HOPPERS CROSSING PUMP WELLS -
AN EXERCISE IN TERRESTRIAL PHOTOGRAMMETRY

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BIOGRAPHICAL SUMMARY

J. F. ADSHEAD

John completed a Bachelor of Surveying degree with Honours in 1981 at the University of Melbourne. After graduation he joined a private company and was involved in all aspects of cadastral surveying. He then commenced a specialisation in computer processing of survey data, initially with the Road Construction Authority in the field of three dimensional road design. Since 1984 John has been part of the Survey and Mapping Branch of the MMBW, involved in information processing and management for all types of survey data. John is currently enrolled in a Master of Surveying Science Degree at the University of Melbourne studying digital terrain modelling of complex surfaces.
DR. M. R. SHORTIS

Mark completed a Bachelor of Surveying degree in 1975 at the University of Melbourne. He then carried out research programs for the degrees of Master of Surveying Science, also at Melbourne, and Doctor of Philosophy at The City University, London, both in the field of close range analytical photogrammetry. Whilst at The City University he was also employed as part of the Terrestrial Photogrammetric Unit.

In 1981 he returned to the University of Melbourne, first as a Research Fellow, and more recently was appointed as a Lecturer.

P. M. ARNOT

Peter joined Gutteridge Haskins and Davey as a cadet surveyor in 1967, and graduated to the position of survey party leader.

For the last 15 years he has worked in GHD’s photogrammetry section, initially as an operator. In more recent times he has been engaged in the fields of control selection and survey, flight planning and close range photography, computing and job design, and management.

Peter was an inaugural member of the Australian Surveying Association in 1974, and since then has continually held positions on the executive of the Victoria Division (now the Institution of Engineering and Mining Surveyors), including president and secretary. He is also a former vice president of the National Council of that organisation.
P. J. TURNER

Peter completed an Associate Diploma of Surveying in 1971 at the Royal Melbourne Institute of Technology. After graduation he resumed employment at the Survey and Mapping Branch of the MMBW. In 1973 he joined a private company in Sale to serve Articles. In 1976 Peter gained his Licence and rejoined the MMBW.

He has since worked on major construction projects at Sugarloaf Reservoir (1976 to 1982) and the Western Trunk Sewer (1984 to 1987).

At these projects he has specialised in the construction of buildings, mechanical installations and close range photogrammetry.
ABSTRACT

This paper outlines the photogrammetric techniques developed to monitor the excavation and to compute volumes for the Hoppers Crossing Pump Wells Project. It deals with the applications of photography, photogrammetry measurement and of map projections of those measurements to calculate the shape of the wells. The paper also comments on the problems encountered and solutions derived during the exercise and draws attention to the future benefits and possible new directions of the technique.

INTRODUCTION

The Melbourne and Metropolitan Board of Works is currently replacing its Western Trunk Sewer which has been in operation since 1897. The new sewer, which is scheduled for completion in 1993, is comprised of two major components:

(1) 15.3 kilometres of tunnel running from the existing Pumping Station at Brooklyn to Hoppers Crossing.

(2) 7.3 kilometres of shallow conduit running from Hoppers Crossing to the Treatment Farm at Werribee.

Both tunnel and conduit are gravity feed, at grades varying from 1:1900 to 1:2600, both having an internal diameter of some 4.4 metres. The tunnel is approximately 30 metres below the surface while the conduit lies only 5 to 8 metres below (see Figure 1). The Hoppers Crossing Pumping Station will pump the sewage from the tunnel to the level of the conduit. Eight pumps will be housed in the complex, basically consisting of two pump wells with interconnecting chambers. A Penstock Well accepts sewage from the tunnel which is fed via suction conduits to the pump wells.

The two pump wells are each 30 metres in diameter and over 50 metres deep.

The size of the excavations necessitated constant monitoring of the volumes and shapes of the wells. If too little material was removed then further excavation would have to be carried out at a later stage. (Because of the nature of the drill and blast technique used, this could have meant re-excavating a surface that was already stabilised with shotcrete and
that was already stabilised with shotcrete and perhaps several metres above the current working depth). If too much material was removed then not only would excavation costs be higher, but a greater volume of concrete lining would have to be placed to bring the surface out to design.

It is for these reasons that accurate sections of the excavated and the shotcreted surfaces, together with their relationship to design and their volumes had to be determined.

THE PILOT PROJECT

In June 1984 the MMBW approached Dr. Shortis of the University of Melbourne for advice concerning the feasibility of determining excavated volumes using photogrammetry. At that time excavation of the Penstock Well was nearing completion and it was to prove to be an ideal test site.

The Board was interested in:

(a) the accuracy of the photogrammetric volumes and position determinations;

(b) the expected interruption to the excavation and construction at the site; and

(c) the cost effectiveness of the photogrammetric solution.

As the feasibility study continued several advantages became apparent.

Firstly, it was determined that the level of precision obtained for individual points would be the same using photogrammetric techniques as with conventional surveying. Further to this, it was found that a much greater number of points could be readily obtained using photogrammetry which would lead to a higher accuracy for the volume.

The second advantage concerned the interruption to the excavation. As could be imagined this was limited to the time necessary to take the photographs. In practice this turned out to be less than two hours which was enough time to
photograph the entire well and was done during a lull in construction. In comparison the time required to measure a reasonable number of points conventionally would have been considerable.

The issue of cost effectiveness is much more complex and no conclusion was reached in the final report to the MMBW (Shortis 1985) other than to say that the cost of photogrammetric measurement is competitive with conventional surveying and may be offset by an increased volume accuracy and decreased construction delays if these were sufficiently important. As both of these were sufficiently important, the Board proceeded with the photogrammetric determination of the Hoppers Crossing Pump Wells.

THE PHOTOGRAPHY

A continuous program of Wild P32 stereo photography was carried out as the excavation of the pump wells progressed to monitor the geology, excavated surfaces and shotcreted and concreted surfaces.

Two Wild P32 cameras were mounted on each end of a 2.5 metre base bar which was seated in a Wild theodolite tribrach. The stereopairs were then exposed from the design centre of each well (and the centre line of the wells if necessary). These were duplicated on both colour roll film and monochrome glass plates. An "epoch" of photography was taken every three metre drop in excavation. This would capture three metres of rock and three metres of shotcrete. In all over 300 pairs of colour film (with glass plates as a back up) were taken during the excavation.

A typical epoch consisted of:

(a) Using a theodolite to determine the centre of the well.
(b) Epoxy glueing a ring of at least 16 permanent photo targets onto the completed shotcrete surface.
(c) Placing a ring of 30 temporary targets on the toe of the excavated surface.
(d) Determining co-ordinates of all new targets from the theodolite.
(e) Replacing the theodolite head with the base bar and cameras.
(f) Taking a round of eight stereopairs at every 45° around the wells. This gave an overlap of several metres between pairs.
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- [ ] REMOVE LENS CAP
- [x] ALIDADE BUBBLE
- [ ] ZENITH DIST.
- [ ] AZMUTH OR LINE
- [ ] f STOP
- [ ] SHUTTER SPEED
- [ ] CHECK CONTROL
- [ ] RELEASE SHUTTER
- [x] CHECK ORIENTATION
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- [ ] REPLACE BACK PLATE
- [ ] ROLL ON FILM
- [ ] C

**TARGET NUMBER**
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- 40A - 999
- 40A
- 40D
- 40E

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**SURVEY TEAM**
P. Turner, L. Price, D. Martin, A. Boros

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Diagram: North Well
(g) Each pair was booked on a proforma field sheet (see Figure 2) which incorporated all station and camera information and a comprehensive check list.

An epoch takes about two hours of uninterrupted work.

During the photography several problems were encountered. Occupying the centre of the well for two hours was not always easy. The space and the time had to be shared with the contractors' men and machinery - usually drilling rigs, bulldozers, excavators and cranes. The ground conditions were never clean or smooth, they were usually wet, muddy and rocky. Targeting was a different problem. Targets were invariably covered with oversprayed shotcrete or mud and dust from blasting and these had to be cleaned before photographing. Target types were experimented with during the project, eventually arriving at two preferred types. The permanent targets were black plastic with a white engraved circle leaving a black dot in the centre. These were glued to the shotcrete. Temporary targets were a square of paper divided into four squares with the two diagonal squares coloured red. The centre of this was then pierced by an aluminium rivet which was driven into the rock. Access was also a problem affecting both men and equipment. If a crane was not available everything had to be lowered to the excavation level by rope. Lighting conditions also presented problems. These were either contrasting light and dark strips from sunlight or background colours, or generally dull with conditions becoming worse with increased depth.

Immediately after photographing, the film and plates were delivered to the Board's Photographic Section for processing. The photos were then inspected, all visible photo targets listed with their co-ordinates and then all forwarded to Gutteridge, Haskins and Davey for measurement.

**MEASUREMENT OF THE STEREO PHOTOGRAPHY**

The Gutteridge, Haskins and Davey (GHD) Photogrammetry Section was commissioned by the MMBW to extract from the Wild P32 stereo models, a series of data points to define both the rock and shotcreted surfaces. GHD operates a Wild BCI Aviolyt Stereoplotter, driven by a Data General Nova 4X computer which controls a series of operating, collection and retrieval programs. This gives the
system a number of significant advantages over conventional analogue stereoplotters. The particular facets of this analytical system which are relevant in this case are:

(a) The system allows orientation of a number of stereo models at any one time. In this case the format of the P32 meant that six models could be oriented at the same time.

(b) The ground control co-ordinate system of easting, northing and reduced level can be accepted in any altitude by the orientation program of the analytical system.

(c) The computer allows ready storage of the digital data.

(d) The collection software offers the opportunity to code data features as "string lines".

**OPERATING PROCEDURES**

Orientation of, and measurement on the stereo models requires that a systematic operating procedure is followed so that the best possible fit to the ground survey control is obtained.

(a) Establish Camera Calibration files (one for each camera) - these files contain the interior orientation components; the focal length, fiducial mark co-ordinates and radial lens distortion.

(b) Compile a Control Point File - containing the co-ordinates, point number and weighting accuracies of the control points.

(c) Camera Orientation Files - these are not obligatory but do assist considerably in obtaining a quick orientation. Files contain co-ordinates, azimuth and elevation angles of the camera as well as its attitude or format rotation.

(d) Menu initialisation of the stereo model data - includes camera stand-off distance and the film type (positives or negatives).
(e) Interior orientation.

(f) One Step Orientation - both relative and absolute are achieved simultaneously.

(g) All models (up to six) are oriented to a proof plot which allows the operator visual control over his location.

(h) Data is collected as discrete points and coded according to the table below. This allows strings to be formed between similar features.

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<td>Points on Shotcrete</td>
</tr>
<tr>
<td>#3##</td>
<td>Top Boundary Strings</td>
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<tr>
<td>#4##</td>
<td>Lower Boundary Strings</td>
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<tr>
<td>#5##</td>
<td>Near Vertical Boundary Strings</td>
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<td>#6##</td>
<td>Corner Strings</td>
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<td>Feature Strings</td>
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<tr>
<td>#9##</td>
<td>Random Points</td>
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</table>

Once collected digital data can be reformatted and output as desired. GHD formatted the data to that suitable for the Board's terrain modelling package "Computas" (Dilley 1983) before the transfer to the Board's VAX computer via magnetic tape.

The photography, either as colour transparent positives or black and white glass negatives combined with the optics of the stereoplottter, afforded excellent viewing throughout the depth of the stereo model. The control fit was of the order of ± 0.015 metres which, from the stand-off distance of 15 metres, meant that a more detailed level of interpretative evaluation of the rock surface could have been carried out if required.
MODELLING THE EXCAVATION

Compared with the Penstock Well the pump wells proved to be many times more complex. Where the penstock was one well with one diameter, the pump wells were two with seven different diameters, and some twenty inter-connecting surfaces. The scope of the model was soon to double as it was decided that two excavation models should be formed, one for the rock and one for the shotcreted surface. In all there were some sixty surfaces being modelled, 24 shotcreted and 36 rock surfaces (see Figure 3).

Figure 3: Hoppers Crossing Pump Wells Site Plan

Projection Zones 2-18

The digital terrain models, once formed, would compute volumes and produce sections using the MMBW's modelling suite COMPUTAS. However COMPUTAS, like all DTM suites encountered to date, is designed to model surfaces relative to the horizontal planar datum. Hoppers Crossing was far more complex and COMPUTAS was unable to model the vertical and overhanging excavation surfaces.
The solution to the problem was not immediately apparent but, after some deliberation, it was decided to break the data into individual surfaces and apply a series of mathematically simple map projections. Each of these map projections would be used to transform the raw data onto a horizontal plane suitable for use by COMPUTAS.

The mathematics for each projection was quite simple. All vertical walls within the complex were "opened out" by making:

- the new Easting the length along the wall
- the new Northing the old RL
- the new RL the distance from the point to the design surface

Similarly, for steeply inclined walls and their conical intersections:

- the new Easting is the length along the wall
- the new Northing is the design slope distance up the wall
- the new RL is the perpendicular distance from the design slope.

These two projections could be readily used to contour the deviations from design and compute the volume of cut and fill required to bring the excavation to the design.

The cylindrical projections for each well were just as simple but had further implications of scale and distortion.

- the new Easting was the design length around the circumference
- the new Northing was the old RL
- the new RL was the radial distance to the design cylinder.

Approximately a thick walled cylinder to a plane surface causes distortion (Shortis and Adshead 1986). The distortion in the volume can be approximated mathematically.
Given that the design radius is \( R \) and the excavation radius is \( R + d \). Then the volume between the excavated surface and the design surface is

\[
\pi(R + d)^2 \times \text{depth} - \pi R^2 \times \text{depth} = \pi(2Rd + d^2) \times \text{depth}
\]

The volume computed from the projection is simply \( 2\pi R \times \text{depth} \times d \).

Therefore the error in volume caused by the projection is

\[
\pi \times \text{depth} (2Rd = d^2) = \pi d^2 \times \text{depth}
\]

Quantitatively this amounted to some 25 cubic metres of the 35,000 in each well. Even though this was insignificant it was added to the computed volumes.

An alternative strategy, to reduce the error, is to compute surfaces of best fit, but this requires duplication of all terrain models and twice the associated data processing.

Initially contour plots proved to be difficult to interpret for the uninitiated (see Figure 4). As an alternative, horizontal sections were plotted with design lines hand plotted for comparison (see Figure 5). The technique for derivation of these sections was similarly simple yet quite lengthy at some RLs. Commencing with the now projected surface, conventional profiles were taken at lines of equal RL (i.e. lines of equal northing on the projection). These profiles were never plotted as such, but rather "unprojected" back to the original map grid. These were then joined to similarly "unprojected" sections and plotted as a continuous line joining the series of points. This became rather lengthy when forming horizontal sections consisting of many projected surfaces.
Figure 4: A Sample Cylindrical Projection - Contour Plot
Figure 5: Horizontal Section
POSSIBLE PROBLEMS

These techniques required a number of unique considerations. Like all DTM data acquisition, the onus is on the observer to measure sufficient points to accurately define the surface. Conventionally this has led to point densities varying with surface roughness. In this case however, smooth areas within the wells would become large flat areas when projected, giving an incorrect representation of the surface and an incorrect volume. This potential problem is best avoided by due consideration at data acquisition stage. Thankfully this was the case with this project.

The second consideration was that of volume. The volume error was applied to the well volumes to eradicate the distortion caused by the cylindrical projection. For the vertical projections the volume problem occurs at the corners. Where a corner is not excavated exactly to design there is a danger of that corner volume being included twice, once on each projection abutting the corner. Once this problem is realised, steps can be taken to ensure that it cannot occur.

The final problem was management of data. In this case a point coding system was adopted by GHD in consultation with the Board. This coding system helped manage the 30,000 points and sped the processing of DTMs considerably. In hindsight these codes could have been improved still further by making them refer to each individual projection surface. This additional work by the observer could have optimised the processing time of the DTMs but would have required constant co-ordination between processor and observer in defining each projection surface.

CONCLUSIONS

This paper illustrates the processing of data for mapping of engineering excavations. Some of the relevant issues and difficulties to be overcome have been discussed. The techniques used have been and will continue to be used successfully, but are dependent on the digital nature of the data so that the appropriate transformations can be made. Without the post processing of the terrain data, digital terrain modelling of the excavations would not have been possible.
The existence of accurate plans of the Hoppers Crossing Pump Wells has led to their greater utilisation. The information has recently been used by engineers as part of the design process for the lining of the wells. Volume information so derived, has been used to accurately estimate the quantities needed to line and fill the excavation.

The cumbersome post processing can only be avoided when a more general digital terrain modelling algorithm is developed. Once this is developed, the volume and data management problems can be reviewed. This is the subject of further research by the MMBW in the field of terrain modelling for engineering excavations.

ACKNOWLEDGEMENTS

Thanks must go to the organisations supporting this exercise:

- The Melbourne and Metropolitan Board of Works - Survey and Mapping Branch

- Gutteridge, Haskins and Davey - Photogrammetry Section

- The University of Melbourne - Department of Surveying and Land Information

REFERENCES

DILLEY, A. W., 1983 COMPUTAS Instruction Manuals

MMBW Internal Reports

SHORTIS, M. R., 1985 Photogrammetric Determination of the Volume of the Western Trunk Sewer Penstock

Department of Surveying Report to the MMBW

SHORTIS, M. R., and ADSHEAD, J. F., 1986 Applications of Digital Data to the MMBW Sewage Pumping Station Project