DEFORMATION ANALYSIS OF DAMS BY PHOTOGRAMMETRY

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Abstract

When dealing with dams, the most important aspect is the dam's safty, without which grave incidents may occur. Therefore, protection, maintenance and precise measurement are very critical issues and must be done with maximum care. Photogrammetry with its advantages such as being a non-contact measurement tool can be useful in this case. Recent years have seen an increase in the use of digital close range photogrammetry in various engineering projects. By using high-resolution cameras along with a proper network design, camera calibration and bundle adjustment, measurements of high accuracy can be achieved. In this paper, the application of photogrammetry in 3D coordinate measurements of large dams is studied. For this, the spillover of an embankment dam (245.7m by 62.8m), named Marun, which is located in south of Iran was considered as the case study. A number of targets were fixed to dam body and imaged using high-resolution (8-mega pixel) digital camera. Various tests were carried out to evaluate the capability of photogrammetry in 3D measurements of the target points. The results indicated that within the experimental configurations accuracy of 4.2175 mm could be achieved, so this method can reveal deformations above this value. The study however, showed that due to complex and difficult conditions surrounding such dams, it is not always possible to use photogrammetry alone in dam 3D point measurements. Photogrammetry can therefore be used at least in combination with surveying techniques especially when a fast and not necessarily too accurate analysis is required.

1 Introduction

When dealing with dams, the most important aspect is the dam's safety, without which grave incidents may occur. Therefore, protection, maintenance and precise measurement are very critical issues and must be done with maximum care. The most effective elements on dams are water temperature changes (exclusively in winter season), water surface increase, grounds motion seismic and concrete crawls. Thus, safty control of dams, detecting these faults and well-timed treatment in order to increase lifetime of dams against above effects are so important. Precise measurement in dams can be divided in two categories:

- Internal and long-term measurements, to determine the affecting forces on dams
- External measurements to monitor and analysis any deformation cause by affecting forces.

Internal measurements can measure with geotechnical instrumentations such as Inclinometers, Extensometers, Telemeters and piezometers in any critical points (during and after dam conformation). The external measurement can obtain by involving proper surveying methods. In table (1), examples of raucousness of dams besides their measurement methods are presented [2].

Elements	Construction type	Examples of raucousness	Type of Measurement	Tools used
Internal Settlement	Concrete/Embankment	Beginning of crackup or internal erosion of dam	Quantity and nature of drains	Settlement gauge
leveling	Concrete/embankment	Movement and deformation	Axis line	Geodetic surveying
Pore water pressure	Embankment	Beginning of instability	Pore water pressure in embankment dams	Pressure gauge
External settlement	Concrete/Embankment	Leaning in concrete dams or reduction of water level in embankment dams	Crest settlement , base settlement	Geodetic surveying, settlement sensors

Table 1: Examples of raucousness of dams and their measurement methods

In this study, we focus on external measurements, in order to use it in deformation measurement of dams. Until now the main technique, which has been widely involved in dam 3D measurement, is Geodesy. However, by considering environmental and atmospherically situations in Iran (mountainous, high humidity and temperature in most areas), measurement and data processing are so difficult and time consuming. On the other hand, no procedure can provide the accuracy (2-3 millimeters) in dams with their large dimensions and other limitations.
By considering photogrammetry and its advantages such as, non-contact direct measurement, rapidity data capture and processing, on-line and off-line automatic or semi automatic measurement, photogrammetry can be used in many engineering projects. As seen in the pervious works e.g. [5,6] until now, photogrammetry has been involved in some applications. In this paper, by involving a high-resolution camera it is aimed to see which level of accuracy can be achieved. In addition, what useful advantages can photogrammetry have along with Geodesy in 3D coordinate measurements of dams.
For this, the spillover (245.7 by 62.8 m) of Marun dam (figure 1) has been selected as the case study. For accurate measurements the digital high-resolution camera "Canon EOS 30D" (pixel size: 6.4 µm) has been employed. To reach maximum accuracy, retro-reflective targets including environmental situation, and motorize total station for reading number of targets (control points) were involved. All the computations have done by "Australis" software.

Figure 1: Spillover of Marun dam

Before discussing photogrammetric measurement procedures in this paper, by concerning above gleanings and difference situation of Iran dams in contrast to other countries, it is necessary to discuss on limitations and difficulties of using this method on dams in Iran.

2 Inspection of environmental and limitations in Iran dams

Whereas photogrammtry has not been involved in 3D dam measurement in Iran until now, before discussing on main study of this research, it is necessary to evaluate all the existent limitations and difficulties of using this method in Iran. In contrast to other researches that have made by Kersten (1995) and Maas (1997), the workspace and environmental situations in Iran are so different. Videlicet we can mention to high temperature (around 50^{oc} in summer seasons) and topographic characteristics of Iran dam (mountainous situation of dams) especially southern dams (Marun, Dez, Karkheh, Karoon). Therefore, besides instrumental limitations and network design, other environmental and workspace limitations must be concerned widely. The photogrammetric limitations are as follows:

- Impossibility of using common targets used in industrial and architectural photogrammetry, according to severe environmental limitations (high humidity, high temperature and sun consecutive sun radiation).
- Impossibility of using any imagery sensor especially CCD sensors according to their working range (mostly between 0^{oc} to 30^{oc}).

In dam deformation monitoring projects, which all the measurement process must be repeated at least twice a year (in first five years of shelf time of dam) [4], It is necessary to use targets, with maximum performance and resistance against all above limitations. This part will discuss in part (5).
After targeting, the photogrammetric imagery must perform. This part is the basis of photogrammetry and accurate measurements directly depends on this part. Therefore, choosing proper camera by considering the environmental difficulties such as high temperature in Iran dams, can be considered as one of the most effective elements that can terminate other process.

Digital camera sensors can be divided in two categories: CCD[1] sensors and CMOS[2] sensors. In each project according to their advantages and considering all working situations it is necessary to use proper camera. In this project because of lower energy consumption of CMOS sensors (1/10 CCD sensors at the same size), a CMOS camera has been used. Unlike CMOS sensors, in CCD sensors signal enforcement must be done for each CCD in computational units restricted from main circuit, which increases the temperature and energy in CCDs [7]. So, using a CCD camera by concerning their advantages (low noise, high sensibility, and high image quality) has not become possible. Today by advances in production of CMOS sensors, these cameras have been used widely besides CCD cameras., and their noises and image quality have been developed [7].
Finally, to reach maximum possible accuracy, all above limitations have to be considered, and a proper solution must be involved. By concerning above gleanings, in this study the high-resolution digital camera "Canon EOS 30D" (figure 2) by specifications such as 3504 by 2336 pixels, pixel size: 0.0064 mm and sensor size: 22.5 by 15 cm have been used. This camera has been produced since 2006 and is known as one of the professional cameras of Canon Company.

Figure 2: Canon EOS 30D

As mentioned above, in this paper, capability of photogrammetry in dam measurements by concerning effective forces such as pressure, stress and strain has to be evaluated. For this reason, the following procedures must be involved:

- Network design
- Targeting and imaging
- Target measurement and network adjustment

3 Network design

In any photogrammetric project, this step is the most important factor to reach the given accuracy. The aim of any photogrammetric network design can be summarized to satisfaction of standards such as accuracy, reliability and cost. Basis of network design in photogrammetric measurements is bundle triangulation as a mathematical model, which 3D coordinates of points, position and situation of camera stations and camera calibration parameters can be computed simultaneously with high level of accuracy [8]. The accuracy of any optical triangulation system is a function of the angular measurement resolution and geometry of intersecting rays at each target points and imaging scale, so these three parameters must be considered in this case [1] .
In network design, a number of interdependent factors, which constrain the design optimization process, must be taken into account. Therefore, Constraints affecting the configuration of camera stations can be summarized as camera to object distance, minimum target diameter, and number and distribution of image points and can be computed as follows:

3.1 Camera to object distance

In manners, which camera distance to each object points is less or greater than this distance, the desirable accuracy may not provide and imaging specifications is not realize. So by concerning this constraint the acceptable working range can be between minimum and maximum range of camera to object distance. Therefore, it is necessary to compute these parameters in details. This constraint can be computed by using equation (1,2).

$$D_{\min} = \max(D_{Dof}^{\min}, D_{point}^{\min}) \tag{1}$$

$$D_{\max} = \min(D_{Fov}^{\max}, D_{work}^{\max}, D_{Res}^{\max}, D_{Scale}^{\max}) \tag{2}$$

By concerning above equations, it is easy to understand that the minimum camera to object distance is a function of camera depth of field and minimum target points in each image, and similarly the maximum camera to object distance is a function of camera field of view, workspace constraint, camera resolution and imaging scale. With this knowledge, the camera to object distance can be computed as follows:

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[1] Charged Couple Device
[2] Complimentary Metal Oxide Semiconductor

3.2 Camera depth of field constraint

Depth of field is an area of object depth that for a known distance between camera and object, the produced images are sharp and clear. Besides distance, this constrain depends on internal camera parameters such as f/stop, focal length and pixel size of camera [8].Therefore, this distance can be computed as follows:

$$d_{near} = \frac{d}{1 + \frac{d - f}{D_{HF}}} = 7.92(m) \tag{3}$$

Here, D_{HF} is hyper-focal length, δ the ambiguity circle diameter and $F_{/Stop}$ the parameter refers to diaphragm aperture of camera. D_{HF} and δ can be computed by the following equations (4,5):

$$D_{HF} = \frac{f^2}{F_{/Stop}\delta} = 8.588(m) \tag{4}$$

$$\delta = \frac{f}{1720} = 0.0163(mm) \tag{5}$$

3.3 Camera field of view constraint

It is always beneficial, though often not possible, to have all object targets appearing in the field of view at each station. This can simply design (sub-network connections are avoided), and enhance economy (fewer images) and the homogeneity of triangulation precision [1]. Practically this constraint is the distance to camera, which covers total space or sections of the object. Therefore, in this constraint, the camera distance must be sufficient; otherwise, object may appear in small portion of image. This distance can be computed as follows:

$$D_{Fov}^{\max} = \frac{D_0 Sin(\alpha + \varphi)}{2Sin(\alpha)} = 143.2703(m) \tag{6}$$

Here, α is half of camera pyramid vertex angle, φ the incident angle between camera and longest object diameter, D_o the longest object diameter.

3.4 Workspace constraint

Practically this constraint is the operator allowable imaging distance to object. Usually, with satisfaction of camera field of view, this constraint can be solved [8], unless the workspace being underside of the object size (this project). By using wide angel lenses this problem can be solved totally, so in this project a 28-millimeter lens has been used.

3.5 Camera resolution

Resolution of object in the imagery must be sufficient to support image menstruation to the desire precision (σ). Practically this constraint can be assumed equal to the maximum target pixels in image. Therefore, maximum distance is a function of focal length, pixel size and target diameter and can be computed as follows (7).

$$D_{\mathrm{Res}}^{\max} = \frac{fD_t Sin\varphi}{p.T_{PoINo}} = 113.666(m) \tag{7}$$

That D_t is target diameter, $T_{Pel/No}$ the minimum target pixels in image and *p* the pixel size of the camera.

3.6 Imaging scale

According to the desirable accuracy ($\overline{\sigma}_c$) , the camera to object distance must not more than a given limit, because the imaging scale may fall down and the measurement error according to equation (8) may become bigger than $\overline{\sigma}_c$.

$$\overline{\sigma}_c = \frac{q}{\sqrt{k}}.S.\sigma = \frac{q}{k}.d.\sigma_a \tag{8}$$

Here, q is design factor, S the scale number, k the average number of exposures in each station and σ the image co-ordinate standard errors. So the imaging scale and h can determine by above equation as follows:

$$s = \frac{\overline{\sigma}_c.\sqrt{k}}{\sigma.q} \cong 11646 \tag{9}$$

$$H = \frac{f}{S} = 326.088(m) \tag{10}$$

3.7 Number and distribution of image points

As has been shown in Fraser (1984), the number of targets within a network has little impact on the precision of object point triangulation, so as there is a sufficient number in each image to support exterior orientation, which is typically by standard bundle adjustment in multiple camera networks. The number and distribution of image points also significantly influences of precision of recovery of sensor calibration parameters in self-calibration [1]. Unlike depth of field constraint, number and distribution of image point constraint is not fix and depends on distance [8]. By increasing the camera to object distance, the number of image points increase but the distribution of image points may decrease [8], so the images must take from distance, which cover all target points. This distance can be computed as follows:

$$D_{Point}^{\min} = \frac{af\sqrt{k}}{d} = 9.639(m) \tag{11}$$

That a is distance between target points, d the frame length of camera and k is number of image points.
By considering above equations, the minimum and maximum camera to object distance can be computed from equations (1,2) as follow:

$$D_{\min} = \max(D_{Dof}^{\min}, D_{point}^{\min}) = 9.639(m) \tag{12}$$

$$D_{\max} = \min(D_{Fov}^{\max}, D_{work}^{\max}, D_{\mathrm{Re}s}^{\max}, D_{Scale}^{\max}) = 113.666(m) \tag{13}$$

3.8 Target size

In photogrammetry in order to reach the highest possible accuracy, target size must select properly. As has been shown in Otepka (2002) for precise measurement, minimum target size in image space must not less than 3 by 3 pixels, and to obtain sub pixel accuracy target size must be within 5 by 5 pixel or 8 by 8 pixel [8].
Choosing proper target size depends on parameters like camera to object distance, focal length of camera and the assumption that generally in photogrammetry target diameter is 1/1000 object size. Therefore, in this project targets with 120 mm diameters have been used. In this case, by noticing equation (14), target size in image space has computed 5 by 5 pixels as follows:

$$n = \frac{D_t}{(\frac{H}{f}) * p} = 5.23 \approx 5 \tag{14}$$

Here, n is number of pixels in horizontal and vertical direction, D_t the target diameter, f the camera focal length and p is pixel size of camera.

4 Targeting and imaging

In this project according to high humidity and temperature of the environment and sun consecutive radiation, 60 circular retro-reflective targets with PVC cover resistant to the following limitations have been used. To run automatic target recognition by Australis Software, all targets have been glued on black background (25 by 25 centimeter) and installed on the spillover (figure 3).

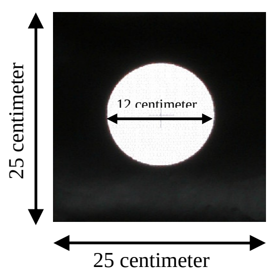
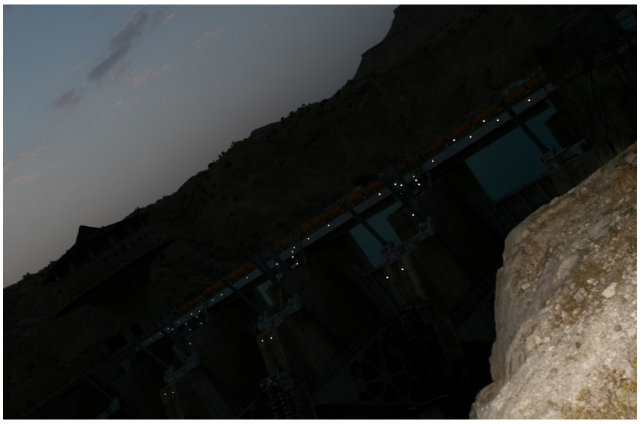


Figure 3: Sample of target used in this research

After targeting, the nest procedure is imaging. To reach images with maximum quality in low light environment with highest level of target illumination according to imagery time (18-19:30) and the camera imagery distance (80 to 100 meters), all images have been taken by combination of 2 flashes synchronize on 1/100 to 1/250 seconds (depends of exposure situation) on F/stop 5.6 to 8. By concerning camera to object distances the lens focus at infinity. In addition, to reduce noises in images, by camera company recommendation, ISO of camera has selected on 100 and entire images have taken with minimum compression in JPEG format. In figure (4), two samples of taken images are presented.

Speed: 1/250 second, F/stop: 5.6



Speed: 1/100 second, F/stop: 5.6

Figure 4: Different images on the spillover according to time of imagery

Finally by noticing the following comments (network design and camera configuration) and limitations such as mountainous environment and difficult work space conditions, total 110 images from 22 stations (5 image per station) have taken from both side of the spillover (figure 5).

Figure 5: Camera stations situation

5 Target measurement and network adjustment

Before measuring target points on the spillover and introduce them to software as control points to unify both coordinate systems and evaluate the accuracy and precision of entire measurement, a geodetic network around the spillover to determine any movement between to epoch of stations has been created. After that, the coordinate of some targets (figure 6), have computed by intersection. Horizontal and vertical angles have observed by the motorize total station "Trimble 5602 (2" accuracy) in 5 acceptable couples. For further computations, entire images beside all computed coordinates have introduced to Australis software.

Figure 6: Control points position on the spillover

In order to begin photogrammetric process, to compute internal parameters such as focal length, principle points and lens distortion of the camera, it is necessary to calibrate the camera. Camera calibration process can be estimated before inception of project (pre-calibration) or can be computed simultaneously with exterior orientation parameters beside unknown coordinate points with bundle adjustment (self-calibration). Whereas used calibration method directly effect on measurements, the optimum method has to be selected. After that, co-linearity equations for entire targets and control points have formed and computed by least square method. Output of this section is the photohrammetric coordinates of all targets in measured ground coordinate system. As has been shown in Shirkhani (2007), the results in pre-calibration method was better than self-calibration, because the accuracy of self-calibration based on network geometry and number and distribution targets in image space, and in this research according to environmental and working limitations, the stability of the network was weak. Therefore, for further tests the results of pre-calibration have been used. In order to test the reliability of this method and assurance of stability of camera parameters during imagery, pre-calibration has done before and after imagery. The camera parameters in both cases were close, and have approved the stability of the used camera [9].
To evaluate capabilities of photogrammetry in dam 3D measurements, and comparison photogrammetry with land surveying, different test has been involved as follow:

5.1 Number and distribution of control points effect on measurements

Number and distribution of control points effect directly on the accuracy of measurements. In any project, these points must choose by concerning network standards such as cost and time. As mentioned above 16 points have been selected as control points and all the computations have done by these control points. in table 2, number and effects of control points on the precision and accuracy of measurements have been shown.

Number of control points	**Precision of bundle adjustment (mm)**				**Check points RMSE (mm)**			
	σ_x	σ_y	σ_z	**Total (95%)**	μ_x	μ_y	μ_z	**Total (95%)**
4	0.6164	0.7122	0.4128	2.0568	1.896	4.027	0.531	8.9656
6	0.5887	0.6694	0.3128	1.8895	1.793	2.207	0.483	5.7685
8	0.5908	0.6772	0.2885	1.8878	1.630	1.248	0.482	4.2175

Table 2: Effect of number and distribution of control points on measurements

According to the results, by increasing number of control points, precision and accuracy of measurements have been increased. The highest possible achievable precision in this study is 1.8878 mm (by using 8 control points) and the accuracy of 4.2175 mm have been achieved. As seen, there is no noticeable difference between using 6 and 8 control points but the only difference is in their check point RMSE (1.551 mm). Therefore, by using 8 control points best results can be obtained.

5.2 Number of images inspection on precision of measurements

One of the elements, which directly effects on the accuracy of results, is the number of images. To reach the optimum network geometry, increasing camera stations and number of images must choose in a way to improve

network geometry. In this case, increasing number of camera stations directly effect on error ellipse of target points and improve their accuracy. After the network geometry has become strong, these changes decrease and extra images must be taken from each station in order to increase k parameter in equation (8). In this case, improvement of point's accuracy can be achieved corresponding to $\sqrt{k}$ [8].
Therefore, the reliability of observation increases and the size of error ellipse of points can decrease homogonous. As mentioned in section (4), total 110 images from 22 stations (5 images per station) have been taken. In this part, number of images and their effect on precision of bundle adjustment in optimum case (using 8 control points) have are shown (table 3).

Number of images	**Precision of bundle adjustment (mm)**			
	σ_x	σ_y	σ_z	**Total (95%)**
22	1.2282	1.3878	0.5196	3.8494
44	0.9398	1.0687	0.4553	2.9884
66	0.7613	0.8606	0.3675	2.4129
88	0.6551	0.7482	0.3211	2.0899
110	0.5908	0.6772	0.2885	1.8878

Table 3: Effect of number of images on measurements

The results accept all above gleanings. It is clear by increasing number of images the precision of measurements has been improved. By using 88 and 110 images, the network geometry has been improved enough and precision difference by using 88 and 110 images is small (0.221 mm) besides using 22 images (1.9616 mm).
The difference between photogrammetric measurements and measured control points by using 8 control points are shown in table (4).

Point No	**ΔX (*mm*) (Xphoto -Xground)**	**ΔY (*mm*) (Yphoto -Yground)**	**ΔZ (*mm*) (Zphoto -Zground)**
1	*0.189*	*0.357*	*-0.003*
4	*2.801*	*0.803*	*0.664*
5	*1.413*	*1.250*	*0.328*
8	*0.677*	*0.351*	*-0.627*
16	*-0.576*	*-0.147*	*0.013*
17	*2.255*	*0.345*	*0.395*
25	*0.432*	*-1.133*	*-0.202*
27	*-0.766*	*0.115*	*-0.591*
28	*-0.463*	*1.088*	*-0.208*
31	*0.661*	*2.946*	*-0.012*
36	*-0.297*	*-1.728*	*0.995*
37	*0.115*	*-0.916*	*0.040*
39	*-1.633*	*1.275*	*0.881*
40	*-0.106*	*0.571*	*0.315*
41	*-1.551*	*2.681*	*0.231*
42	*0.824*	*0.168*	*-0.004*

Table 4: Difference between computed coordinates by photogrammetry and surveying

Result shows that maximum difference between calculated and measured coordinates in X,Y,Z directions are 2.801 mm, 2.946 mm and 0.664 mm.

5.3 Reliability

One of the effective elements on quality of each network is reliability. Reliability can be divided in internal reliability[3] and external reliability[4], which directly contributes on precision of measurements [8]. At the design stage, it seems reasonable to concentrate on the issue of internal reliability, for we are seeking a network configuration that will best support the detection of any gross errors present in the observation. The assumption can be made that optimal precision coupled with a high internal reliability will lead to optimal external reliability [1]. Therefore, redundancies are very important in internal reliability and express the contribution of each observation. In multi-station, convergent configurations, there is sample scope to improve internal reliability through increased redundancy. Although network geometry directly effects on alignment of freedom numbers, in cases that changing them is not possible, the best way to increase their redundancy is taking extra images from each station [8]. Therefore, number of image rays for each target points can be used to control ability of internal reliability. In order to increase network strength and to decrease size of error ellipse of target points, increasing

[3] Internal reliability measures the ability of detect the presence of gross observation errors within a photogrammetric network.
[4] External reliability measures the influenced undetected gross errors on the final estimated parameters values in the object point triangulation.

image rays on target points are very important. In this part, number of image rays by using 22 and 110 images have been caparisoned (figure 7).

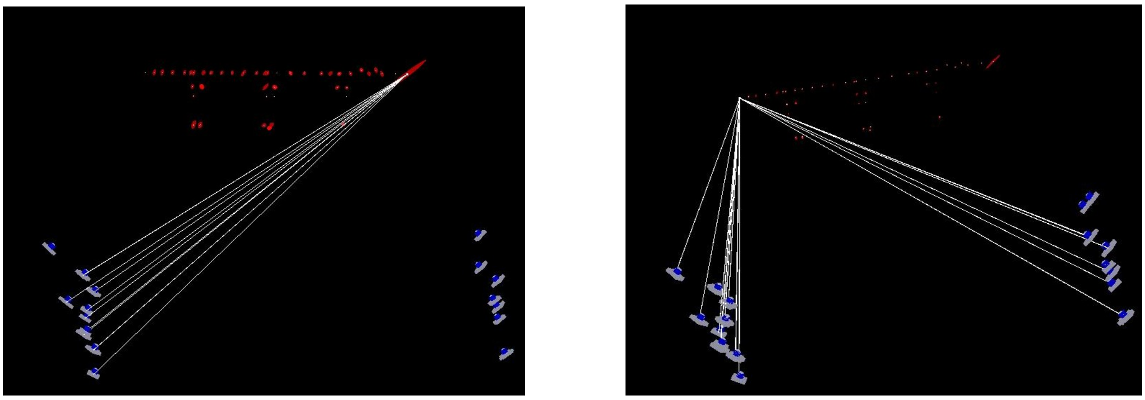


Figure 7: Ellipse errors in two cases (left) using 22 images, (right) using 110 images

It is clear that ellipse errors by using 110 images is much better than using 22 images, this base on number of images and the image rays for each target points. To understand these gleanings its better to discuss it in details table (5). In this table, number of image rays and their effects on the RMSE of measurements for two points (1, 26) are shown.

Number of images	Point number	Number of image rays	σ_x (mm)	σ_y (mm)	σ_z (mm)
22	1	16	0.1855	0.2735	0.0523
	26	11	7.8352	7.8989	1.1522
110	1	80	0.1760	0.2570	0.0502
	26	55	3.3660	3.4022	0.4938

Table 5: Number of image rays in precision of measurements of points 1 and 26

Result shows that, the total amounts of images and number of image rays directly effects on precision of target measurements. For point (26) in both cases the ellipse errors due to lack of image rays are high, but increasing the number of images (110 images correspond to 22 images), have increased the RMSE of the points about 4.4692 mm, 4.4967 mm and 0.6584 mm in X,Y,Z directions. However, for point (1) in both cases, the ellipse error is low and increasing the number of images have not any noticeable effects on precision of measurements, because this point is observable from most camera stations and the network geometry is strong enough for this point.

6 Conclusions

As mentioned before, the main aim of this research was to evaluate the capabilities of photogranmmetry in 3D measurements of dams to monitor any deformations. By noticing, the advantages such as direct measurement of non-contact points on spillover due to safety problems and total time (time of targeting and imagery 4 hour and time of processing about 3 days) photogrammetry can be used as an acceptable measurement tool. In this project, we obtained a total accuracy of 4.2175 mm and a precision of 1.8877 mm. In optimum case (using 8 control points) maximum difference between photogrammetry and geodesy are 2.801, 2.946 and 0.664 mm in X,Y,Z direction. therefore this method can be used to monitor any deformation above this range and it is not acceptable as standard 3D Dam measurement in Iran (2-3 mm) but this method can be used after shelf time of dams.
In this project, different cases have been tested. Result showed that geometry strength of network beside number of images, number of image rays for each target point and selecting proper camera positions in the network design are the most effective elements on precision of measurements and have to be considered during executive phase of any similar projects. Therefore, to reach maximum possible accuracy, these elements must be considered in detail. Today, by using digital cameras, there is no problem in taking number of images, and choosing camera stations and the entire images can be achieved in minimum possible time, correspond to analogue cameras.
One of the effective elements in using this method is dam construction. On embankment dams because of their characteristics and their surfaces (filling with rocks and soils) this method cannot be involved. For further studies on embankment dams, this must be noticed and design of special targets is recommended.
As seen in the project, by considering camera to object distance (80-100m), target diameter is so important. By looking in images, it is clear that in edges of entire images respect to far distance to camera and the characteristics of the camera lens (28 mm), targets diameter are small so it is better to use targets with diameter 2 times larger than the one which have been computed in network design.

Other effective parameter on this method is the instrumental limitations, for example by using platfoRMSE in front of the spillover, network geometry may be improved and, better result can be achieved.
Finally, photogrammetry at least can be used in combination of surveying techniques especially when a fast and not necessarily too accurate analysis is required.

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