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TITLE

PHOTOGRAMMETRIC PROCEDURES FOR A NORTH SEA OIL RIG LEG REPAIR

ABSTRACT

A description is given of the method used to calibrate a non-metric underwater camera for use in the data acquisition phase of a photogrammetric survey of the damaged area of an offshore platform leg. Procedures used in the survey will be discussed together with the methods of data reduction and the adjustment of the block of models.

TEXT

In late summer 1977, divers discovered serious damage to a main corner support leg of an oil production platform, at a depth of 100 m in the North Sea. This had happened during offshore piling operations, when a shackle broke and one of the main foundation piles weighing 240 tonnes fell almost vertically for about 40 m before hitting the jacket.

The damage, consisting of severe buckling and tears, covered an area of about 6 × 2 m. With the point of contact on the leg at the cone-shaped section of the bottle, the pile glanced off the cone, buckling the plate, and punched a hole in the cylindrical shell. At the cone and shell junction there is a critical ring stiffener designed to contain the hoop stresses at this change of section; this was also badly damaged. The damage had to be repaired to regain the structural strength of the leg in order that the platform could be recertified by Lloyds. Several alternative proposals for the repair were examined, including hyperbaric welding, but because of its relative lack of complexity, a bolted method of repair using high strength friction grip connectors to transfer the loads was selected. For this method to be successful the repair patches covering the holes and the buckled area should match the distorted surface very closely. The essential step was thus to obtain a topographic map of the existing surface. Two techniques were employed to do this: a mechanical pin-board templating technique and, as an alternative,

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underwater stereo-photogrammetry. As no similar photogrammetric survey was known to have been undertaken at that time, consultation with Fairey Surveys Ltd and Hunting Surveys Ltd took place in November 1977, and NEL undertook to co-ordinate the exercise.

Preparation and Data Acquisition

Underwater stereo-photogrammetry had the advantage of being simple to use on site; the damaged area could be prepared for photography by a single diver, and the photography could be carried out in a relatively short time. In addition the density of measured points could be as many as was necessary to adequately describe the surface. The major drawbacks were that no underwater metric camera was available and the timescale did not allow one to be obtained. It was also impossible to have three-dimensional control in the damaged volume.

A pair of Benthos 35 mm cameras comprised the only underwater photographic equipment available at the time, and it was decided to test these on a calibrated volume in a swimming pool. These cameras have an interlens separation of about 120 mm and were designed to allow stereo-pictures to be taken for qualitative viewing. We decided to use a base of 300 mm for our photogrammetric system, but still use both cameras so that the stereo model could be formed either with left-hand or with adjacent right-hand pictures. It proved fortunate that we did have such a back-up system. The three-dimensional calibration structure comprised a metal grid base, with two pairs of scale bars fixed at right angles approximately 158 and 307 mm above and in the same alignment as the base. Both grid and scale nodes were numbered and three-dimensional values were supplied to a precision of ±0.025 mm. As no fiducial marks existed both cameras were modified by the insertion of cross wires just forward of the focal plane.

The test negatives were taken at the proposed mean working distance of 1 m, and with the stereo-camera translated a distance of 300 mm to give the required base. The model co-ordinates obtained from the test negatives were reasonable and it was decided to design the survey procedure using these cameras.

A diver cannot be expected to perform work of great complexity at this depth, so the work was simplified into specific tasks.

The surface of the leg was marked to ensure good stereoscopic pointing, and permanent marks were punched and numbered on the surface of the leg for use as reference points.

Eight graduated rods were affixed to the damaged leg with magnets, to assist in correctly establishing scale during the block adjustments. The ends of some of these rods were supported off the surface at known distances to give local height control.

A camera-locating frame was designed and constructed out of 50 mm^2 hollow cross-section steel bars, in the form of a 300 mm pitch grid. This was slightly larger than the damaged area, and was provided with feet, so that it could be rigidly clamped against the leg to serve as a reference plane and aid the diver to locate the cameras over the correct stations. The cameras were firmly held in a steel cradle designed to hook accurately into each aperture of the 300 mm pitch locating frame, and thus maintain the 300 mm base both vertically and horizontally.

Additional underwater photographs of the calibrated volume and a refractive index rod were made on the new rolls of film which were loaded into the cameras before they were crated up and sent offshore. The refractive index rod, which comprised two scale bars fixed 800 and 1000 mm from a reference point on the steel cradle, accompanied the cameras to the damaged platform and was photographed by the divers at the survey site just before starting the survey proper. This was done to check that the variations of pressure, temperature and salinity between the calibration site and the survey site did not have adverse effects on the model distortions. No significant differences were noted however. The divers were instructed to make five exposures at each of the apertures in the camera-locating frame and finish up with five additional exposures of the refractive index rod before the cameras were sent up to the surface.

The cameras were then recrated and sent back to NEL, where we again made a number of exposures of the calibration frame and the refractive index rod in the swimming pool. The film was then removed from the cameras and processed.

Unfortunately the electronic flash gave trouble towards the end of the survey, which resulted in the bottom four rows of the area not being recorded. These were fortunately below the damage and were covered on the pin-board templates. When the film was processed it was also discovered that the shutter of the left-hand camera had developed a fault early in the survey. We did however have sufficient exposures at each of 60 stations well recorded on the right-hand camera.

Analysis of Data

An original negative from each of the stations together with some additional calibration negatives were passed to each of the survey firms; the approach of these firms was different though the project itself was identical.

Fairey Surveys Ltd, adopted a method of photogrammetric analysis based on independent model aerial triangulation, observed in the plotter using 4.5 times enlargements of the photography made on dimensionally stable film. Photography gave adequate stereoscopic cover of the area in a block of 57 models (see Fig. 1). Adjacent frames in this block overlapped more than 50 per cent in either direction which enabled the independent models to be formed into continuous strips both laterally and longintudinally.

Before observing the block of photography covering the damaged leg, the overlap of the calibration structure was oriented in the plotter and three-dimensional measurements were recorded for all visible graduations on the elevated scaling bars, as well as for the grid intersections. Plotter values were transformed, compared with the known dimensions and the results used to construct a correction graph which could be used to remove the combined effect of lens distortion and refraction from subsequently observed models.

The main block of photography was then observed as an aerial triangulation of independent models in a Wild A8. Three-dimensional instrument coordinates were recorded for control points, principal points of the photographs, tie points and points spaced at approximately 100 mm centres (50 mm centres in certain areas) over the surface of the leg to define its shape.

Three-dimensional coordinates of the two perspective centres for each of the independent models were computed from single image observations of arrays of points, made at widely separated projection distances in the plotter.

Corrections to the plotter coordinates were made by referring to the graph constructed from the photogrammetric analysis of the swimming pool photography. These corrections were to the z values, only, as the planimetric displacements had been found to be less than 1.0 mm (r.m.s. error) at natural scale when the swimming pool photography was analysed.

The corrected independent model coordinates were transformed into strips by connecting them at the spatial triangles formed by common perspective centres and values of common points observed at the edges of adjacent models. An analysis of model joins after formation of longitudinal strips is given in Table 1. Five lateral strips were also formed, as indicated in Fig. 1.

Each strip was then scaled initially using the coordinates of perspective centres, which were assumed to be in line and at a spacing of 300 mm. Residual planimetric differences at perspective centres after this operation are given in Table 2.

A preliminary height ('Z') adjustment was carried out using the initially scaled coordinates, by first applying a parabolic correction to each of the five short laterial strips to obtain a least squares fit to the common Z value of the perspective centres. Values of Z for pass points situated close to the nadirs, as derived from the lateral strips, were then used to apply a height adjustment to each of the longitudinal strips.

Parameters derived from the preliminary height adjustment of the longitudinal strips were then used to rotate the coordinates so as to obtain an orthogonal projection of the area of interest with respect to the plane of the perspective centres.

Next, a planimetric (x, y) block adjustment of the orthogonally corrected coordinates was done by allowing each strip to rotate about the Z axis, change its scale and shift in x and y so as to obtain the best agreement at tie points. The known distance between two widely separated perspective centres was used to control absolute scale for this adjustment. The internal photogrammetric fit at tie points after this block adjustment is given in Table 3. Final scaling factors for the block were derived by comparing the photogrammetric lengths of the eight scaling rods with their known dimensions.

A final block adjustment for height was carried out by giving each longitudinal strip freedom to change its shape in Z using the formula

$$\Delta Z = a_o + a_1 x + a_2 y + a_3 x^2$$

to obtain a least squares fit at the pass points near to nadirs, as derived from the lateral strips, as well as keeping differences at tie points to a minimum.

The result of the final height block adjustment is summarized in Table 4.

In order to give the photogrammetric results some form of independent checking, the final coordinates of points observed on the eight scaling rods were tested to see how far they deviated from straight lines. The result of this check is summarized in Table 5. A further accuracy check was also possible using final coordinates of points which had been observed along the images of two pile guides; these points were tested for coplanarity and the result is shown in Table 6.

TABLE 1

ANALYSIS OF MODEL JOINS AFTER STRIP FORMATION USING MODELS CORRECTED FOR CAMERA DISTORTION (DIFFERENCES ARE MICRONS AT ORIGINAL NEGATIVE SCALE)

Strip	No of models	RMSE, µm			Range, µm		
		X	Y	Z	X	Y	Z
1	5	2	15	62	-1 +7	-45 +4	-32 +160
2	11	10	8	31	-28 +25	-19 +25	-102 +105
3	6	2	7	32	-3 +6	-16 +16	-27 +80
4	4	1	5	15	-2 +1	-10 +2	-21 +38
5	3	1	3	17	-1 +1	-4 +7	-23 +24
6	6	3	9	40	-7 +8	-19 +18	-69 +84
7	11	11	13	53	-32 +29	-28 +38	-92 +132
8	5	2	12	48	-2 +5	-4 +35	-96 +129
9	3	1	3	7	-1 +1	-4 +3	-11 +11
10	3	4	15	72	-2 +9	-8 +29	-78 +138

TABLE 2

RESIDUALS AT PERSPECTIVE CENTRES AFTER INITIAL SCALING (DIFFERENCES ARE MILLIMETRES AT NATURAL SCALE)

Strip	Range X mm	Range Y mm	Strip length mm
1	-15.4 +21.7	-6.4 +9.8	1500
2a	-7.9 +14.2	-6.1 +6.3	1500
2b	-19.4 +25.5	-7.8 +8.4	1500
3	-10.9 +6.4	-7.3 +7.2	1800
4	-5.4 +5.2	-5.8 +8.4	1200
5	-3.7 +2.9	-6.5 +3.6	900
6	-13.1 +19.2	-10.1 +13.8	1800
7a	-19.7 +19.0	-8.0 +6.5	1500
7b	-19.6 +30.0	-14.0 +9.9	1800
8	-11.2 +10.3	-18.6 +13.9	1500
9	-16.6 +11.2	-2.1 +2.3	900
10	-24.1 +14.5	-0.9 +0.7	900

TABLE 3

INTERNAL PHOTOGRAMMETRIC FIT AT TIE POINTS AFTER ITERATIVE PLANIMETRIC BLOCK ADJUSTMENT (RESIDUALS ARE MILLIMETRES AT NATURAL SCALE)

No of iterations	RMSE		Range	
	X mm	Y mm	X mm	Y mm
1	11.9	9.8	-37.2 +25.2	-34.9 +29.2
25	3.5	2.9	-10.3 +14.4	-5.4 +5.4

TABLE 4

RELATIVE AND ABSOLUTE FIT OF PHOTOGRAMMETRIC DATA AFTER ITERATIVE HEIGHT BLOCK ADJUSTMENT (RESIDUALS ARE MILLIMETRES AT NATURAL SCALE)

	No of observations	RMSE	Range
		Z mm	Z mm
Tie points (= relative fit)	217	4.5	-18.1 +13.9
Control points (= abs. fit)	79	5.7	-11.8 +16.0

TABLE 5

DEVIATIONS OF PHOTOGRAMMETRIC COORDINATES ON RODS FROM A STRAIGHT LINE (RESIDUALS ARE MILLIMETRES AT NATURAL SCALE)

	X mm	Y mm	Z mm
RMSE	±5.9	±2.3	±3.4
Range	-20.4 +17.3	-5.0 +4.5	-8.5 +6.4

TABLE 6

DEVIATIONS OF PHOTOGRAMMETRIC COORDINATES ON PILE GUIDES FROM A PLANE (RESIDUALS ARE MILLIMETRES AT NATURAL SCALE)

	Z mm
RMSE	±6.6
Range	-12.3 +10.4

Hunting Surveys Ltd adopted an analytical approach to the work and all measurements were made on a Zeiss Jena Stecometer using the original negatives.

Nine separate photographs of the three-dimensional structure were measured to obtain a calibration. The recording accuracy was ±5 μm and an average of 200 grid nodes were measured on each of the exposures.

A program was written to analyse the departures of measurements made on the negatives from those physically measured of the structure. The differences found were largely attributable to the geometric projection of the three-dimensional subject on to the two-dimensional photographic plane, and to the unknown object distance and camera attitude. The balance was attributable to the combined effects of lens distortion, film distortion and film unflatness at the moment of exposure plus small random observation errors.

For each photograph an approximating distortion surface was computed by superimposing a radial cubic on to a projective transformation, with least squares distribution of residuals. The output from the program comprised:

10 distortion surface coefficients
principal distance
coordinates of principal point
coordinates of point of symmetry
a list of residuals.

Differences in results were attributed to variations in film flatness. The photograph with the best format coverage, and in which most grid points were observed, was adopted for subsequent production operations. This also was one of the better results having a mean square error of 12 μm at the 220 grid nodes which were measured.

Stereoscopic observations of the photography covering the damaged leg were made in both horizontal and vertical pairs of photomodels and, in total, 115 models were recorded. The tie points established were suitable for the connection of models in both directions and generally models contained six or more tie points. The area where the metal had been torn during the accident had been cut into a hole and photography in this locality was poor. The damaged remains of the ring stiffener, being the only detail in the hole, proved inadequate for the inclusion of two models in the block and in retrospect it would have been better had a rigid lattice been fixed over this important area. Two scale bars on the conical section were found to have moved between adjacent exposures having the effect of reducing their usable length by approximately one fifth.

The grid of surface points required at 100 mm intervals, and 50 mm intervals in critical areas, were observed from the horizontal photomodels except in perimeter areas. It was not feasible to follow the network precisely on the stereocomparator but the approximate intervals were maintained. In addition variations in the surface not depicted by the grid of points was recorded as also were perimeter points defining the hole, tears in the structure, sheer plates, scale bar intersections at intervals and the punch marked reference points.

Relative orientations, strip formations and block adjustments were performed with existing programs on a DEC PDP 11/50 computer. It was evident after strip formation that height variations introduced by film unflatness were excessive as had been expected. The planimetric accuracy appeared to be good and comparable with conventional photography.

Separate independent model adjustments were carried out for the conical and cylindrical sections and models observed both horizontally and vertically were included in each block. The blocks overlapped by three runs.

The blocks were formed by sequential transformation of subsequent strips into the coordinate system of the first strip, and each block was transformed as a unit to fit one known distance and three arbitrary heights to obtain a first approximation. The block adjustment applies three-dimensional similarity transformations to individual sections, utilising all available control and connection points by least squares minimisation of the residuals. Each iteration comprises one forward and one reverse pass through the block. The initial iterations reduce systematic linear errors by using multi-model sections corresponding to strip units. Non-linear systematic errors are then reduced by a sequence of iterations using one-model sections but with only three degrees of freedom in the transformations (X, Y and Z shifts). Final iterations act upon one-model sections with seven degrees of freedom (shifts, rotations and scale change).

The coordinate system adopted was aligned to the inner corners of the sheer plates on either side of the leg, with the left-hand corner as origin. The height reference plane for the conical section was referenced to the mean surface down its centre and the height reference plane for the cylindrical section to the alignment of the sheer plates.

The preliminary adjustments enabled the evaluation of known data and each block was finally adjusted using values at control points which provided a balanced adjustment. The results of the conical section appeared to be good, the torque at the camera stations was negligible and scale bar differences were in agreement within 1.5 mm. The bars did however bow by 5 mm at their centres and it is not known if this was fact or an error. Results of the cylindrical section proved to be weakened by the absence of two models in the area of the hole and by the poor quality photography in this locality. The overall scale bar distance in this instance varied by as much as 3 mm and again bowed by 5 mm. There was also a small amount of torque at camera stations in the vicinity of the hole but values of these stations were not imposed as control as their true coordinates and heights were not known precisely.

An additional adjustment utilising all models covering both the conical and cylindrical sections was carried out in order to improve, if possible, the overall accuracy. The height reference plane was defined by the Z coordinates of the corner camera stations and scale determined by the distance between the sheer plates which had been established. The initial result indicated a change in plane at the alignment of the hole and also that the two sections were no longer compatible in scale. By adopting a mean scale with additional values incorporated to maintain the height reference plane in the centre of the block a second computation was obtained and submitted as an alternative to the individual adjustments.

The data delivered comprised plots at 1:4 scale produced by flatbed plotter showing all points measured. Tabulated results and values on 8-track punch tape for further analysis were also passed to the National Engineering Laboratory.

There was also the requirement to ascertain the angle between the cone and the cylinder in order that the repair plates could be manufactured with flanges to effect their connection. The omega tilts established from the absolute orientations of the independent blocks gave a mean angle of 22° 13' but this was thought unreliable because of the poor results obtained from the cylindrical section at the join of the blocks. Calculations from the overall block adjustment gave an angle of 19° 06' and it was recommended this value be used.

The analytical methods of calibration, corrections and block adjustment produced results which appeared to be satisfactory for the project although it was not possible to give a reliable estimate of the accuracy achieved.

Refinement of Data

The 2000 points of coordinate data supplied by the survey firms were fed into the NEL Univac 1100/21 and a special purpose program written to interpolate between the known points in order to give equispaced templates. The ring stiffener plate had been replaced between the photography and the analysis of the data, as at this stage of the repair the leg regained some 70 per cent of its original load-carrying capability. However it did mean that the position and orientation of the plate had to be interpolated. This led to a degree of uncertainty in the later comparisons of information with the pin-board templates, and extended the computer studies to provide various reorientations of the data in order to match the two sets of results. The final program was configured in such a way that it could output the final shape in different forms; first of all listings showing template data purely in the form of numbers; secondly drawings to check that the numbers actually sent to the fabricators are accurate. By using the program in conjunction with NELAPT, a general purpose machining program, we were able to produce control tapes for an NC milling machine to make a model of the damaged area, Fig. 2.

Conclusions

It should be concluded that both templating techniques produced results of an acceptable tolerance and particularly that the use of underwater photogrammetry can produce effective results in a most arduous environment; 100 m below the North Sea in mid winter.

Reference

THOMPSON, J. M. and WHITE, A. R. The Heather platform leg repair. OTC 3529. Offshore Technology Conference, 1979.

Acknowledgement

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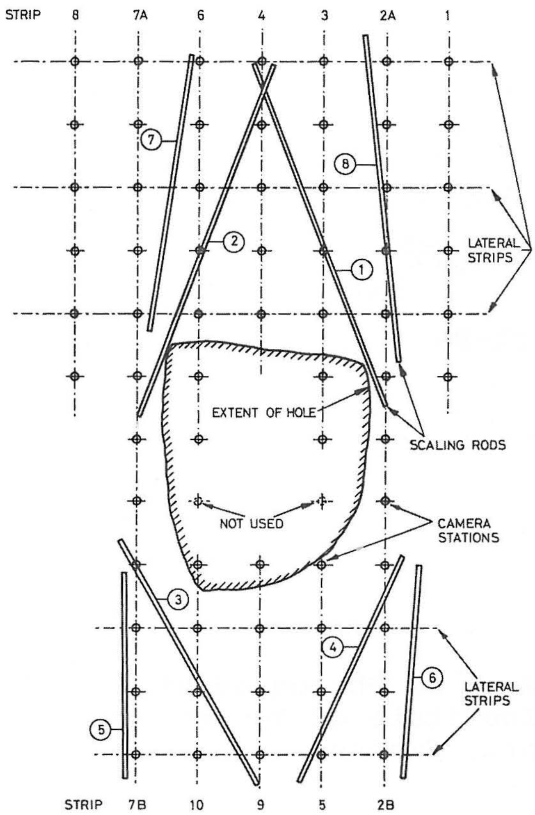

FIG 1 LAYOUT OF SITE PHOTOGRAPHY
(HEATHER JACKET DAMAGE)

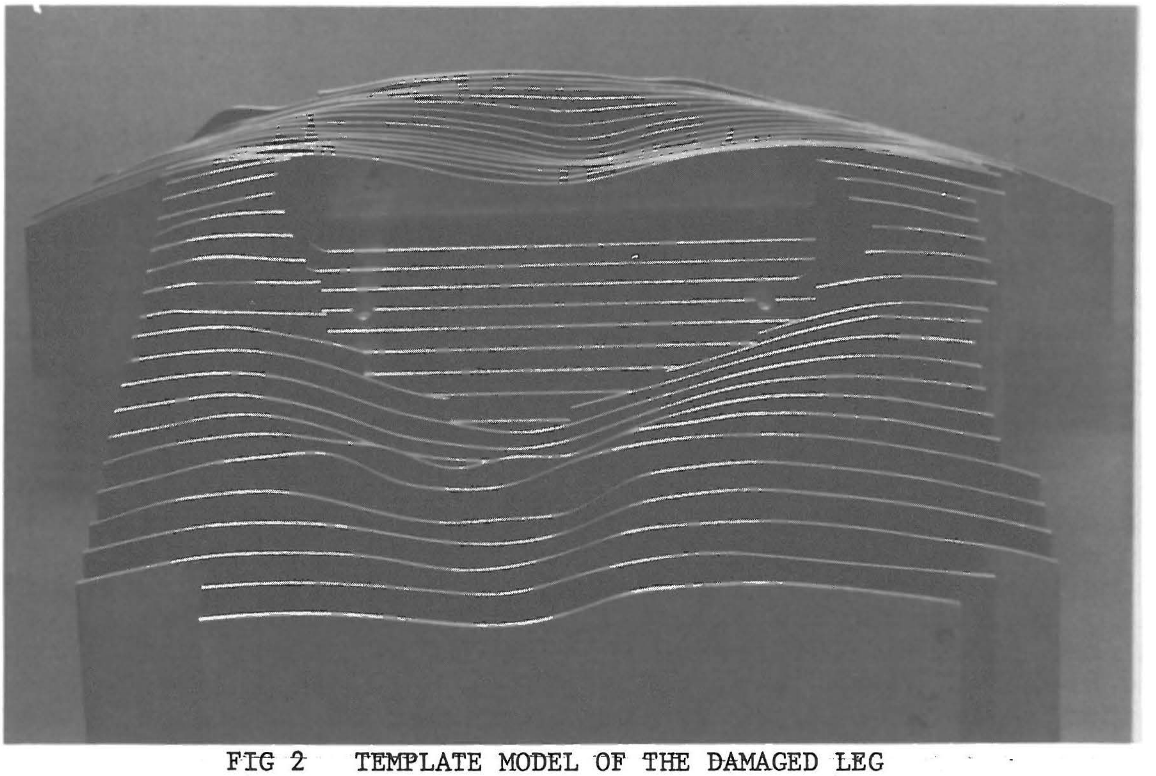

FIG 2 TEMPLATE MODEL OF THE DAMAGED LEG