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Deformation Measurements of Power Dams

It seems desirable to improve further the photogrammetric system to such a degree that an accuracy would be achieved which is superior to that of a precise geodetic microtriangulation.

Introduction

For safety reasons it is necessary to perform periodic control surveys of large engineering structures such as power dams in order to determine whether the structure remains stable or whether it is subject to movements or local deformations as a function of time. Movements of specific points of the structure occurring between consecutive measuring phases can be represented by respective displacement vectors, or for sufficiently large local movements by overlays of consecutive precise contour line plottings. From the displacement vectors or eventually from contour line overlays of, example given, a power dam, the civil engineer can draw the following conclusions:

- The dam is stable (time invariant), and consequently safe.
- There are forward and backward movements or deformations of the dam depending on the level of the water behind the dam.
- The dam is subject to local deformations caused by climatic conditions such as frost.
- Displacements are increasing as a function of time which would be an alarm signal to reinforce the dam before it is too late to avoid catastrophic consequences.

Considering the great responsibility involved, it is becoming increasingly mandatory that in power dam construction contracts a clause be included providing for periodically measuring of a sufficient number of points on the dam. This requirement recently led to the formulation of a recommendation of the International Association of Dam Constructions that 0.7 percent of the overall costs for the completion of such power dams should be spent for periodic control surveys. This represents a large amount of money; several hundred million dollars if all the world's existing power dams are considered, an amount which can be estimated as being the equivalent of between 10 to 20 percent of the entire world's annual surveying and mapping expenditures.

This requirement represents an unique challenge for the application of precision photogrammetry methods, an application which offers the following advantages if compared with the conventional geodetic procedures for power dam measurements

Abstract: *According to a recent recommendation of the International Association of Dam Constructions, 0.7 percent of the overall costs for the completion of such dams should be spent for periodic control surveys. On a world-wide basis, such control surveys cost a large amount of money. The use of photogrammetry, due to its methodological and economic advantages, for such control surveys represents a real challenge if the required accuracy can be secured. In recent years, this goal has been indeed achieved and an increased use of photogrammetry for dam control surveys can be foreseen. The paper deals with the development of approhriate systems and the application of a specific system to control surveys of the power dam of a 100-million-dollar power plant in the Province of Quebec.*

(provided that the photogrammetric procedure yields a sufficient accuracy):

- ★ The photographs periodically taken provide a complete and permanent record of the power dam at the times of exposures. Measurements on the photographs can be repeated and checked for previous observation times; this advantage does not exist if one uses the conventional geodetic method; measurements cannot be repeated or checked for previous observation periods as possible dam movements and deformations have to be taken into account which would result in an inconsistent measurement system.
- ★ There is a requirement to measure the entire dam at the same time for each repeated observation phase. In the past, this condition has not been sufficiently considered and this is because of the use of the conventional geodetic method that consists of measuring point after point by intersection. This has the disadvantage of requiring a considerable measuring time; in case of hundreds of points possibly a measuring time of up to two days might be spent. There is no guarantee that all dams remain completely stable during this measuring time. As a consequence, small dam displacements might, as a function of time, mix with measuring errors resulting in an inconsistent measuring system and in wrong conclusions as to possible dam movements and deformations. This disadvantage is considerably diminished if the photogrammetric method is used because in this instance recording of the entire dam structure by the necessary photographs can be done in a much shorter time, say between a few time minutes to not more than two hours.
- ★ In case of critical dam movements or deformations it might be desirable to add at a later time additional points to the already measured points. As the points in question might have moved, meanwhile, the use of the conventional geodetic method is out of question. However, if one uses the photogrammetric method, this restriction does not exist, as additional points can be added (if identifiable) and measured on the photographs of past observation phases.

Under the condition that the necessary accuracy can be achieved, power dam measurements can be either performed by terrestrial photogrammetry or aerial photogrammetry. The choice of one of these two methods, or of both combined, depends on the nature of the dam structure in question, the slope of the dam, and is conditioned by operational and logistics factors. Thus, if numerous dams spread over a large area have to be recorded or control surveyed, it might be preferable to use the aerial photogrammetric approach in view of the accessibility, transportation and logistics problems involved and in view of the local climatic conditions. On the other hand, the terrestrial photogrammetry approach might be preferred for a single dam project, and where no particular accessibility, transportation, climatic and logistics problems are to be encountered. An example of this kind of terrestrial photogrammetric power dam control survey is described in the following section.

PERIODIC MEASUREMENT OF MOVEMENTS AND DEFORMATIONS OF THE POWER DAM "OUTARDES 4 (1)", PROVINCE OF QUEBEC

In 1972 Hydro Quebec awarded to our department a research contract with the task to develop further our terrestrial photogrammetry dam deformation measuring system and, subsequently, to apply it to the dam of the $100 million *Outardes 4 (1)* Power Plant located approximately 400 km north-northeast of Quebec City (see Figure 1). The contract specified the photogrammetric measurement, twice a year (in spring and autumn 1972), of 17 points marked on the downstream face of the dam (see figure 2, points indicated by empty circles) to an accuracy of, if possible, better than ± 1 inch (standard error) and again, twice a year, the precise contour line plotting of some critical zones of the dam to discover local deformations as a function of time.

The accuracy requirement of better than ± 1 inch (standard error) was considered as being sufficient as the 2,000-ft long and 310-ft high dam is covered by an envelope of large blocks of rock (up to more than 10 ft in diameter) of which some are slightly loose. The main objective of the project was to find out whether, in view of the methodological advantages of the photogrammetric approach, this method would produce the required accuracy insofar as the numerical photogrammetric point determination as well as the graphical contour line plottings are concerned. As the dam holds an artificial lake approximately 50 miles long, the water pressure on the dam is considerable and care had to be taken to select the two measuring periods (spring and autumn) at approximately equal water levels.

The size of the dam structure and consequently the distances between the terrestrial camera stations are such that the requested accuracy for numerical photogrammetry single point determination calls for a relative accuracy of better than $\pm 1/_{10,000}$ (relative standard error). To achieve such an accu-

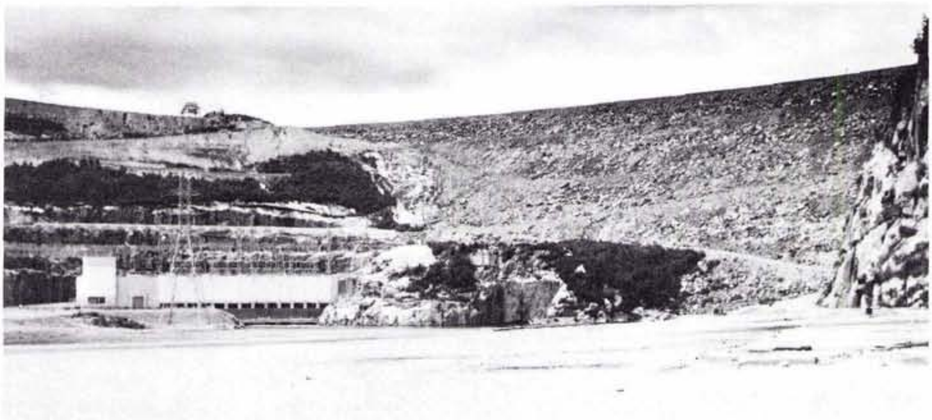

FIG. 1. General view of the Hydro-electric Power dam *Outardes 4 (1)*.

racy it would be desirable to have available a high-precision terrestrial camera with a sufficiently long focal length, say of the order of 300 mm. Unfortunately such cameras, specifically designed for this purpose, are not available on the market. All cameras presently and readily available are precise phototheodolites. In view of this situation it was decided to use the Wild Phototheodolite P30 (focal length, 165 mm; image size, 100 × 140 mm) of our Department for taking the necessary photographs and to design and apply a geodetic/photogrammetric surveying system capable of producing the desired accuracy.

The basic geodetic reference system was determined by Hydro-Quebec and consists of four monumented points on solid bedrock (D11, D15, D16 and D17) forming a central system (see Figure 3). For movement and deformation control, Hydro-Quebec established 12 additional monumented points (M22, M26, M32, M36, M40, TH1, M2, TH5, M6, TH4, M7, M21) on the dam (see Figure 2). According to contract specifications the directions of this 12-point network was to be remeasured by the field crew of our department during the same periods when the terrestrial photographs were taken, using a Wild Theodolite T3 and resulting in standard errors of the local coordinates X and Y for these points of approximately ± 1 cm. During the same periods the field crew determined the heights of these points by ordinary levelling (instrument: Wild N2) and trigonometric levelling to an accuracy corresponding to third-order accuracy representing, in this application, a standard error of slightly less than ± 1 cm.

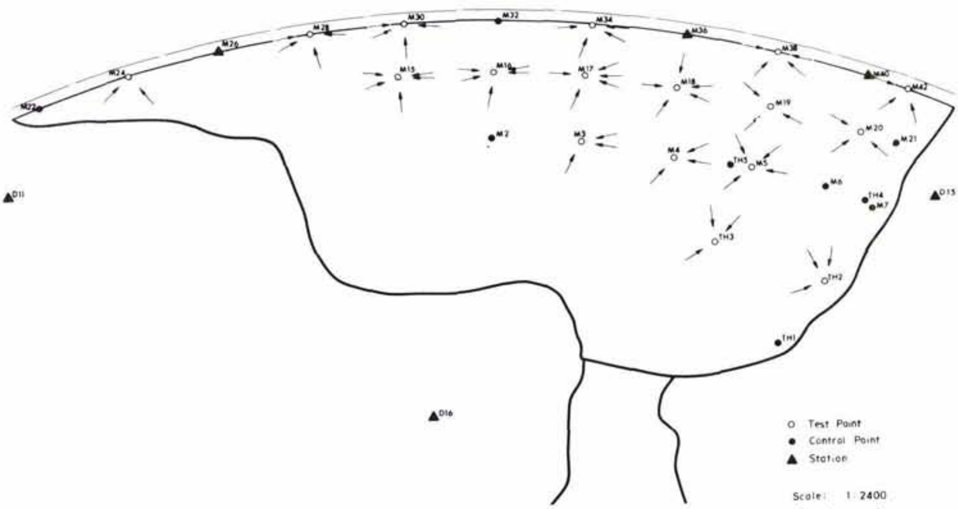

FIG. 2. Map showing the photogrammetrically determined points (empty circles) on the power dam *Outardes 4 (1)*.

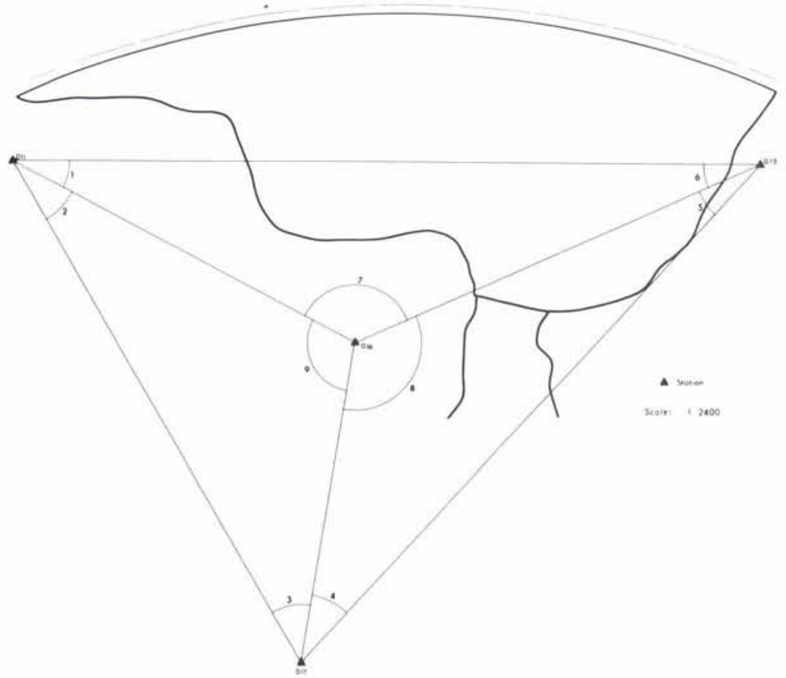

FIG. 3. Basic geodetic reference system, *Outardes 4 (1)* Dam.

The strictly terrestrial photogrammetry phase consisted of taking a total of 16 photographs according to a multiple-intersection scheme (see Figure 4) and as close as possible to the same time, say possibly within the same day. For the geodetic and photogrammetric targeting of all points to be surveyed, and to be identifiable on the photographs, a special system of targeting was used consisting basically of a pendulum system with a plastic sphere at the top and a counter weight at the bottom (see Figure 5). This system not only allows precise centering above the monumented points, unaffected by wind, but also produces precisely circular shaped image points on the photographs independent of the directions from which the photographs are taken.

Kodak Spectroscopic Type III, Class G plates were used for the first field mission

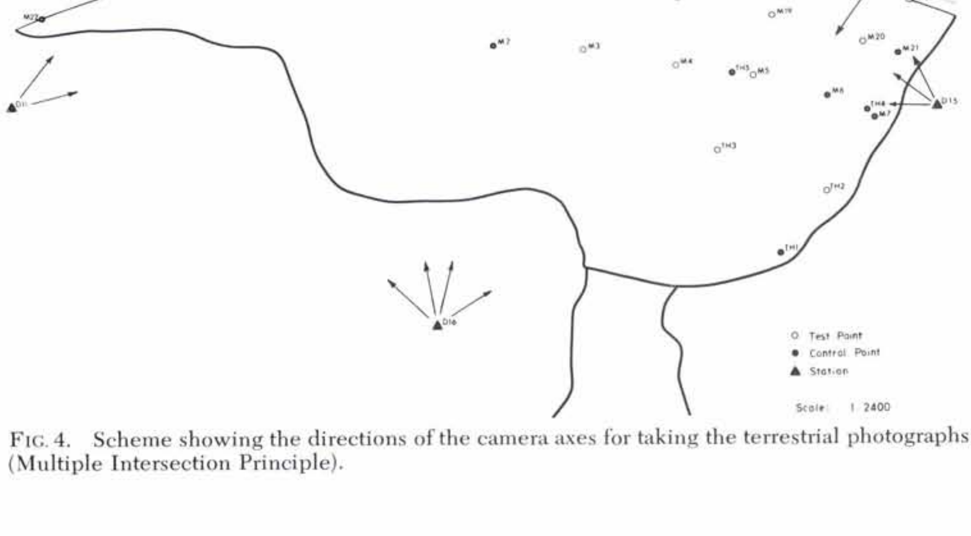

FIG. 4. Scheme showing the directions of the camera axes for taking the terrestrial photographs (Multiple Intersection Principle).

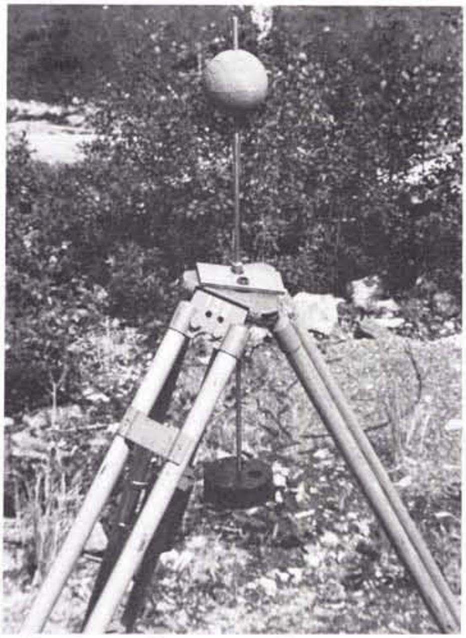

FIG. 5. System for targeting the points to be surveyed and photographed.

(July 1972) whereas for the second field mission (October 1972), Agfa-Geveart Aviophot plates were used. All plates were photographically processed directly after exposure in the dark room facility of the *Outardes 4 (1)* Power Plant to make sure that useful photographs were produced, and this before returning to Quebec.

For the data processing, the photo coordinates of all given points and of the test points were measured monocularly, on the photographs using the Wild comparator STK1. These photo coordinates were then corrected for all pertinent errors of interior orientation using a slightly modified computer program developed in our department by Dr. M. Erez. Subsequently, the ground coordinates X, Y and Z of all given points and the test points were computed according to a combined system: resection of the camera projection centers on the basis of given points—multiple intersection of all points. For this purpose a slightly modified rigorous least-squares adjustment computer program developed by Dr. M. Erez was used. The photogrammetric accuracies, in terms of standard errors, achieved for X, Y and Z of the determined points, and for both field missions, were as follows:

Mission July 1972 (12 points):

$$m_X = \pm 2.1, m_Y = \mp 1.9, m_Z = \pm 1.7$$

Mission October 1972 (17 points):

$$m_X = \pm 2.0, m_Y = \pm 1.6, m_Z = \pm 1.8 \quad (1)$$

(all dimensions in cm).

In obtaining these results, two points for the July Mission and three points for the October Mission had to be rejected because of blunders. The accuracies achieved are equivalent (in terms of relative standard errors compared to the average distance between the determined points and the camera stations) to about ± 1:15,000. A further analysis of the accuracy obtained in this test is presented under the Section, "Discussion, Conclusion and Recommendations".

It is evident that the attainable accuracy for single-point determinations in such a test depends very much on a precise and appropriate targeting of the points in question. Although the selected system of targeting in the *Outardes 4 (1)* experiment proved to be quite satisfactory, the photogrammetric field crew also studied other systems and performed special tests. One of these tests consisted of taking photographs at night by illuminating the spherical targets against white screen panels. The resulting photographs proved to be satisfactory and the image points were generated of a resolution comparable to that for the daylight experiment. However, it must be said that the night experiment proved to be more cumbersome and, because of a lack of time and funds, point determinations on the basis of such night photographs was not performed although this approach might be worthwhile for further consideration.

From the coordinates X, Y and Z of the targeted dam points for both field missions the displacement vectors for the points were determined, i.e., the displacements of the points measured in October 1972 with respect to the positions of the same points measured in July 1972. These displacement vectors indicate dam movements or deformations and are shown in Figure 6. From this figure it can be clearly concluded that a forward movement (downstream movement) of the upper center portion of the dam took place during the period July-October 1972 (3 cm in the downstream direction and 2 cm upward). This indicates a dam deformation in a downstream direction with a maximum at the center top portion of the dam and diminishing toward the anchorage of the dam at the bedrock.

This systematic trend, which is in accordance with engineer-mechanical assumptions, also indicates that obviously the photogrammetrically determined coordinates X

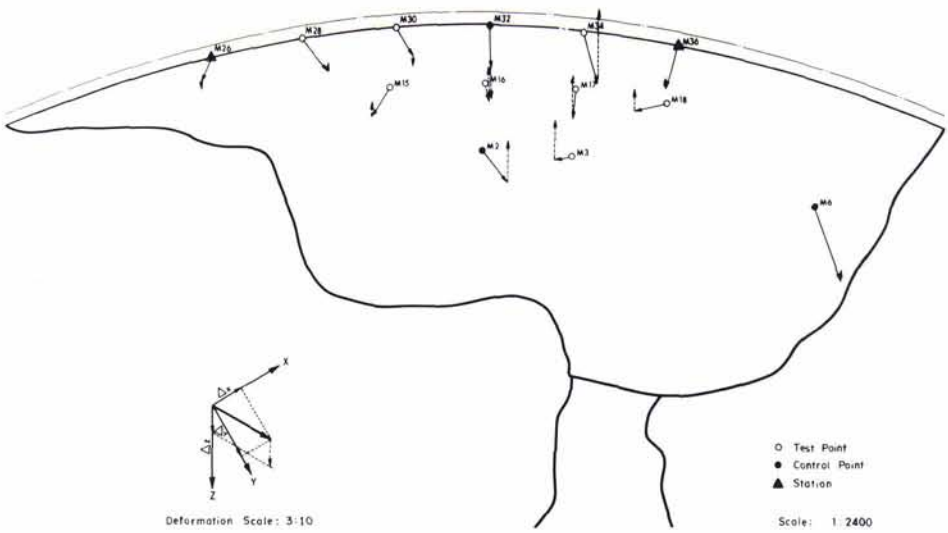

FIG. 6. Photogrammetrically determined displacement vectors indicating movements and deformations of the Dam *Outardes 4 (1)* during the period July-October 1972.

and Y of the test points have been determined with a somewhat higher accuracy than indicated by the standard errors under the initial premise. On the other hand, the approximately 2–cm upward movement of the dam's upper central portion is more difficult to explain, and it might be that in this instance the measuring errors interfered to a higher degree if compared with the X and Y movements, although the vertical and upward displacement vectors in this portion are clearly systematic.

The measurement of movements and deformations of an earth dam whose downstream surface is formed by a large number of irregular blocks of sizes varying from a fraction of a foot to up to 10 feet and more in diameter is a complex problem. Such blocks might be subject of local movements, particularly if they are loose without, however, being caused by a global or local movement of the dam itself or of portions of it. To distinguish local block movements from global or local dam movements and deformations it would be necessary to measure for each of the measuring missions a large number of points, possibly thousands of points for a large dam. This becomes restrictive for practical and economical reasons. Considering the present state-of-the-art, there remains only the plotting of precision contour lines, which reveals itself as a practically and economically justifiable solution.

This approach, however, has the disadvantage of producing a limited accuracy, i.e., an accuracy which is restricted by the accuracy of graphical contour line plottings, i.e., by the graphical accuracy as such. To analyze to what extent precise graphical contour line plotting would be useful to determine local block movements, the contract with Hydro-Quebec specified a graphical contour line plotting of the right hand portion of the dam *Outardes 4 (1)* for the July as well as for the October 1972 Missions. For this purpose a pair of terrestrial photographs were taken from a predetermined terrestrial base (012-013) during both field periods (July and October 1972) using the Wild Phototheodolite and with camera axes parallel and turned to the left (see Figure 7). It should be mentioned here that the terrestrial base could not be chosen in the most favorable direction (which would be parallel to the dam) because of prevailing topographical conditions. The plotting of the contour lines for both missions was performed at the Wild Autograph A7 of our department using as control an abundant number of available and targeted control points. Plotting was performed at the scale 1:250 and, as this was considered as an experiment only, 10–m contours were plotted on transparencies with an accuracy as high as possible. To achieve this, all contours were plotted twice (forward and backward, and everywhere if the deviations exceeded 1 mm on the plot, the plotting was repeated.

The final contour lines were obtained by averaging the two or more plottings. As a consequence of applying this procedure it can be expected that the contour lines were affected by a planimetric standard error of not more than ± 0.5 mm or ± 12.5 cm on the dam. For the entire plot the average planimetric stan-

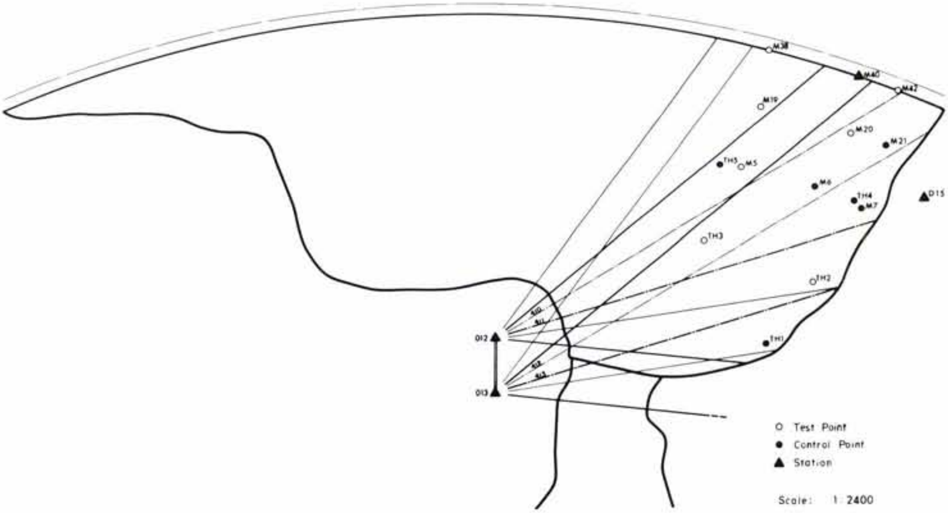

FIG. 7. Terrestrial base for dam area with contour lines.

dard error can be expected to be approximately ±7 to 8 cm which is equivalent to a relative standard error of about ± 1:2,000 if referred to the average distance between the plotting area and the terrestrial base. Comparison of both plottings by superpositioning did not reveal any global or local dam movements or deformations which were to be expected as these displacements (in the order of 2 to 3 cm) were too small to become evident in the 1:250-scale plotting. Nevertheless, the plottings showed differences for some large rocks–differences which are essentially larger than the plotting errors and, consequently, it can be concluded that these rocks were subject of considerable movements (translation and rotation) between both field missions.

Discussion, Conclusions and Recommendations

Although the specified project accuracy for the targeted test points by numerical terrestrial photogrammetry has been practically attained, it must be stated that the achieved accuracy is only about half as good as that which was achieved for the underlaying precise geodetic microtriangulation using precise instruments such as T3 and N2. In view of the methodological advantages of the photogrammetric approach it seems to be desirable to improve further the photogrammetric system to such a degree that an accuracy would be achieved which is equivalent or even superior to that of a precise geodetic microtriangulation. In our opinion this is hardly possible by means of the presently on the market available terrestrial cameras (phototheodolites). What is obviously needed are precise terrestrial plate cameras with an essentially longer focal length, say 300 mm. This would allow one to attain with the described numerical photogrammetry system standard errors of approximately ± 1 cm, or an equivalent to that of a precise geodetic microtriangulation, for a dam structure of the size of *Outardes 4 (1)*. This would be more than sufficient for earth dams. However, it has to be pointed out that even such an accuracy is not sufficient if movements and deformations of large concrete dams have to be periodically measured for which standard ground coordinate errors of not more than about ± 0.5 cm can be tolerated. Such an accuracy can only be achieved if each camera projection center, using a 300 mm focal-length camera, is determined by resection from at least 16 to 20 targeted control points and if each targeted test point is determined by intersection from at least 16 photographs and this compared with the average 4 to 5 points photographic resection and the average of four-directional photographic intersection occurring in the *Outardes 4 (1)* project.

It would not be appropriate to draw any conclusion as to the economy of the photogrammetric approach in the case of the *Outardes 4 (1)* project, as this project was limited to perform an accuracy test using only 17 test points on the dam structure. However it should be considered that, for a comprehensive periodic determination of movements and deformations of large dam structures, a large number of targeted test points must be determined, a number which might be in the order of several hundreds (say every 10 m a point in directions parallel to the dam and perpendicular to it). In this application the numerical photogrammetry approach becomes superior to the geodetic approach for two reasons:

- Methodologically, it allows one to record all test points in an essentially shorter time if compared with the geodetic approach, thus fulfilling better the condition that for one field mission all test points should be measured insofar as possible at the same time.
- Economically, the larger the number of test points, the more economical the numerical photogrammetric approach becomes if compared with the geodetic approach, meaning that beyond a sufficiently large number of test points, the numerical photogrammetric approach will be more economical than the geodetic approach.

As a consequence, it is recommended that photogrammetric instrument manufacturing companies be more concerned with this problem with the ultimate result of producing high-precision terrestrial plate cameras with a focal length in the order of 300 mm or even larger, for which there is at present and even more so in the future, a great field of application, not only for power dam measurements, but also for many other high-precision periodic movement and deformation recordings and measurements in the field of sciences and engineering, e.g., bridge deformation or vibration measurements, antenna measurements, etc. The availability of such cameras would also allow one to reach an improved accuracy for precise graphical contour-line plottings to determine local movements of large blocks on earth dams and, eventually, even large dam movements and deformations, provided that there is available a precise plotting instrument which allows one to plot photographs of a focal length of 300 mm or more.

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