XIII Congress of the
International Society for Photogrammetry
Helsinki, 1976

Commission V
Invited Paper

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A Review of Close-Range Engineering Photogrammetry

Recent applications of close-range photogrammetry to engineering, and some of the problems encountered, are discussed.

Abstract: *There is little doubt that photogrammetry will be applied to an increasing extent in the solution of measurement problems in engineering. Already there are indications that the number and variety of applications is growing. An attempt has been made to review recently published examples, the majority of which have been reported from the United Kingdom. They include the recording and measurement of dam displacements, unstable geological structures, snow cover, soil, structural and hydraulic models, constructional problems, and box girder load tests. The paper concludes by indicating some of the problems which beset these applications of close-range photogrammetry. Their solution would help to further the wider acceptance of these techniques.*

Introduction

It is possible to gain a certain degree of satisfaction from the achievements of Commission V of the International Society for Photogrammetry during recent years. Non-topographic photogrammetry is being applied in an ever increasing number of ways. More and more measurement problems are being solved by photogrammetric techniques. In 1968, Commission V directed our attention towards the needs of architecture, archaeology, and the conservation of what is worthwhile of our man made heritage. The result was the establishment of the International Committee on Architectural Photogrammetry which has since fostered developments in this field with conspicious success. Their most recent publication (Carbonnell, 1974) is the third in a comprehensive series of reports on developments in architectural photogrammetry which have taken place since Carbonnell (1969) gave an invited paper to this Commission at the XIth International Congress of Photogrammetry in Lausanne. Attention has since been focussed upon medical applications of photogrammetry and the Commission V symposium in 1974 was devoted to this topic (Karara and Herron, 1974). An International Exploratory Committee on Biomedical Photogrammetry has since been seeking ways of furthering this development.

It would appear that engineering or industrial applications of photogrammetry might offer a further rewarding field of activity. Those who are in a pessimistic frame of mind may say that several attempts to apply close-range photogrammetry to engineering problems have met with only limited success and their widespread adoption has not occurred. Lacmann (1950) described many examples in his text book, several of which date from the early part of the 20th century. To this writer's knowledge, applications in the motor and chemical industries were eventually discontinued, despite the proven success of the photogrammetric methods (Farrand, 1965). This appears to have been because, very often, the engineer chooses to use those methods and equipment with which he is familiar, unless the alternative offers distinct advantages. If photogrammetry is just as good as, but no better than, an established technique, it is unlikely to be adopted because it requires expertise and equipment which are relatively unusual. However, there are circumstances in which photogrammetry may be applied to advantage and this paper enumerates some of them and indicates possible lines of development.

Recent Engineering Applications, with Particular Reference to Work in the United Kingdom

In an attempt to limit the coverage of this paper, it was decided to review engineering applications of photogrammetry which have been published since January, 1972 or which are known to be in progress. The majority of examples which will be cited have originated in the United Kingdom but similar work has taken place in a number of other countries. January, 1972 was chosen as a suitable date because most work reported at the XIIth International Congress of Photogrammetry in Ottawa would have been prepared or published before that date. Readers in search of examples of earlier work could consult, for example, *Bulletin de la Société Française de Photogrammétrie*, 22 (1966) which contains articles on the application of close-range photogrammetry in the hydro-electric power industry; *Journal of Japan Society for Photogrammetry*, Special Volume 2 (1966) which contains the papers given at the Commission V symposium of that year; and reviews by the author (Atkinson, 1968 and 1972b), both of which include sections on, and references to, close-range engineering photogrammetry.

The period under review has seen further gradual development of non-topographic photogrammetry in the United Kingdom. Engineering applications form a substantial section of this development. Perusal of the *Directory* which was compiled and edited by Dowman (1974) confirms this impression. A significant application in shipbuilding, which was described by Newton (1974), has now been joined by the establishment of a photogrammetric unit associated with the construction of oil rigs. Both aspects will be fully explained in another invited paper* to be given to the XIIIth International Congress. These developments have resulted from cooperation between the University of Newcastle upon Tyne and the British Ship Research Association in the first case, and between the University and Longdin and Browning (Surveys) Ltd. in the second.

Because they are the subject of an invited paper** from the United Kingdom, it is appropriate to mention here the impact of coherent optical methods on measurement problems in engineering. Developments have already been reported by Gates (1975) and Burch and Forno (1975) of methods which are being evolved at the National Physical Laboratory and, in the latter case, in collaboration with the Transport and Road Research Laboratory. Burch and Forno were specifically concerned with measurements of deflections of a large beam under load by using techniques which, hitherto, had not

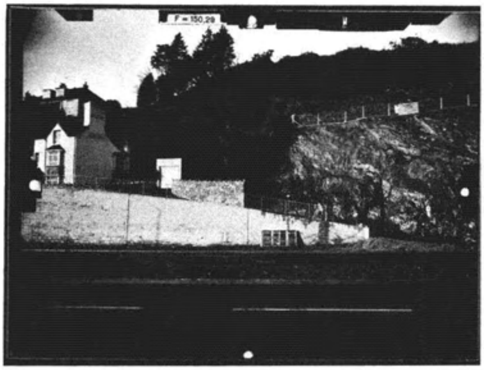


FIG. 1 A scheme to double the carriageway of a road near Plymouth, Devon involved a section of excavation in rock. The southern extremity is shown in one of the survey photographs, together with adjoining property and a retaining wall and slope stabilisation measures. The determination of quantities for a further extensive retaining wall could be made from the results of a photogrammetric survey which was carried out by University College London and Cartographical Services (Southampton) Ltd. for Devon County Council.

Invited papers, Commission V, International Congress of Photogrammetry, 1976.

* Close-range photogrammetry as an aid to measurement of marine structures, by I. Newton.

** Three-dimensional location and measurement by coherent optical methods, by J.W.C. Gates.

been easy to apply away from the stability of laboratory surroundings.

An area in which commercial photogrammetric companies have been able to contribute to the application of close-range techniques is that of dams and rock outcrops, both natural and excavated. Fairey Surveys Ltd. carried out a survey of Edinburgh Castle Rock (Cheffins and Rushton, 1970) in 1969 using a Wild RC5A camera, and since that time several other companies have been involved in similar surveys in places as widely separated as Muckle Flugga in the Shetland Isles and Plymouth in Devon (Figure 1). The engineering contractors need these surveys because of the instability of the rock surfaces. Rock bolting, construction of retaining walls, rock blasting and related safety aspects, and prefabrication of structures all require the information provided by, typically, a 1:50 scale survey with contours or isometrons* related to a vertical datum plane. A dam is a structure of similar size and its behaviour is of the utmost concern; photogrammetric surveys of dams have been reported in the United Kingdom and elsewhere. The Building Research Station and Hunting Surveys Ltd. were jointly responsible for the photogrammetric study of the constructional displacements of the rockfill dam at Llyn Brianne in mid-Wales (Moore, 1973). The dam is 90 m high and 200 m wide. A Wild P30 phototheodolite was used to provide stereoscopic coverage, at eight different stages of construction, of both upstream and downstream shoulders. Ground control was established on the valley sides, together with 80 targeted points at various levels on the dam. Three dimensional co-ordinates were required of these premarked points and in fact three dimensional displacements were determined to an average accuracy of 0.05 m. Profile lines through the dam also were obtained. Brandenberger and Erez (1972) and Brandenberger (1974) also have reported on dam surveys which involved photogrammetric techniques. Brandenberger achieved greater accuracies at Outardes, Quebec than Moore reported from Wales but of course so much depends on the configuration of the site and on the equipment which happens to be available for the survey.

The Building Research Station has also conducted a photogrammetric study of joint influence on weathering of steep chalk faces; it has determined the joint disposition and material volume after slide failure in Oxford Clay; and it has monitored a deep, steep rock cutting on the Trans-Pennine (M62) motorway.

An interesting variation on surveys of this type and magnitude of structure is reported from Poland (Butowtt *et al.*, 1974) where studies of erosion of a number of scarps on the banks of the River Vistula have been carried out. A modified Fairchild air survey camera (cf. Cheffins and Rushton, 1970), carried on a launch, was used for photography, and contoured plots and profiles were derived from the photography.

Collaboration between the Institute of Hydrology and The City University has led to the use of terrestrial photogrammetry in an analysis of snow distribution (Blyth *et al.*, 1974). A research catchment on the eastern slopes of Pumlumon Fawr in Wales contained a test area, 300 m × 100 m in extent and ranging in height between 460 m and 525 m. This site was photographed, both free of snow and under snow cover of about 100 mm depth, from each end of a 100 m base. Encouraging results for the determination of snow depth when compared with site checks may lead to the use of photogrammetric monitoring in connexion with provision of hydrological data for use in flood warning systems. Photogrammetry may also be used in an examination of the physical processes of snowmelt.

Fairey Surveys Ltd. have, over the years, shown a refreshing readiness to attempt the solution of a variety of measurement problems. Reference already has been made to Edinburgh Castle Rock (Cheffins and Rushton, 1970) and, in a recent paper, Cheffins (1975) has described other applications of non-topographic photogrammetry in which his company has been involved. Two of the applications which are described in that paper are of interest at this juncture. The first concerned the determination of distortions in the area adjacent to the static vent of a BAC 1-11 aircraft. Close-range stereometric photography of an area just in excess of 1 m^2 was analysed to provide a regular grid of depth values of the area of interest. The cameras (f=150 mm) were about 1.5 m away from the fuselage and the overall repeatability of depth measurements from four different sets of photography of the same subject, when analysed photogrammetrically, was ± 0.36 mm root mean square error (or 1 part in 4200 of the object distance).

* O.C. Gibbins has used the term *isometron* for lines which pass through points having the same depth or distance from a vertical plane. See Gibbins, O.C., 1970. Searching for hydroelectric power schemes in Tasmania with special reference to the Dove River. *Cartography,* 7(2): 59-68.

The second engineering application which Cheffins (1975) described concerned the definition of the complex shapes of a steel respirator mould. Photography and plotting both were achieved with a modified Williamson multiplex unit (described by Cheffins and Clark, 1969) which allows the reprojection of a distortion free 1:1 scale stereomodel.

During the period under consideration, Grün and Stephani (1974) published an account of a photogrammetric survey of a German atomic reactor and they reported that standard errors of ± 1 mm in plan and ± 2mm in height were achieved when a maximum object distance of 10 m was involved. Some years ago, Fairey Surveys Ltd. were active in a similar field and, although no results were published, a personal communication from Cheffins (1967) gave some details. In the course of designing reactor vessels for nuclear power stations, the Central Electricity Generating Board constructed and tested model pressure vessels. During the testing procedures, it was necessary to measure surface distortions which took place in the vicinity of 1 m diameter panels which contained several nozzles. A panel was located on the underside of a vessel which was 3 m in diameter and more than 13 t in weight. The vessel was installed in a pit for safety reasons and for some of the trials it was subjected to high temperatures as well as to high pressures, which made direct measurement of a test panel difficult if not impossible. Stereoscopic photography was taken by phototheodolite at two successively occupied camera stations on the floor of the pit and with the camera axis pointing vertically upwards. Later, a pair of suitably modified Kelsh plotter projectors were used to acquire photography. Coordinate analysis was carried out on a Wild A8 with machine co-ordinates transformed to a control system in the object space.

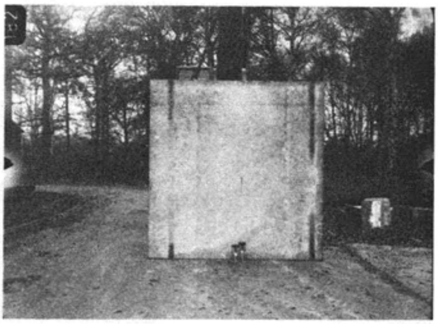
One of the most fruitful fields of application for close-range photogrammetry lies in the analysis of models. In engineering, a number of interesting examples have been reported. Particularly noteworthy is the centrifugal testing of soil models, initiated by Professor A.N. Schofield at the University of Manchester Institute of Science and Technology. Photogrammetric aspects of these tests were reported by El-Beik (1973). They began in 1969 and serve to obtain precise measurements of surface movement of soil models which rotate in a centrifuge at speeds up to 45 ms^{-1}. Tests are monitored by closed circuit television and, at appropriate or critical stages of a test, a pair of Zeiss (Jena) UMK 10/1318 cameras can be lowered into the centrifuge in order to take survey photography. Synchronised with the two cameras is a powerful high speed flash unit which provides 100 J for 2.5 μs. The accuracy of measurements is claimed to be about ± 0.2 mm which is considered to be acceptable.

Butterfield *et al.* (1970 and 1972) and Andrawes and Butterfield (1973) have made use of false parallax techniques in their studies at the University of Southampton in soil mechanics and in simple channel flow in hydraulic experimentation. The fluid surface was enhanced by paper tape punchings so as to improve stereoscopic pointing. Similar work is reported from the University of Bristol in Dowman (1974) and from Switzerland by Schmid (1973).

In this section of the paper, it has been possible briefly to review photogrammetric activities in branches of engineering which include marine structures, dam displacements, scarp erosion and rock face instability, snow depth measurement, aircraft vent deformation and respirator mould shape, atomic reactor geometry, and soil and hydraulic model behaviour. These applications of close-range photogrammetry have involved research establishments, commercial companies, and university departments. Some of the British survey companies already have received specific mention but others also are involved in close-range applications, notably Meridian Airmaps Ltd. who have carried out tunnel surveys, bridge surveys for restoration work, landslip analysis and displacement measurement of earth retaining banks. Photarc Surveys Ltd. has been formed since 1972 and this company has a special interest in close-range engineering photogrammetry. There will be more to say about the contribution of the commercial survey companies in the concluding section of this paper. However the author would now like to turn to some projects with which he has been involved at University College London.

Building and Structural Engineering

Figures 2 and 3 show examples of precast concrete panels which were contoured at 2 mm vertical intervals in order to show the extent of deformation from an ideal plane surface. Figure 4 shows a building constructed of precast units and Figure 5 illustrates the deviations of panels from the vertical in that building. This kind of information on manufacturing and erection tolerances was provided for the Building Research Station between 1961 and 1963 at a time when solutions were being sought for these construction



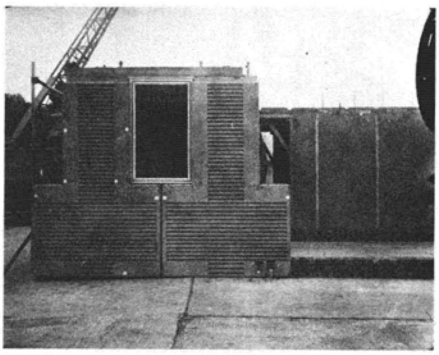


FIG. 2 & 3. Examples of precast concrete panels which were photographed and contoured in order to assess flatness.

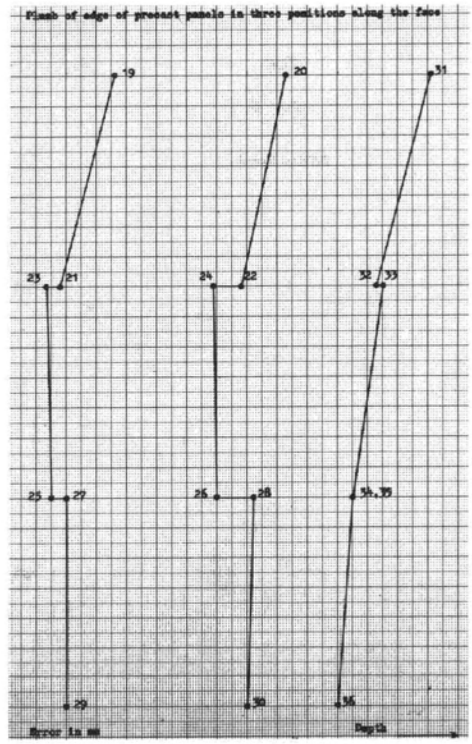


FIG. 5. Sample measurements of the building (Fig. 4) which show departures from the vertical in the YZ plane. The depth (Z) scale is in mm at 1:1. The height (Y) element is diagrammatic.

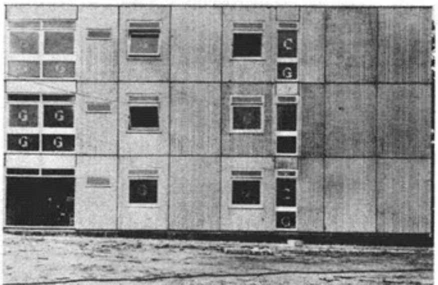


FIG. 4. A building at Aldershot, Hampshire which had just been erected using precast panels.

problems in the building industry (Atkinson and Newton, 1968).

Huby's Tower, Fountains Abbey (Figure 6) is a ruin, approximately 47 m high and 18.5 m wide at the base. It was built about 1500 and has been in a ruinous condition since the dissolution of the monasteries by King Henry VIII in 1539. The four walls have no internal or external structural support and a gradual movement or settling of the tower, over a long period, produced numerous fractures in the fabric. The Ministry of Public Building and Works (now a part of the Department of the Environment) were anxious to strengthen the tower against further structural deterioration or possible failure and, in order to assess the position and to decide upon remedial measures, large scale drawings of the tower elevations were needed, showing all masonry joins and fractures. Plotting at 1:50 scale conveniently allowed all joins to be shown. Small fractures could, however, only be represented by a single line while both sides of larger gaps could be plotted. At first sight, the fractures appear to have been exaggerated or drawn more heavily but this appearance derives either from the double line representing both sides of the fracture or from the irregular pattern contrasted with the regular courses of stonework. A full account of this survey was given to the symposium of ISP Commission V in Paris (Atkinson and Proctor, 1970).

Model structures have been subject to

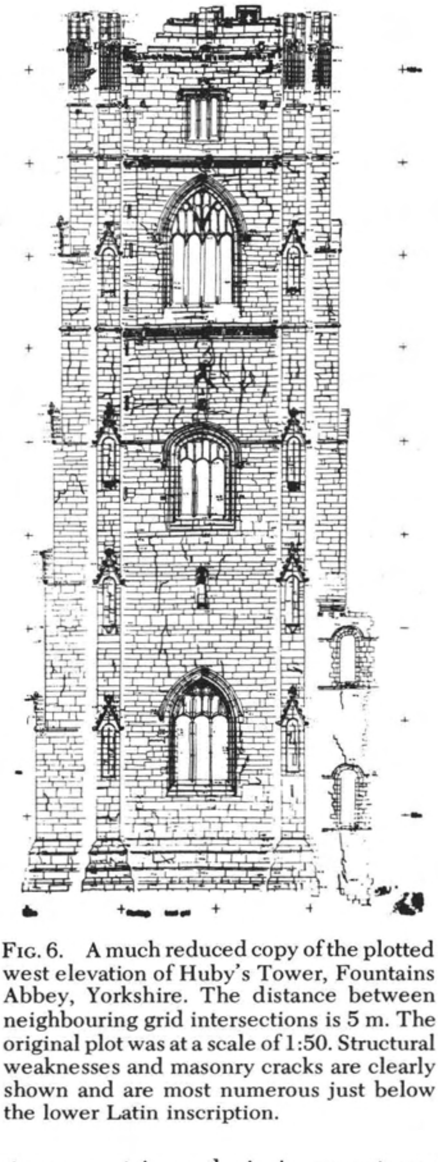


FIG. 6. A much reduced copy of the plotted west elevation of Huby's Tower, Fountains Abbey, Yorkshire. The distance between neighbouring grid intersections is 5 m. The original plot was at a scale of 1:50. Structural weaknesses and masonry cracks are clearly shown and are most numerous just below the lower Latin inscription.

photogrammetric analysis in recent years. The work of Professor K. Linkwitz and his colleagues at the University of Stuttgart is well known in connexion with the digital modelling of roof structures for the Montreal Expo 67, the Munich Olympic Stadium and, recently, the Mannheim garden exhibition (Linkwitz, 1967; Linkwitz and Preuss, 1971 and 1974; Happold and Liddell, 1975). At University College London, we have been involved in two modest experiments, one of which analysed the effect of wind deformation on model high rise flats and the other determined the geometry of a 1:50 scale model of a prestressed cable roof. This experimental investigation, fully described by Nooshin and Butterworth (1974), related to a cable roof which now provides partial cover for the Farahabad sports stadium near Teheran. The roof consists of a number of suspension cables which are connected at one end to a reinforced concrete spatial beam and at the other end to a flexible cable which is in turn supported by two pin-ended steel pylons. A family of prestressing cables is arranged orthogonally to the suspension cables. The object of the investigation, carried out in the Space Structures Research Centre of the University of Surrey, was to check the preliminary design and to provide information for the final design of the cable roof. The detailed shape of the net was determined at one stage during testing by employing close-range photogrammetry (Atkinson, 1972a). Stereometric photography of the model and five premarked control points was taken with an Officine Galileo camera mounted on the laboratory ceiling above the model (Figure 7). From observations in a Thompson-Watts Mk.2 plotter, the coordinates of all points of cable intersection were determined with a standard deviation of ± 0.1 mm in plan and ± 0.3 mm in elevation. The photogrammetric technique provided a simple and elegant solution to a measurement problem which would have been difficult to solve by other means.

A Photogrammetric Wriggle Survey

In recent years, construction has been taking place of a new twin tunnel under the River Mersey between Liverpool and Wallasey. The consulting engineers, Mott, Hay and Anderson, were in possession of suggestions for the provision of a photogrammetric wriggle survey made by the Swedish photogrammetrist, Dr. (now Professor) K. Torlegård. In order to test the feasibility of this scheme, we were

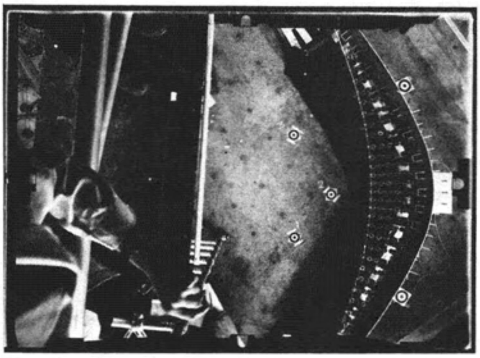


FIG. 7. One photograph of a stereopair of the structural model of the Farahabad stadium roof. Five control points may be seen, as well as the 207 cable intersections which were coordinated.

invited to undertake a trial survey of a length of tunnel which already had been surveyed by conventional ground survey methods.

A wriggle survey determines the extent to which a tunnel has departed, during construction, from its designed position. The Second Mersey Tunnel is lined with precast units which contain the road deck supports. If, for example, these deviate from their designed position by more than the allowed tolerances there will be difficulty in constructing the road deck while maintaining the statutory height of vehicle clearances. A 50 m length of tunnel was photographed in January 1970 with one stereopair, using an Officine Galileo camera (Figure 8). Analysis on a Thompson-Watts Mk.2 plotter resulted in a root mean square difference between 151 photogrammetric measurements and field survey values of 5.5 mm. This degree of accuracy is satisfactory for the wriggle survey and commercial companies have subsequently undertaken production surveys. If successful, a serious obstacle in road and rail tunnel construction will be overcome since photography does not occupy a tunnel for the long periods required by ground survey. A very detailed account of the methods and results of this wriggle survey has been published by Proctor and Atkinson (1972).

Box Girder Deformation Measurement

Since 1973, there has been collaboration between the photogrammetrists of University College London and engineers in the Civil Engineering Structures Laboratories at neighbouring Imperial College of Science and Technology. Their investigations into box girder behaviour, sponsored by the Highway Engineering Computer Board of the Department of the Environment, have benefitted from the use of close-range photogrammetry as one of several measurement techniques. We have been involved in two projects, the first of which has successfully been completed while the second is in progress at the time of writing (July 1975).

FIG. 8. A survey photograph of the length of the Second Mersey Tunnel which was subject to an experimental wriggle survey. Coordinates were determined on alternate rings (every 8 ft (2.44 m)). Points were observed on both premarked and natural surfaces. Concentric bull's eye targets and paint markings were used for premarking. The tunnel diameter was 31 ft 7 in (9.63 m).

The first project concerned the testing to failure of two steel box girder models which incorporated high strength friction grip splices. Harding (1974) gives exhaustive details of the tests. Their aim was to provide data on the behaviour of large scale joints in complete structures so that existing design data on small elemental behaviour can be studied in relation to overall joint behaviour. The box sections were manufactured from mild steel. Each section was 3 ft (0.91 m) high by 8 ft (2.44 m) wide. Two of the three sections used in each test were 14 ft 3⅞ in (4.37 m) long while the third was 12 ft 5 in (3.78 m) long. These sections were connected by high strength friction grip bolted joints. Only one of the joints was under test; the other was significantly overstrong.

The main purpose of the tests was the observation of joint behaviour, but the observation of both spliced and unspliced panel buckling behaviour was of importance. For this secondary purpose, 150 (test 1) and 100 (test 2) strain gauge elements were positioned on web and flange panels to monitor panel strains while close-range photogrammetry was used to measure out-of plane movement of both web and compression flange panels. Dial gauges also were used to measure overall box deflection and twist.

A single Officine Galileo ($f=150$ mm) camera was used in these experiments (130 × 180 mm format). It was mounted on an overhead crane with the camera axis pointing vertically downwards. An operator was able to sit with the camera to load plates and release the shutter and camera and operator were moved by the crane controls (Figure 9). It was possible to tilt the camera mount about x, y, z axes prior to each photograph so that tilts were reduced to a minimum and complete coverage was ensured. Eight camera stations were occupied at each load stage of a test providing two strips of four photographs and, therefore, six stereomodels for analysis. The camera stations were positioned 3.1 m vertically above the web on each side of the box girder by using a plumb bob so that the lateral overlap between the two strips of photography ran

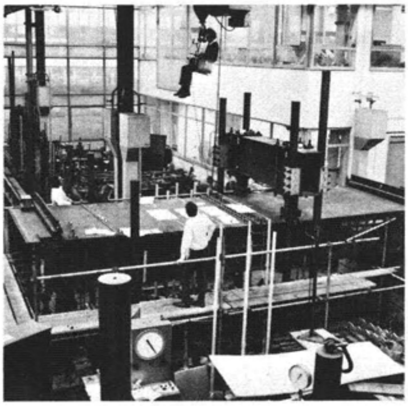


FIG. 9. A general view of the box girder test arrangement. The camera and camera operator are suspended from the crane above the area of interest to the left of, and including, the bolted joint. Control bars can be seen immediately above the compression flange to the left of the tie-down reaction beam. The left hand end of the box is supported on hydraulic jacks.

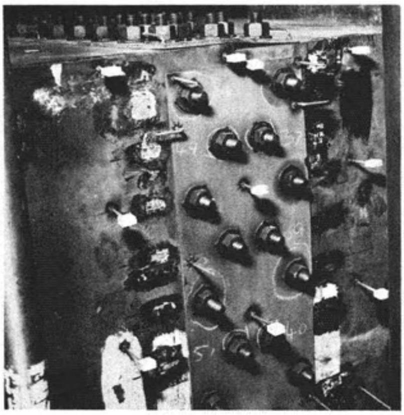


FIG. 11. A view of a splice in the compression region of the web showing combined compression and shear slip. Several premarked points are visible.

longitudinally along the upper surface of the box girder. The six stereomodels covered an area which included the two compression flange panels to the left of the bolted splice which is clearly visible in Figure 9. All points for which co-ordinates were required were premarked with photographically reproduced crosses. The flange targets were stuck on the flange surface. Web points consisted of crosses which were stuck onto studs and they, in turn, were welded to the web plates (Figures 10 and 11). The length of the studs varied with web depth so that all targets could be imaged from the relevant camera stations. The cross dimensions were chosen to suit the scale of photography for a given depth.

The control system consisted of bars which crossed the box girder (Fig. 9) along lines joining corresponding principal points of photographs in the two strips. The bars were mounted on posts which were prestressed to the floor. Crosses were stuck to the bars at known intervals. Additional posts were also constructed outside the box and in line with these bars to provide points for relative orientation which were in focus. As these points were fixed throughout a test, they were used to compute relative displacements of the box. Lighting was provided by two flash units

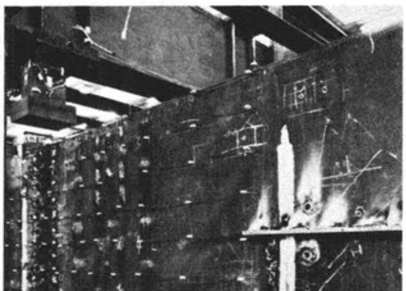


FIG. 10. The tie-down reaction beam (top left) and premarked points on rods welded to the web. The maximum length of rods was 75 mm. Photogrammetric observations were made to all premarked points. The photograph shows buckles in web panels at failure.

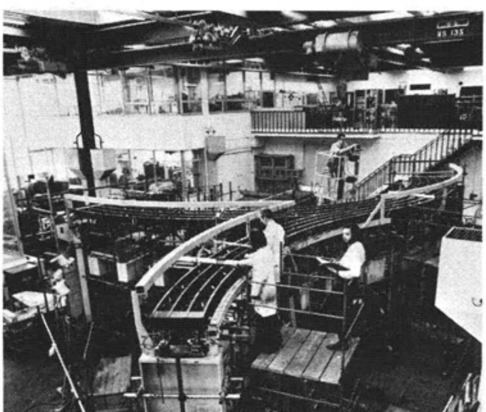


FIG. 12. A view of the bifurcated box girder bridge model.

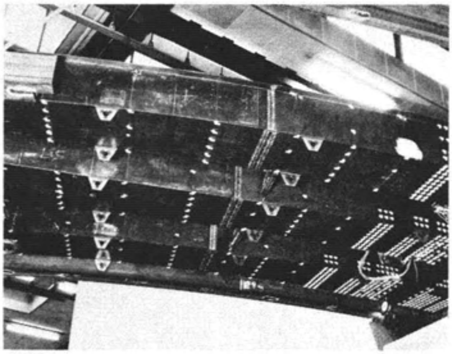


FIG. 13. The underside of the box girder bridge model, showing some of the premarked points whose relative movements are to be determined.

which were attached to the camera and three auxiliary flash units which were mounted around the box. The use of a short flash duration overcame any problems which might have arisen from camera movement.

The photography was observed on a Hilger and Watts stereocomparator. Relative and absolute orientations were computed analytically. Accuracies in the horizontal plane were good but movements in depth were determined less satisfactorily (average root mean square error at height control was 0.34 mm). However, their determination was not so important in these tests. Scale control at the base of the box and triangulation of the control points which were provided would have improved this accuracy.

A second deformation measurement project is now in progress. The author is indebted to Mr. P.J. Scott of University College London for the note which follows.

> "A 1:12 scale model of a bifurcated box girder bridge (Figure 12) is to be load-tested at Imperial College of Science and Technology. Measurements will only be required in the localised areas where the failure occurs but their location will not be known until the failure has taken place. Close-range photogrammetry thus provides the means of recording all points and of providing co-ordinates for only the required few when their location is known. The model bridge carries approximately 4000 premarked targets (Figure 13). Relative movement between them is to be determined to better than 0.3 mm. This requirement has necessitated the use of a small object distance of 2.3 m. The shape of the bridge dictates the large depth of field of 1.8 m to 3.4 m. The majority of the related research is thus centered around the variation of the principal distance with object distance throughout the field. A photographic calibration method has been devised which evaluates this variation as well as the change in principal distance with radial distance. In order to calculate correction terms for observed co-ordinates, the approximate distance of each target will have to be determined.
>
> Control points on the bridge will take the form of marks on plumb wires, each 1 mm in diameter and 1 mm long. These wires are hung on the stable mounting frame of the bridge. They will be surveyed from four concrete pillars erected specially for the purpose. Control points will be placed at the front and back of each overlap area. The survey of these marks presents several problems and it will require much careful planning to keep the horizontal and vertical scale factors equal.
>
> The nature of the box girder is such that the direction of deformation of any point can be fairly well predicted. This gives rise to the possibility of using false parallax techniques on pairs of photographs taken from the same point before and after deformation. Since there will be approximately 30 camera stations, it will not be possible to relocate the camera exactly. A fairly simple adaptation of the false parallax principle is being investigated which requires that the photographs need only be taken from approximately the same point and with roughly the same orientation."

ROCK MECHANICS

Collaboration over an eight year period between the Rock Mechanics Group at Imperial College of Science and Technology and the Department of Photogrammetry and Surveying, University College London, led to several applications of photogrammetry. Wickens and Barton (1971) have explained how close-range photogrammetry was used to determine roughness profiles of model joints (Figures 14 and 15). Similar model material was then used in the construction of two-dimensional open pit excavations. Stages in these excavations and associated displacements in the structure were analysed by false

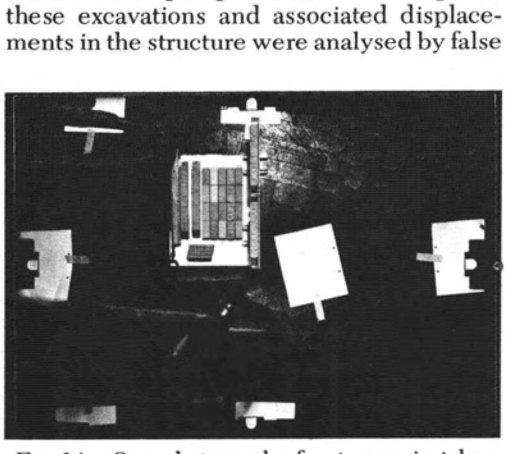


FIG. 14. One photograph of a stereopair, taken in order to determine surface roughness of model joint material.

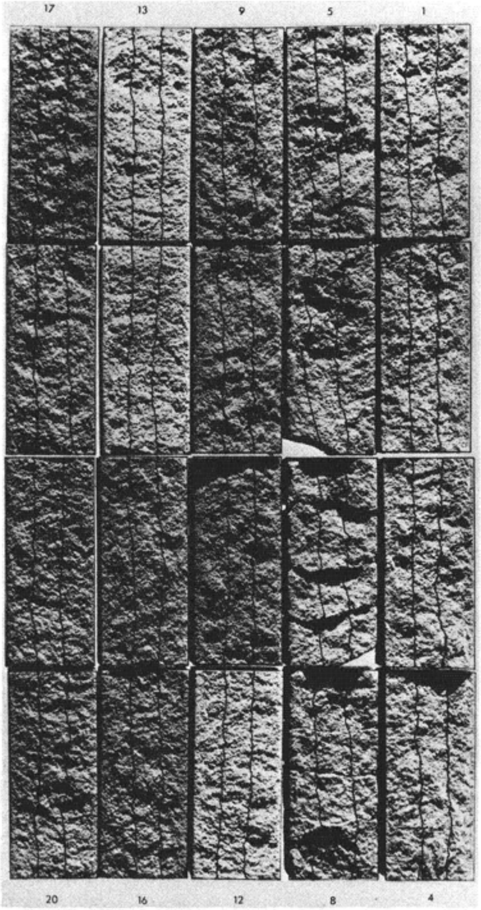


FIG. 15. The block of 20 samples which appears in Fig. 14 reproduced with overlying roughness profiles. The profile data were digitised and computer plotted. The information on roughness was used to determine suitable materials for the two-dimensional open pit excavations.

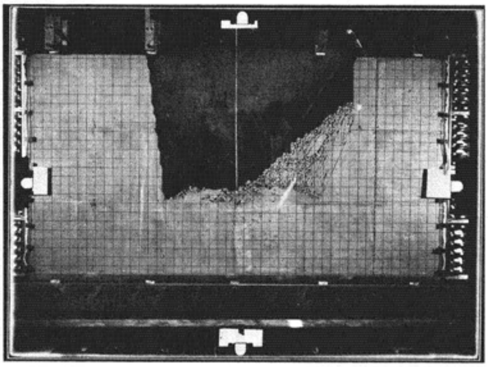


FIG. 16. The ultimate stage in model excavation. The measurement of displacements around an excavation was carried out by false parallax methods. Movements of 0.1 mm were detected.

parallax techniques which Wickens and Barton (1971) also explained (Figure 16). This work formed part of the experimental background to geological joint mapping of open pit mines. Practical photogrammetric techniques were evolved and modified for use in a mine situation. They were based on the Wild P30 phototheodolite equipment (Ross-Brown and Atkinson , 1972). Analysis of the survey photography (Figure 17), some of which has been carried out by a commercial company (Meridian Airmaps Ltd.), involves a conventional relative orientation in a plotting instrument but absolute orientation is a computational procedure. This makes it possible to employ principal distances and photographic tilts which some plotting instruments could not accept. The orientation of each joint is determined by four points whose co-ordinates are observed and recorded in the steromodel. Details of geological interpretation and joint selection, together with case histories and accuracies, will be found in Ross-Brown *et al.* (1973). The co-ordinates of the points on the joints are used in a subsequent plane fitting procedure. This involves setting up the normal equations for a linear least squares fit and solving these normal equations. From the resulting symmetric coefficient matrix the three direction cosines may be determined and subsequently transformed by means of the transformation matrix previously obtained. The planes may then be described in terms of dip and dip direction or azimuth.

A related development of this application has occurred in work carried out by the Transport and Road Research Laboratory with a Wild P32 in Colombia (Kempson and Heath, 1972). The Laboratory investigated a number of landslides in order to determine slope angles, sizes of cracks and fissures, and earth volumes. Analysis of the photography was undertaken by Meridian Airmaps Ltd.

CONCLUSIONS AND SUGGESTIONS

There is a great deal of activity and interest in engineering photogrammetry although much of the work is being carried out in a research context. When that research work reaches a conclusion, there may be no further employment for the photogrammetric techniques which have been used as a measuring tool. Other projects, though entirely commercial, are often unusual or "one off" and design, erection, setting out survey, control or monitoring are peculiar to that project. In cases such as these, there is still an enormous need for education of the engineer so that he is aware of the full possibilities of photo-

FIG. 17. A survey photograph, taken at Atalaya mine in Spain, for geological joint mapping. Areas within a stereomodel are interpreted and marked on paper print enlargements. In any one area, photogrammetric observations are made to determine the orientation of identifiable joints or planes.

grammetry. There is also a place for liaison and co-operation between the university department with research capabilities, the engineering consultant or contractor, and the commercial survey organisation. Methods of close-range photogrammetry can then be devised and tested and, if found to be suitable, the engineer can use the methods himself or sub-contract the work to a commercial survey company. These survey companies have, on occasion, been reluctant to involve themselves in non-aerial photogrammetry because, to do so, would be uneconomical in their estimation. It would be safe to say that this view has changed and there should be a reasonable return on those photogrammetric surveys which involve either repeated photography (over months or years) from the same survey stations, as in construction work, or where there are a large number of photographs to be analysed. Unfortunately, companies have been guilty of extremely expensive quotations for photogrammetric analysis, possibly because they did not really want the work, but the effect on the engineers and on the development of the subject was not helpful. Several government research establishments in the United Kingdom possess photogrammetric cameras and it should be possible for them to seek quotations for the analysis of their photography. It is rarely possible for an engineering problem to warrant an exclusive photogrammetric unit. Earlier in this paper, the demise of units in the motor and chemical industries was mentioned. Now we note the establishment of a unit in the north of Scotland associated with oil rig construction. Another solution to this type of problem would be for the survey company to offer the services of a mobile analysis unit. The appearance of the Zeiss (Oberkochen) stereocord G-2 prompts this suggestion, for the provision of co-ordinate information of the kind which is required in oil rig fabrication could be provided by an organisation with this type of equipment. Proctor (1973) summarised these problems when he noted that "most of the equipment and expertise is to be found amongst, and has been developed for, the surveying profession. There is no scientific reason why this should remain so but there are practical problems, equipment and education being foremost, in extending photogrammetric practice to all user disciplines."

Mention of equipment brings us back to a frequently ridden hobby horse! Strictures on the non-compatibility of camera and plotting instrument principal distances have been made frequently (for example, Atkinson, 1974). Now the problems posed by the instrument manufacturers have been joined by the photographic material manufacturers' reluctance to supply glass plates. Constructive suggestions for the equipment manufacturers include the provision of an improved means of determination of instrument height. In providing control for the photogrammetric survey of a high structure, probably the most critical observation lies in measuring the height of the theodolite trunnion axis above a levelled ground mark (Atkinson and Proctor, 1970). The same criticism is valid if camera co-ordinates and exterior orientation data are being determined, as Erlandson and Veress (1974) have pointed out. They also call for a manufacturer's calibration, to the same accuracy as the principal distance, of horizontal and vertical eccentricity constants.

However, these are relatively minor points when considered in the overall context of the advancement of close-range photogrammetry. We should not seek to oversell these techniques, for that could be extremely unfortunate and counter productive, but we should endeavour to promote the use of photogrammetry in appropriate circumstances. Proctor (1973) considered that "just so long as the practice of photogrammetry remains mostly the prerogative of the surveyor there will continue to be a sales resistance mitigating against its acceptance in other disciplines." Commission V of the International Society for Photogrammetry should strive for that necessary diversification.

ACKNOWLEDGMENTS

I am indebted to O.W. Cheffins, A.H.A. El-Beik, R. Farrand, M.W. Grist, J.E. Harding, W. Heath, the late R.I. Horder, J.F.A. Moore, I. Newton, G. Owens, A.N. Schofield, P.J. Scott and G.A. Stoker for correspondence and discussions about their work over a period of several years. Projects which have been carried out at University College London could not have been undertaken without the active support of Professor E.H. Thompson and my colleagues in the Department of Photogrammetry and Surveying.

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