography, the requirement for the deformation monitoring was more demanding. Accuracies at the millimetre or sub-millimetre level would only be economically achieved with a suitable large format/long focal length camera. To this end, the Board purchased a CRC-1 camera with a 240mm focal length lens from Geodetic Services Inc., which was delivered in August 1985.

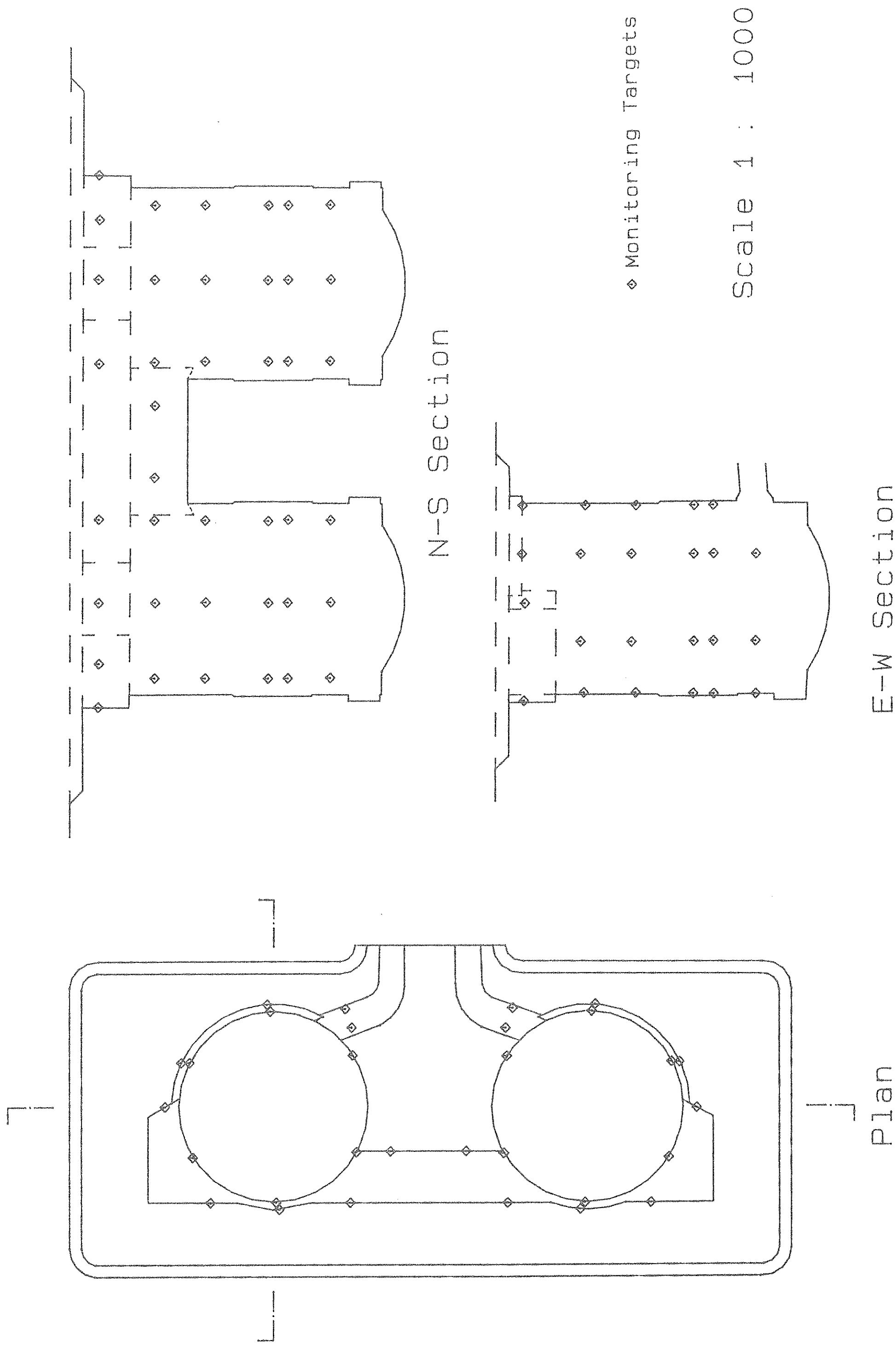


Figure 1. Hoppers Crossing Pumping Station Pumpwells Design.

This camera was preferred above all others because of its demonstrated performance in the field of deformation monitoring, due in part to the quality of the film flattening device and the use of retro-reflective targetting combined with Kodak TechPan high resolution film.

Further simulations were carried out which suggested that a combination of CRC-1 photography, stereocomparator/analytical plotter observation to a precision of 0.002mm and reduction using TBO would lead to accuracies of the order of 1mm. This represents a relative accuracy of approximately 1:80000.

## 3. WILD P32 STEREOPAIR PHOTOGRAPHY

A continuing program of Wild P32 stereopair photography is being carried out to monitor both the geology and the volume of the pumpwells. It is expected that some three hundred pairs of colour transparencies and monochrome glass plates will be required during the excavation of the wells. Photography is periodically acquired at deepening levels, generally during lulls or pauses in the excavation, to obtain full vertical coverage with some overlap. Each level requires a strip of approximately sixteen stereopairs to obtain full horizontal coverage, again with some overlap.

The stereopairs are exposed from the design centre of each well, and from the design north-south centre line of the pumpwells if required, at each level. This camera station layout leads to a reasonably consistent image scale and coverage for every stereopair. To minimise the access time to the camera stations and the setting out task, a 2.5 metre aluminium base bar was manufactured with attached Wild P32 mounting brackets. The photography is therefore close to normal case, has a consistent base to height ratio of 1:6 and a constrained relative orientation.

Each stereopair is individually controlled by at least four coordinated targets. The targets are circular with a central spot and square background in a contrasting colour. Target coordinates were initially established from phototriangulation, but this practice was discontinued in favour of conventional surveying due to unavoidable photographic and photogrammetric processing delays between photography and supply of coordinates.

With the exception of interruptions due to the construction works, stereopair photography has been carried out on a regular basis. The combination of the base bar and consistent placement and orientation of the stereopairs ensures that the photography and subsequent restitution is a routine task. At the time of writing, approximately one hundred and seventy pairs have been successfully processed.

## 4. GEOLOGY AND VOLUME MONITORING

The monitoring of the geology of the excavation has to date been a largely qualitative task. Although controlled Wild P32 stereopair coverage of clean rock face has been obtained for a large percentage of the excavation, no quantitative mapping has been carried out apart from the delineation of some strata interfaces.

However the first 11.4 metres of excavation has been compiled into mosaic for interpretative analysis. Produced from colour prints of unrectified Wild P32 transparencies, few problems were encountered with edge matching due to the consistency of the image scale. The effectiveness of the mosaic as an aid to geologic interpretation is reduced somewhat due to the large variations in the image quality caused by lighting conditions. Deep shadows and bright sunlight are unavoidable when photographing an ever deepening hole, especially when there is a limited time available between a newly excavated clean rock face changing to a face which is obscured by extraneous materials, machinery or construction works.

In contrast, the monitoring of the volume of the excavation has been intensive and continuous. All stereopairs have been restituted analytically, either by the initial technique of post-processed Zeiss Jena Stecometer stereocomparator observations and control from phototriangulation, or more recently by the combination of a Wild BC1 analytical plotter and conventional survey control. Typical accuracies of the restitutions are of the order of a few millimetres. Point data is recorded on the surface at densities varying with the roughness of the wall face.

Two complete digital terrain models of the excavation will be formed, one of the clean rock face and one of the shotcreted surface. The newly excavated rock surface is stabilised, usually after a delay of less than one day, by a covering of steel mesh and then shotcrete sprayed onto the surface to an average thickness of 0.15 metres. Both surfaces must be recorded, the former to determine the amount of material removed, the latter to determine the amount of concrete fill necessary to reach the lined diameter. Initial photography showed only the rock face, whilst later coverage allows new rock face and earlier shotcrete surface to be acquired from the same stereopairs.

The average point densities of $2\text{-}3/m^2$ for the rock face and $1\text{-}2/m^2$ for the smoother shotcrete is likely to give totals of the order of 30000 and 20000 points respectively, of which 20000 and 10000 have been acquired and processed to date. Fortuitously, the surfaces must be broken up into regions corresponding to the different mathematical surfaces involved in the design. The design is largely cylindrical, but there are intermixed planar and conical regions. Digital terrain model data is first segregated into such regions and then projected onto the design surface.

Contours of the difference between the design and the rock or shotcrete surfaces can be drawn and intrusions on the design highlighted or overcut areas noted. Figure 2 shows a cylindrical projection of the rock surface for part of the south pumpwell. As an adjunct to the contour plots, horizontal sections through the pumpwells have been prepared by reversing the projections and joining adjacent regions. Figure 3 is an example of such a section and displays clearly the relationship between the design and rock surfaces.

Volumes are computed when necessary to specific levels in the excavation. The current method of computation is to add departures from design to the design volume, but this is under review.

## 5. GEODETIC SERVICES CRC-1 PHOTOGRAPHY

Early experiences with photography in the partially excavated pumpwells very quickly indicated two potential problems with the CRC-1 photography for the deformation monitoring. Firstly, the likelihood of successful use of retroreflective targets was extremely low. Mud and water thrown up by blasting operations left a continually replenished thin film over any permanent targets. This layer could be removed with difficulties associated only with access.

A more permanent layer was deposited by the shotcreting operations. In fact, targets placed on the shotcreted surface for volume recording gradually disappeared completely even though they were well clear of the direct spraying. The continuous mist of extraneous matter in the atmosphere would probably effect any targetting system, real or imagined, and certainly disallow retroreflectors.

Furthermore, it was very obvious that severe angles of view of some targets were inescapable. Regular fracture planes of the rock resulted in block-like surfaces presented at varying attitudes to the proposed camera stations. Targets extended to well clear of the surface were dismissed due to the danger of interference by excavation machinery or material ejected by blasting.

The targets eventually adopted were those already in use for stereopair control, that is standard close range photogrammetric targets. The targets had proved to be visible under adverse conditions and were amenable to rough treatment and cleaning. The permanence needed for meaningful comparisons between measurement epochs was assured by attaching the targets to steel rods which were grouted into solid rock for an average distance of one metre. The number of targets increases with the depth of the excavation, reaching a maximum of 76 (see Figure 1).


Figure 2. Typical Contour Plot of a Cylindrical Region of the Rock Face of the Pumpwells Excavation.

The second potential problem was indicated by the Wild P32 exposures. The use of conventional rather than retroreflective targets would require that ambient light exposures be made. Harsh variations in lighting between sunlit shotcrete and shaded rock face combined with high contrast film would leave little latitude in exposures. When enquiries were made it was found that Kodak TechPan was not available in aerial format for the CRC-1. The nearest alternative, Kodak 2412, has a lower contrast but also a lower resolution. However even this emulsion gives poor exposures unless lighting conditions are close to ideal, a situation rarely obtained because of time and contractor interference constraints. Photographic processing to reduce the contrast further reduces the resolution, leading to "washed out" negatives.

Finally, the camera did not survive the air freight journey perfectly. High frequency vibrations drifted loose a number of components in the lens cone and camera body, which were subsequently tightened. The items affected included the fiducial marks, which will need to be re-calibrated at some time in the future.

In any event, photography began in September 1985 and six epochs of measurement have been recorded so far. Only the most recent four are considered useful as far as the deformation monitoring is concerned, the early epochs have only a single ring of targets which subsequently had alterations to the installation. The layout of camera stations consists basically of six stations around the top and current bottom levels of each pumpwell. Up to 28 photographs are exposed to ideally obtain every target on at least four frames.

## 6. DEFORMATION MONITORING

Negatives from the four most recent epochs have been observed monoscopically on a Wild BC1 analytical plotter. The frames are optically rotated to four orientations to remove the bias of the operator, leading to an average precision of image coordinates of 1.8 micrometers. The target images in most circumstances were acceptable, but not exceptional. As expected, lighting conditions and lack of resolution had degraded the quality of the imagery.

The image coordinates were then processed through the TBO suite of programs. An affine transformation has been used with nine reseau points to convert comparator coordinates to pseudo-plate coordinates. Lack of calibrated fiducials has been overcome by simply carrying the principal point coordinates as constrained additional parameters in the adjustment solution. All other additional parameters have been fixed at their calibrated values.

Control for the adjustment has been supplied by conventional survey and the observation of additional, non-monitoring targets imaged on the negatives. The control is introduced into the adjustment as constrained coordinates to supply a transient datum, scale and orientation of the network which is later removed by similarity transformations.

Results of the four adjustments, a recent calibration on a small test range (at a focussing distance of 3.5 metres) and a simulation of the pumpwells network are shown in Table 1. As before, the simulation predicts a target precision at the millimetre level, but the simulation does not include the effects of acute viewing angles and targets eliminated because of poor visibility. The calibration results are included here to indicate that under good lighting and observing conditions an acceptable adjustment result is obtainable.

The results for the four epochs of measurement fall far short of expectations. The RMS plate residuals indicate that there are systematic errors in the adjustment. The target precision vector and relative accuracy indicate that there are significant deficiencies in the networks. Neither of these results is entirely unexpected given the discussions in previous sections, however the degree of degradation was a surprise.

The systematic errors can be simply explained by inaccuracies in observing the target images, that is the image coordinates are precise but not accurate.

The primary cause of this problem is undoubtedly the masking of targets by extraneous materials such as shotcrete. A secondary influence may be the calibration of the camera, especially in the light of the adjustments made after the air transport. The small test range calibration indicated some departures from the manufacturer's certificate, and the calibration of the CRC-1 will require further investigation.

| Adjustment | Image Coordinate Precision (μm) | | RMS Image Residuals (μm) | | Variance Factor Estimate | Target Precision Vector (mm) | Relative Accuracy |
|---|---|---|---|---|---|---|---|
| | x | y | x | y | | | |
| Epoch 20 | 2.3 | 2.1 | 13.5 | 12.4 | 7.9 | 1.8 | 1:48000 |
| Epoch 25 | 1.6 | 1.8 | 6.8 | 9.5 | 6.7 | 1.9 | 1:47000 |
| Epoch 28 | 1.6 | 1.6 | 12.3 | 11.1 | 9.6 | 2.0 | 1:44000 |
| Epoch 30 | 1.7 | 1.6 | 20.3 | 15.8 | 12.9 | 2.0 | 1:44000 |
| Calibration | 2.5 | 3.9 | 1.9 | 3.6 | 1.1 | 0.2 | 1:20000 |
| Simulation | 2.0 | 2.0 | - | - | 1.0 | 1.1 | 1:81000 |

Table 1. Results of Multi-Station Bundle Adjustments by TBO.

The deficiencies in the network are largely caused by an overall reduction in the number of monitoring target images observed. In each epoch a number are rejected due to either poor visibility or high angles of view.

In the light of the adjustment results, comparisons between epochs are an academic exercise. The method of analysis uses repeated similarily transformations, progressively excluding points which fail a significance test against a Fisher statistic. Due to the poor reliability of the networks, only points which have been interfered with or misidentified have been statistically rejected as points where movement has occurred. Root mean square differences between epochs of approximately ten to fifteen millimetres are considered to be statistically insignificant by the testing procedure.

## 7. FUTURE DEVELOPMENTS

The photogrammetric monitoring for volumes has been successful and will continue in the present form. The monitoring of the geology of the excavation is implicit in the Wild P32 stereopair photography and can be utilised when required.

The photogrammetric monitoring for deformations was discontinued, due to the poor accuracies of the results, after Epoch 30. At present the monitoring task is being carried out by conventional surveying, but this cannot continue indefinitely for a variety of reasons. The photogrammetric monitoring is under review in terms of the targetting, the calibration of the CRC-1 camera and the film type used. If the major obstacles to accurate results can be overcome the photography is likely to be restarted on a trial basis.

At the conclusion of the excavation works the photogrammetric measurement tasks will continue. Photography for an "as constructed" record will be necessary and the constructed pumping station will require monitoring surveys. The use of photogrammetric techniques in this role will depend greatly on experience gained and the correct assessment of an entirely new set of physical circumstances, prevailing environment and accuracy requirements.

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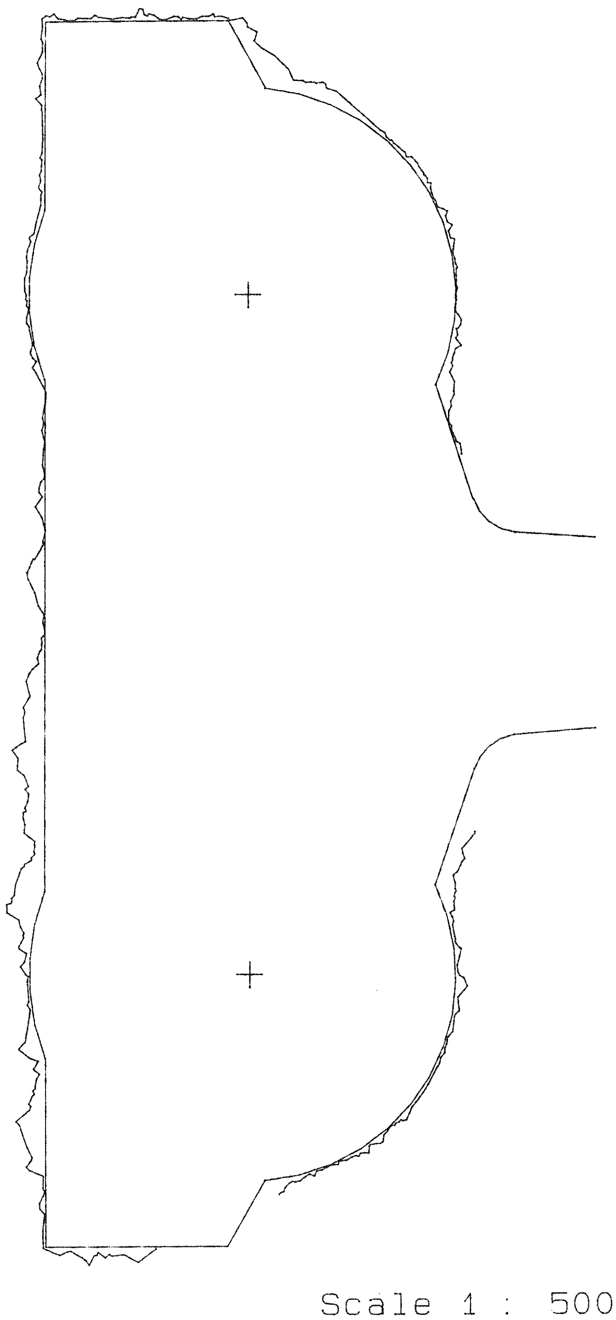


Figure 3. Typical Horizontal Section of the Pumpwells Excavation.