

# MONITORING ONE OF EUROPE'S LARGEST RETAINING WALLS USING OBLIQUE AERIAL PHOTOGRAPHY

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## ABSTRACT:

Oblique aerial photography acquired with a hand held Zeiss 300 mm UMK camera from a helicopter is being used for the long term monitoring of two large retaining walls currently under construction. The location of the site has dictated the use of a helicopter to obtain suitable convergent geometry so that high homogeneous precision can be obtained. Various cameras and emulsions have been tested in order to develop a system to satisfy the unique problems of the task. Preliminary results (using inner- constraint bundle methods and congruency tests), including detected movements and rotations of individual pre-cast concrete panels which comprise the walls are discussed. Methods for visualising the displacements and rotations are also considered.

KEY WORDS: Deformation, Engineering, Hand held, Helicopter, Monitoring, Oblique, Presentation

## 1. INTRODUCTION

The A55 is a major trunk route in North Wales to the port of Holyhead on the island of Anglesey. Over the last twenty years most of the route has been converted to dual carriageway. One of the few remaining single carriageway sections is the short stretch between Penmaenmawr and Llanfairfechan. Work has now begun on providing a second carriageway at this point. This involves driving a 880 metre long tunnel through a granite headland. At each portal large retaining walls are being constructed. The wall at the west portal will be 220 metres long and 35 metres high thus making it one of the largest retaining walls in Europe when completed. These walls are being constructed from the top down and consist of 3 metre by 2 metre pre-cast concrete panels anchored to the rock with two tensioned rock anchors per panel.

The Ground Engineering Division of the Transport and Road Research Laboratory (TRRL) of the Department of Transport are undertaking a monitoring study of the behaviour of these retaining walls during construction and after completion. One of the aspects of this exercise is deformation monitoring. Based on previous monitoring work (Cooper and Clark, 1984) TRRL approached City University for advice on how monitoring of deformation of these structures could be achieved.

## 2. PRELIMINARY WORK

The situation of the site concerned indicated that photogrammetry provided the best and most efficient method of monitoring the walls. The site is on the side of a cliff above the sea with the existing road being 28 metres above a railway at the shoreline. Monitoring by traditional geodetic surveying methods would not yield sufficiently accurate and homogeneous results because of poor network geometry, as all sight lines would have to be observed up from the existing road level and would result in highly inclined lines of sight to points on the top half of the walls. For good redundancy an excessive number of instrument stations would be required. Additionally as monitoring was required during construction it would be almost impossible to sight to targets through all the construction plant and other obstructions that would be on site, particularly in the early stages of construction. Using photogrammetry it would

be possible to get much better convergent geometry by using camera stations raised above the existing road level and most of the plant. One possibility investigated was to employ an elevating platform to raise the camera to the high positions. However this would have resulted in severe congestion to the existing road, which is a major trunk route, with the platform parked at the roadside with outriggers extended, especially during the construction phase.

Low altitude vertical aerial photography has been used in the past for monitoring unstable hillsides (Fraser, 1983, Fraser and Gruendig, 1984). In this present study oblique aerial photography of the almost vertical walls seemed ideal and therefore it was decided to use a helicopter to obtain the required photography. This had the added advantage of rapid acquisition of all the required exposures per site. Helicopters with special mounts have been used to acquire vertical photography (Stanbridge, 1987) but in this instance it was very quickly decided that the camera would be hand held for the oblique photography. Therefore with no requirement for specialised camera mounts not only could the cost be reduced but, more importantly, allowed much greater flexibility in chartering the most conveniently situated helicopter.

In order to obtain a large enough image scale for accurate measurement it was decided to use a Zeiss Jena UMK 30/1318 camera with 300 mm lens and glass plates. Consideration was given to using a film back but this would have proved too heavy to hold conveniently and the weight of the control box and provision of a power supply was also a problem. It was felt that with some practice glass plates could be changed quickly enough for the operation to run efficiently.

It was also decided to hire a Linhof Aerotechnica 45 EL camera with a 250 mm lens for the first sortie to compare the operation of the two cameras in the helicopter and also their suitability for providing accurate results.

One of the major tasks was the design of a suitable hand held mount for the UMK. The resultant design had to be strong enough to support the weight of the camera but enable pointing and plate-changing to be accomplished easily and quickly. The final design (Figures 1 and 2) utilised the harness of a bus conductor's ticket machine attached to a metal plate from which a short aluminium

pole protruded outwards and upwards at an angle. A fluid head for a video camera could be slipped over the top of the pole. The UMK was attached to this head by means of a specially manufactured plastic mount. Thus the camera could be tilted and swivelled for pointing at the wall and then the camera body lowered so that the back of the camera was uppermost to facilitate changing of plates. The design of the mount was such that most of the weight of the camera was borne by the operator's stomach and not by his arms thus reducing strain. A simple wire open sight to aid pointing was manufactured and slipped over the lens cone. None of the UMK's normal electrical system was incorporated in this mount so that the fiducials and shutter had to be fired sequentially by hand.



Figure 1 Original design of UMK mounting plate

One of the largest sources of concern was the choice of emulsions. The UMK is not designed for aerial photography and therefore the lens aperture does not open sufficiently to allow the fast shutter speeds required for aerial work. It was essential that a fast emulsion could be used to allow for sufficiently fast shutter speeds to obtain sharp images. The range of emulsions available on glass plates for the UMK is limited. Therefore a compromise had to be made between high resolution so that the targets would be satisfactorily imaged and a high enough film speed so that vibration in the helicopter would not produce unacceptable blurring of the image. Initially it was decided to use Kodak T-Max 100 plates which could be pushed to 400 ISO in subsequent processing. These were available in 5 inch by 7 inch (127 mm by 178 mm) 1 mm thick plates by special order from Kodak in the United States. For the Linhof, Ilford HP5 panchromatic on 5 inch (127 mm) NATO standard rolls were purchased. Delivery of the plates from Kodak was quite time consuming so that very little time was available to test them between delivery and the first flight.

A major problem was in the design of the monitoring targets to be used. Obviously the photogrammetric requirement was for a high contrast target of sufficient size that would guarantee its imaging on the photography from the proposed maximum taking distance of 150 metres. However, aesthetic requirements imposed by the Welsh Office meant that the walls could not be covered with many large unsightly targets. A number of designs were

produced and tested using the 300 mm UMK hand held at representative taking distances. The final choice of target was a white diagonal cross 10 mm thick on a 60 mm square black background.

The targets were to be positioned on a number of vertical rows of panels on each wall. Five targets on each panel, one in each corner and one in the centre, would enable any rotations of individual panels to be detected. Additional targets were to be positioned on the bare rock faces above and beside each portal close to the heads of rock anchors for the detection of any movement in the original rock. The positioning and mounting of the targets were the responsibility of TRRL and the Consulting Engineers, R Travers Morgan and Partners.



Figure 2 300 mm UMK on original mount

Some network design was undertaken. After a series of simulations it was decided that three runs of photography were required. Two runs would be taken close in to the wall, with one run being level with the base of the wall at a distance of 90 metres from the wall and the other run being taken 100 metres higher at a distance of 70 metres. A third run would be taken from a mid level position at a range of 150 metres to provide overall coverage of the walls and to provide a good connection between rows of targets. Using a priori standard deviations for the plate observations of +/- 3 microns these simulations indicated that a precision of coordination of the targets of the order of +/- 1 mm in all three coordinates would be achievable.

### 3. ACQUISITION OF PHOTOGRAPY

Shortly before the first photographic sortie the local Police informed the contractor that they would require the road to be closed when the close-in photography was being taken as they were worried that traffic accidents would occur with motorists' attention being on the helicopter and not on the road. Additionally they stipulated that the road could only be closed for a maximum period of ten minutes and they reserved the right, if traffic backed up excessively in that time, to order the helicopter off and reopen the road before the ten minute slot was up. Two slots were allocated at 10.00 hrs and 13.00 hrs. Therefore

very good coordination would be required in the helicopter so that all the required photography at each site could be obtained within the ten minute restriction. It was decided to photograph the smaller of the two sites, the east portal, in the morning slot to enable experience to be gained before the larger site at the west portal was photographed in the lunchtime slot.

The first sortie was flown in July 1991. A crew of three, in addition to the helicopter pilot, was employed. The navigator sat in the left front seat beside the pilot and provided guidance instructions to the pilot. This crewmember also operated the Linhof. The camera operator sat in the left rear seat with the third crew member on his right to assist with and organise the changing of the plates. An immediate problem not encountered during pre-flight testing was that the T-Max plates were slightly undersize for the UMK plate holders. This, added to their thinness of only 1 mm, made them vulnerable to vibration and movement within the plateholders. As a result a number of these plates cracked as the dark slides were being replaced in the plate holders. With the ten minute slot constraint per site it was not possible to take these exposures again.

It had also been decided to take whatever photography was possible of the site from the ground using the Zeiss Jena 10/1318 camera with 100 mm lens. This was as an insurance against some of the aerial photography not being useable because of blurred targets, etc. For this ground photography Agfa Avipan 100 ISO 130 mm by 180 mm (5.1 inch by 7.1 inch) glass plates would be used.

After the first sortie it was decided not to use the Linhof on future sorties. Although much simpler to use than the UMK with glass plates the Linhof's smaller focal length and resulting smaller image scale resulted in some targets not being resolved on all of the images at the maximum taking distance chosen for the UMK. As the UMK system had proved workable and had yielded good results it was decided that further hiring of the Linhof was an unnecessary expense.

A number of modifications were carried out after the first sortie. Firstly the stomach plate for the UMK mount was greatly enlarged and curved to spread the pressure on the operator's abdomen. Additional handles were attached to the sides of the plastic mount to make pointing easier. Switches for firing the fiducials and shutter were attached to these handles. An improved sighting system was also built (Figure 3). The most significant change however was in the choice of emulsion for the UMK plates. Firstly it was decided not to use Kodak T-Max 100 plates again as the breakage rate in the first sortie was unacceptable. Additionally a faster emulsion was desirable as the second and third sorties were to take place during the winter and there was a strong possibility that lighting conditions would not be as good as during the first sortie. It was decided to use Kodak T-Max 400 which could be pushed to a rating of 1600 ISO during processing. However it was not possible to obtain this emulsion on plates so a decision was taken, somewhat reluctantly, to use film glued onto plates. 10 inch by 8 inch (254 mm by 203 mm) sheets of T-Max 400 were purchased, cut to size and mounted on old Avipan plates using Scotch Spray Mount.

It was realised that the resulting film unflatness would result in a lower precision for the second and subsequent sorties. Previous tests with the 100mm UMK using cut film on plates had indicated that errors in image



Figure 3 UMK in redesigned and improved mount

coordinates of up to 60 microns could be expected. However with the longer focal length, 300 mm, and resultant narrow lens angle these errors would be reduced to the 20 micron region and, with sufficient photographs in the bundle, would not result in unacceptably large errors in the coordinates of the targets. This loss of precision was deemed acceptable if the faster film rating would guarantee the acquisition of measurable images.

The second sortie was flown in October 1991 and a third sortie, much delayed by weather, was flown in April 1992.

#### 4. MEASUREMENT AND ANALYSIS

All photographs were measured on an Intergraph Intermap Analytic (IMA) analytical stereoplotter operating in monocomparator mode. Each fiducial and target point was measured three times and the observations meaned. The resultant mean standard deviations for the plate measurements were of the order of +/- 3 microns. These observations were transferred to a Sun Sparcstation where they were run through City University's General Adjustment Program (GAP). This is a program written in C for adjusting any combination of geodetic and photogrammetric observations. In this case there were only photogrammetric observations. A feature of GAP is that any combination of datum constraints can be used (ie points can be fixed, weighted or free). GAP will recognise any datum deficiency and automatically border the matrix of normal equations accordingly. In this instance no target points were held fixed and "inner constraints" were used where the starting values of the coordinates of the target points were used to define the datum. The camera positions were not used in the definition of the datum as these would vary from sortie to sortie.

Table 1 lists the results from GAP for various combinations of data for epoch 2. These are: using just the aerial photography; using just the ground photography; and using both sets together. It can be seen that there is a great increase in precision when both the aerial and the ground photography are used. It was noticed that when using the *a priori* standard deviations for the plate observations for epoch 2 that the variance factor after running GAP with the aerial photography only

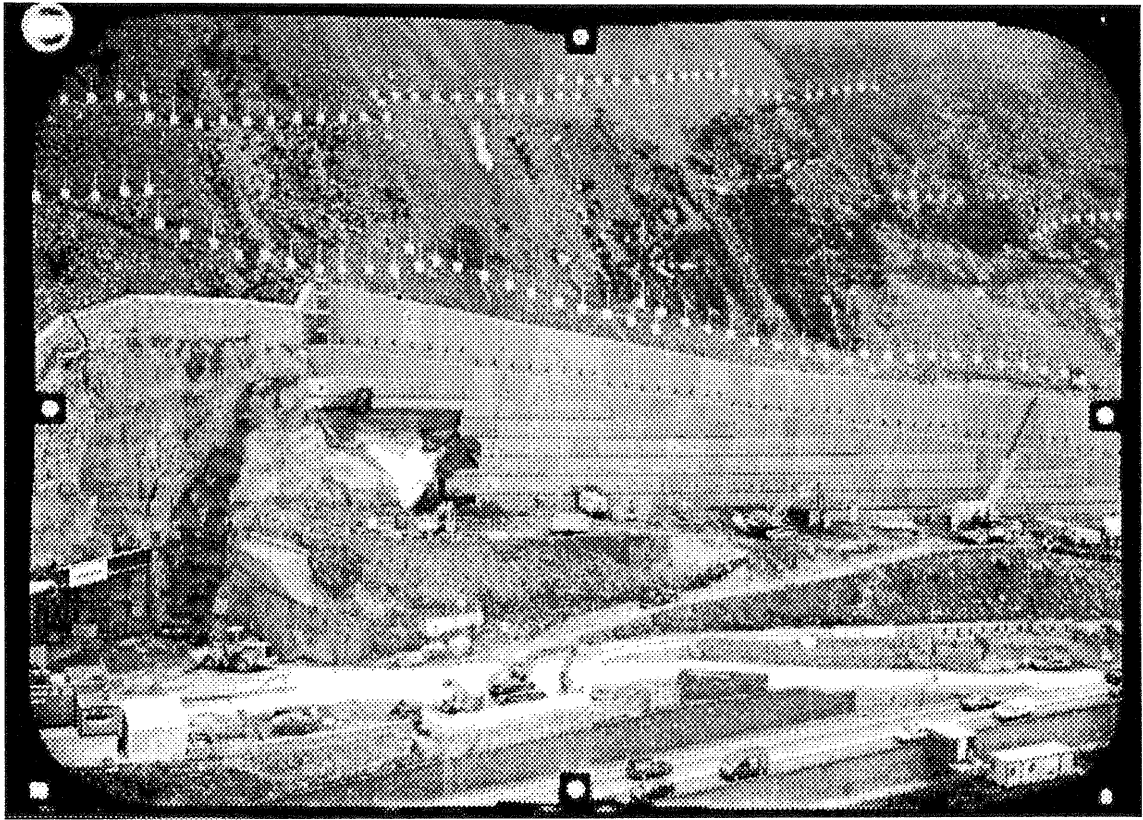


Figure 4 300 mm UMK photograph taken from distant location - epoch 1

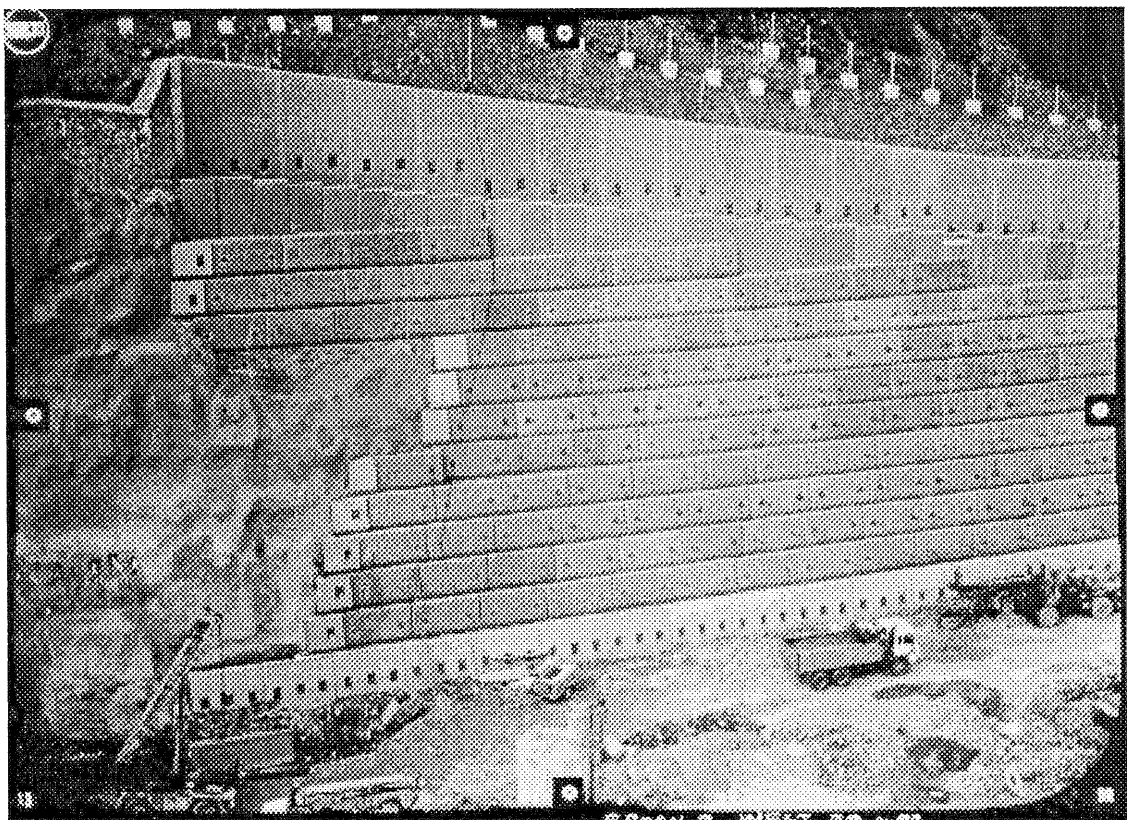


Figure 5 300mm UMK photograph taken from low level close in position - epoch 3



Figure 6 300mm UMK photograph taken from high level close in position - epoch 1  
(Note obstructions owing to construction plant)

was about 3. At epoch 1 the comparable variance factor was 1. The results listed in Table 1 are those after the *a priori* standard deviations of the observations of the aerial photographs have been increased globally so that the resulting variance factor was 1.

Analysis of plots of residuals on the plate measurements for the aerial photography for epoch 2 have shown that each plate has a systematic array of residuals but that between plates and over the block as a whole the residuals are random. The most probable cause of this is effects of film unflatness with the cut film stuck to the glass plates. Therefore it is apparent that if suitable glass plates could be found for the UMK that a high precision could be obtained from the aerial photography alone. It is fortuitous, therefore, that the decision to take back-up photography from the ground was taken as this has enabled the original specification to be achieved.

#### 4.1 Analysis of deformation

The next stage in the data processing was to input the GAP outputs from epochs 1 and 2 into a program called ANDEF (ANalysis of DEFOrmation). The data from GAP that ANDEF uses are the coordinates of both sets of target points ( $x_1$  and  $x_2$ ), the cofactor matrices of these two sets ( $Q_1$  and  $Q_2$ ), the degrees of freedom for each epoch ( $r_1$  and  $r_2$ ) and the estimated variance factors ( $\sigma_1^2$  and  $\sigma_2^2$ ). ANDEF checks that the same datum of inner constraints has been used in both epochs and also tests that both results have the same variance factor (5% significance level). A common variance factor is then computed from :-

$$\sigma^2 = \frac{r_1\sigma_1^2 + r_2\sigma_2^2}{r_1 + r_2}$$

The matrix of displacement vectors is calculated from :-

$$d = x_2 - x_1$$

The cofactor matrix for these displacements is :-

$$Q_d = Q_1 + Q_2$$

A global congruency test is then carried out using :-

$$\Omega = d^t Q_d^+ d$$

where  $Q_d^+$  is the pseudoinverse of the singular cofactor matrix  $Q_d$  which, in this case, is rank deficient by 7.

These are then used in a series of congruency tests to isolate a set of targets which, at a specific confidence level, can be regarded as stable. The displacements of the other targets relative to this sub-set are derived. Tests based on hypotheses about the geotechnical and structural properties of the wall should be included in this process; it is intended to do this later in this project.

Table 1 Summary of results from GAP for west portal - epoch 2													
	Number of			Standard Deviations of coordinates						Residuals			
	Phot	Targ	Obs	RMSE			Maximum			RMSE	Max		
				x	y	z	x	y	z				
				( millimetres )						( microns )			
Aerial only	16	83	410	2.7	5.5	2.5	5.9	15.2	8.5	5.3	38.5		
Ground only	8	59	169	6.6	5.3	2.9	17.3	17.6	7.1	4.4	19.7		
Both combined	24	86	597	1.1	1.6	0.8	2.9	4.9	1.6	7.0	49.3		

### 5. PRESENTATION OF RESULTS

Once a satisfactory set of solutions from GAP and ANDEF has been obtained the resulting deformations can be tabulated along with their standard deviations or can be represented graphically.

A series of routines written in Intergraph's MicroStation Development Language (MDL) have been created to read data from an ANDEF output file and produce three-dimensional graphical line strings representing the vectors of detected movement of each target point in a MicroStation design file. Along with the vectors are associated ellipses indicating the 95% confidence level for each vector. Each movement vector has three ellipses associated with it: one in the XY plane; one in the XZ plane and one in the YZ plane. This design file can then be looked at from any direction and at any scale. In this way the engineer should be able to obtain a better understanding of the movement of the structure than when restricted to tabulated data or simple two-dimensional paper plots

In order to provide a background image so that the vectors can be shown in context a number of pairs of the aerial photography for epoch 2 were set up in the IMA and the main features of the walls, including individual panels, and their surroundings digitised. Figures 7, 8 and 9 show three different generated views of the results for the east portal for movements between epochs 1 and 2. The X axis of the coordinate system is aligned with the mean axis of the panelled section of wall with the Z axis being vertically upwards.

The large vectors of movement above the tunnel portal to the right of the diagrams also have large confidence ellipses. This is because of poor geometry at epoch 1 caused by the loss of coverage when the thin Kodak T-Max 100 plates cracked in the helicopter. Because of the height of the rock face at this point the additional ground photography was insufficient to bring the precision of the coordinates of these targets within the specification

Further MDL routines have been written to enable graphical displays to be produced to illustrate rotations of

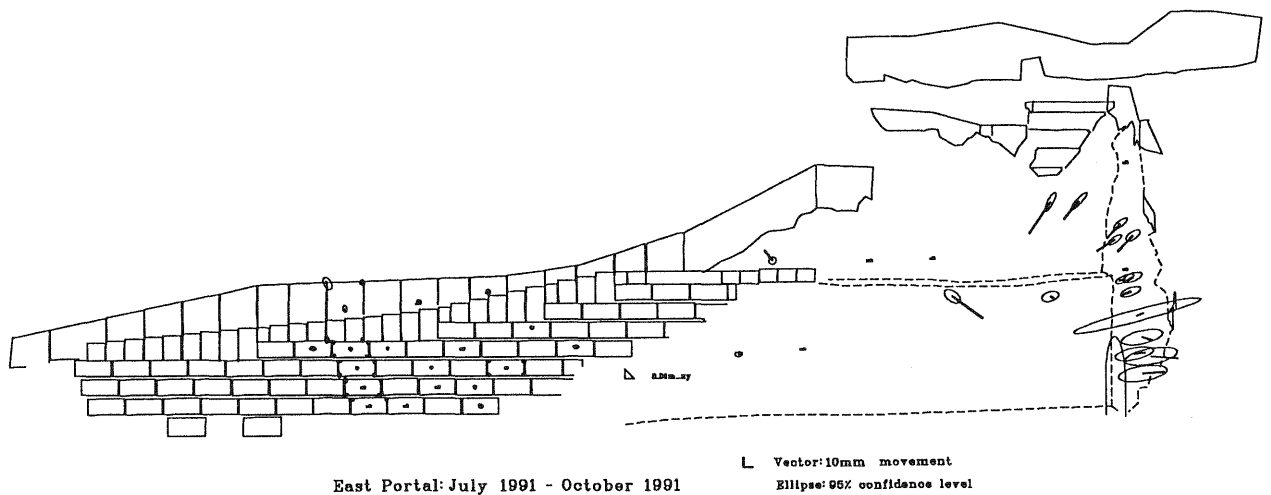


Figure 7 Plot of vectors of movement and confidence ellipses for east portal, epoch 2- epoch 1

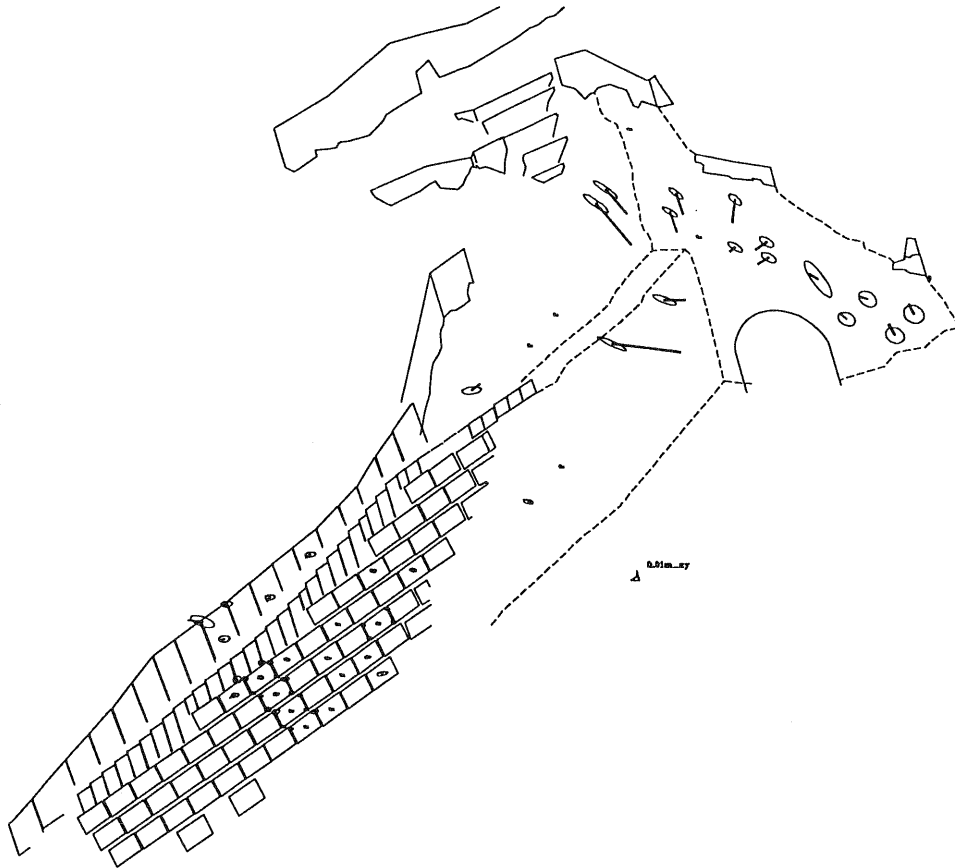


Figure 8 Isometric view of vectors of movement and confidence ellipses for east portal, epoch 2 - epoch 1

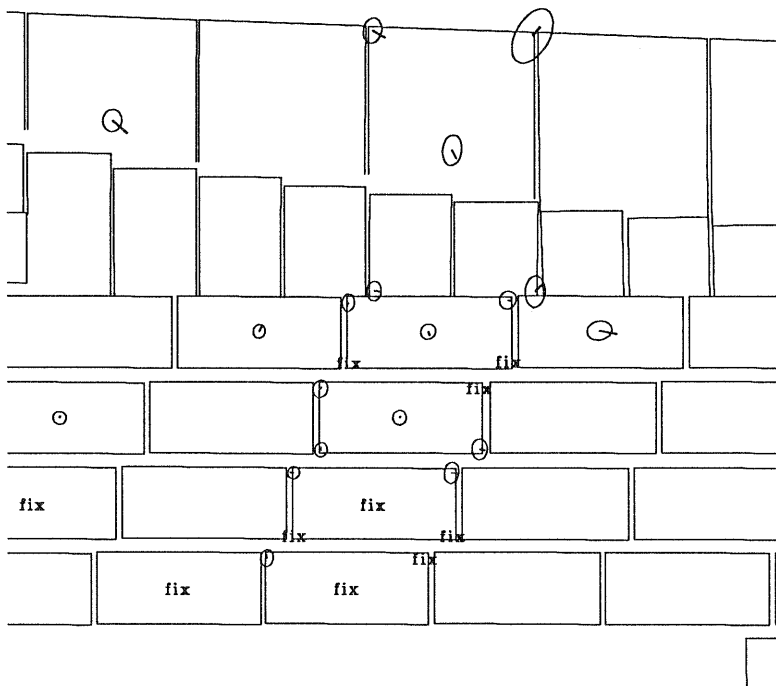


Figure 9 Enlarged view of vectors of movement and confidence ellipses for east portal, epoch 2 - epoch 1  
Note points held fixed in the final adjustment

those individual pre-cast panels which have five targets. These have not been required as of yet as no significant rotations have been detected.

At the time of writing (early May 1992) the epoch 3 photography has yet to be measured and analysed.

## 6. CONCLUSIONS

Initial results from epochs 1 and 2 indicate that the system which has been developed has proved capable of providing coordinates of targets on the wall to the required precision of +/- 1mm despite problems with thin plates at epoch 1 and having to resort to cut film stuck on plates for epochs 2 and 3.

The UMK hand held mount worked successfully although further refinements are being considered. One major change being considered is to use the film back on the UMK. There is a wide range of suitable high speed high resolution emulsions available on film which can be cut to fit the UMK magazine. The vacuum film flattening facility should reduce problems associated with film unflatness and enable the original specification to be met without the need for the ground photography. However this ground photography will probably still be acquired for the next few epochs as further insurance against unforeseen eventualities. Although originally rejected on the grounds of weight the problems experienced with plates and cut film have led to a reevaluation of the problem. Additionally a larger helicopter was chartered for the epoch 3 sortie so lifting capacity would not have been a problem. Also the workload has increased as TRRL has requested that some additional small walls between the two main sites be monitored as well. It has not been possible to obtain additional slots or increase the slot times so that there is now very little latitude during each sortie. However a major redesign of the mount would be required to distribute the extra weight on the operator. One possibility being considered is to produce a mount where the weight of the camera is evenly distributed between the abdomen and the shoulders. It is still hoped to operate without any physical connection between the camera and the airframe, not only to limit the transmission of vibration but also to widen the number of available helicopters.

The data analysis software, GAP and ANDEF, is undergoing continual development and enhancement. Most of this development is concentrated on data snooping techniques. However a significant development planned for the near future is the inclusion in ANDEF of tests for comparing expected movements based on geotechnical and structural properties with detected movements.

## 7. ACKNOWLEDGMENTS

The authors would like to take this opportunity to thank other members of the Engineering Photogrammetry Unit and the Engineering Surveying Research Centre of City University for their contributions to the project. Thanks are also due to Ken Brady and Dave Barrett of the Ground Engineering Division of the Transport and Road Research Laboratory for instigating and supporting the study and also to Paul Selley of R Travers Morgan and Partners for his assistance and liaison on site.

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