

## Investigation into Deformation Monitoring of Mosul Dam

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### ABSTRACT

It is crucial to monitor the deformation of dams for saving lives and properties, economy and the environment. Many critical observables have to be studied on the dam and the near vicinity. Mosul dam have been monitored according to many engineering standpoints since its construction more than two decades ago. In the last few years there was a debate on the safety of the dam. In this paper, the author made his own analysis on a subset of archived surveying measurements and field observations. Problems in data processing and probable causes of large errors in results are discussed. It shows that errors in measurement and analysis can cause fears and misleading concepts about safety of the dam. Full conclusions of the safety of the dam can only be obtained from a wide range of critical engineering limitations among which is the deformation monitoring.

**Keywords:** Mosul Dam deformation monitoring.

### مناقشة مراقبة التشوه في سد الموصل

#### الخلاصة

من المهم اجراء مراقبة التشوه على السدود باستمرار لأجل الحفاظ على الأرواح والممتلكات و اقتصاد البلد وسلامة البيئة. فهناك الكثير من المتغيرات على جسم السد وما حوله التي تتطلب المراقبة. ومنذ انشاء سد الموصل قبل اكثر من عقدين من الزمن كان موضع دراسة ومراقبة من زوايا هندسية متعددة. وفي السنوات الأخيرة تكرر الحديث حول سلامة السد. في هذا البحث تم اجراء تحليل مستقل من قبل الباحث على جزء من ارشيف القياسات المساحية التي تم الحصول عليها ومن خلال بعض الملاحظات الحقلية. وقد تمت مناقشة بعض الاسباب المحتملة لظهور اخطاء عالية في النتائج. وتبين ان وجود بعض الأخطاء في القياس أو التحليل يمكن ان يثير المخاوف ويؤدي الى رؤية خاطئة عن حالة السد. ان استحصال خلاصة محددة بشأن سلامة السد لا تظهر الا من خلال الاعتماد على مدى واسع من المحددات الهندسية والتي احدها هو مراقبة التشوهات.

### INTRODUCTION

**M**onitoring of dams is fundamental in order to guarantee the safety of lives and properties and to optimize the exploitation and the maintenance of the dam and to the economic, social and environmental issues [1, 2]. A complete dam

monitoring program must include all critical observations in the body of the dam and the nearby area, few of these are listed below.

1. Deformation and positional translations (horizontal and vertical) of key locations on or near the dam. [3, 4, 5]
2. Seepage water quantity, quality and location.
3. Change in soil and rock properties in the whole vicinity.
4. Seismic activity of the region.
5. Upheaval, settlements, cracks and any odd behaviors in the structure and the surrounding area.

The collected data from these different perspectives must be analyzed carefully. Accordingly, a clear view of the safety situation of the dam can be assessed.

Deformation monitoring of dams is required to assess the amount of horizontal and vertical movements of the body of dam and to control the water storage and assess safety. Mosul dam was built on Tigris river more than two decades ago at approximately 50 km northwest of Mosul city at 36°37' N, 42°49' E (figure 1).

It was one of the largest manmade water reservoirs in the region [6]. The main dam embankment is zoned earth fill construction It contains as shown in Figure 2 a central clay core extends full depth to the foundation bedrock, graded filters in the upstream and downstream, shells, conglomerate, inclined chimney drain, and a blanket drain. The embankment has 3.6 km of crest length. The maximum height 113 m, the top elev. 343.4 m.a.s.l, the crest width is 10 m, the base width 650 m. with full designed volume capacity of  $11.1 \times 10^9 \text{ m}^3$ . The aims behind construction of the Mosul Dam are to prevent flood hazards from threatening the Iraqi cities, store water for irrigation, hydro power generation, fisheries and tourism purposes with positive effect on the environment.[7]. The location of the dam is near to an active seismological zone. Moreover, the geology of the region shows the possibility to develop karst or solution weathering within the limestones and the anhydrite and gypsum layers [7]. This composition shows that it can develop cavities due to prolonged water passage. Accordingly, an extensive cement grouting is constantly going on to strengthen the supporting soil and foundation.

The yearly cycle of water level fluctuations behind the body of the dam creates high pressure fluctuations on the upstream side. Seasonal and long term positional movement of the crest perpendicular to the dam axis is predicted. A settlement in the vertical direction is also predicted due to the high weight of the dam body.

The general directorate for surveying of the ministry of water resources authority performs periodic surveying observations. Their aim is to monitor the movement of the body of the dam and observe the horizontal network of control points originally constructed by the Swiss consultants [10]. According to the yearly cyclic fluctuations of water level behind the dam, the observations are performed twice a year since the completion of the dam construction. Each observation was given an epoch number. For example epoch zero was made in 1989 [10]. Surveying measurements (angles, distances, elevations) and results of adjustment analysis are documented. This paper briefs the findings of the author gathered from field observations and from investigations made on a subset of archived surveying data of deformation monitoring.

During the construction of the dam, several types of monuments and survey marks have been established for surveying and location monitoring. Major kinds are:

- A. Geodetic bench marks.
- B. Leveling bench marks.
- C. Survey pillars.
- D. Ordinary bench marks.

The whole system of marks composes horizontal and vertical control networks. Several marks are distributed on the dam crest, upstream, downstream sides and into the dam body (gallery). Other points are fixed on the earth surface on east and west banks and extend up to few kilometers away from the dam. These points differ in their location, construction details, stability and shape. Different kinds of points have different uses, different instruments are fixed upon them and different schedules of monitoring were followed.

The observation pillars are concrete cylinders of 60 cm diameter of which 130 cm above ground. A typical pillar is shown in figure (3). The top of pillar is a closing metallic cover. Pillar heads are suitable for mounting surveying instruments by forced centering [10].

In a surveying network (mixed triangulation and trilateration), horizontal angles are measured using theodolites, distances are obtained with electronic distance meters (EDMs). Recently, total stations are used for coordinate calculations as shown in figure (4). Level equipments are used for vertical control monitoring.

During the last few years there were concerns over the dam instability and a debate regarding the safety of the Mosul dam [7]. Al-juboori et al, [10] have made adjustment analysis on the pillars of the dam. They concluded that an actual deformation has occurred in the middle of the dam structure specifically at pillars (P62, P63, and P64). But their analysis didn't include all surveying marks.

A major concern was about a maximum planimetric movement of 0.8 m that was documented during the measurements of epoch 36 in 2005 performed by the general directorate for surveying. For the sake of detailed study of the possible causes of this high value, the author has obtained the following sets of archived surveying measurements.

- 1- Measurements and adjustment analysis results of epoch 36.
- 2- Measurements and adjustment analysis results of epoch 35.
- 3- Only the results of adjustment analysis of epoch 9.

Accordingly, the author made his own independent analysis using available measurements of the three epochs (9-35-36). The network analysis program ADJUST was used [11]. This program uses least squares method to calculate the most probable values of unknowns. In our case, the program adjusts simultaneously the measured distances, angles and azimuths using the following structures of equations [11].

For distance observation equations.

$$\left(\frac{x_i - x_j}{IJ}\right)_o dx_i + \left(\frac{y_i - y_j}{IJ}\right)_o dy_i + \left(\frac{x_j - x_i}{IJ}\right)_o dx_j + \left(\frac{y_j - y_i}{IJ}\right)_o dy_j \\ = k_{lij} + v_{lij}$$

For angle observation equations.

$$\left(\frac{y_i - y_b}{IB^2}\right)_o dx_b + \left(\frac{x_b - x_i}{IB^2}\right)_o dy_b + \left(\frac{y_b - y_i}{IB^2} - \frac{y_f - y_i}{IF^2}\right)_o dx_i \\ + \left(\frac{x_i - x_b}{IB^2} - \frac{x_i - x_f}{IF^2}\right)_o dy_i + \left(\frac{y_f - y_i}{IF^2}\right)_o dx_f + \left(\frac{x_i - x_f}{IF^2}\right)_o dy_f \\ = k_{\theta bif} + v_{\theta bif}$$

For azimuth observation equations.

$$\left(\frac{y_i - y_j}{IJ^2}\right)_o dx_i + \left(\frac{x_j - x_i}{IJ^2}\right)_o dy_i + \left(\frac{y_j - y_i}{IJ^2}\right)_o dx_j + \left(\frac{x_i - x_j}{IJ^2}\right)_o dy_j \\ = k_{Azij} + v_{Azij}$$

Solution is performed by iterations after linearization of nonlinear equations by Taylor's Theorem. The aim was to perform detailed adjustment analysis.

The following sections will brief findings.

### Evaluation Of Surveying Works

The author has recorded the following notes during field inspection and studying some archived records of measurements and analysis.

- 1- Since the construction of the dam in 1985, several ground control points have been disappeared and many have been added elsewhere due to different circumstances. In many locations, the observer may not find a match of points required to compare point movements on measurements at different dates.
- 2- Network analysis of point locations was determined based on planimetric 2D coordinates (X,Y only). Available elevations were not included in this stage of analysis.
- 3- Specifications of surveying equipment used is not well documented.
- 4- The adjustment software used in the original analysis has few limitations. For example it works on a maximum of 100 stations.
- 5- Many pillars having metallic cover plates were found weathered and loose in their position. Usually these pillars are used to force centering of measuring instrumentations such as theodolites and total stations during field data collection.
- 6- Many pillars and bench marks are probably affected by minor movements (i.e due to nearby traffic).

An independent analysis study have been performed on the available archived surveying measurements. A new run of the least squares adjustment program was performed to study carefully each step of analysis. We can notice that in both epochs (35, 36), a limited number of points included in the adjustment calculations. In horizontal

pillar network adjustment, only 26 pillars were used. Two pillars (P42, P44 see the solid line on figure 4b) were used as control stations for this bunch of points. These two points are on the downstream side, not far enough from the zone of effect of the dam body. It would be better to select control points at extreme locations far from the body of the dam. Figure 5 shows partial list of results of analysis.

The result of adjustment are displayed in figure (6). Error ellipses are elongated in diverse directions. Elongated error ellipses indicate the poor geometry of network points [11, 12].

Monitoring the horizontal displacement between epochs 9 and 36 is shown in figure (7). Although many points moved normally in the downstream direction in the order of 0.2 m., there is considerable number of points that have erroneous results. i.e unpredictable directions and magnitudes of movement. Some points moved toward the east side, others to the west, and even some movements were directed towards the upstream side. A movement that exceeds about 0.8 m is seen in point BM120 directed toward the east. Figure (7) also shows other large values of deformations directed to the east or west. This may indicate large error resulted from blunders in measurements. Probably no attempt have been made to remove blunders or to repeat suspected measurements prior to making final analysis. These erroneous results can give wrong interpretation of amount of dam deformation.

Monitoring the horizontal displacement between observations 35-36 is shown in figure (8). Here a complete randomness of directions and magnitudes of deformation is seen, no clear conclusion about direction movements can be obtained in this case. We interpret these as random errors in measurements. These types of errors can be reduced if more redundant measurements have been collected.

Vertical settlement of the dam crest was measured using leveling methods. Figure 9 shows the 3D shape of deformed surface. The maximum downward settlement occurs approximately at the point of maximum height of the dam.

## **CONCLUSIONS**

This paper investigates field notes and the results of adjustment analysis performed by the author. It shows that the interpretation of point movements reported in archived data can be misleading and make unnecessary fears regarding dam safety. The movement amount of 0.8 m possibly comes from a kind of error. The source of this error may be due to blunder in data collection, loose control points or it may be due to the misuse of the adjustment software. An adequate improvement strategy of monitoring and analysis must be adopted using a more stable set of control points of reference frame and making more measurements for higher redundancy. Note that the findings of this investigation are limited only to the used set of data and the methods of analysis. A decision about dam safety requires as well measurements and monitoring of other critical engineering issues of dam stability, such as seepage, cracks, cavities etc.

## **ACKNOWLEDGEMENTS**

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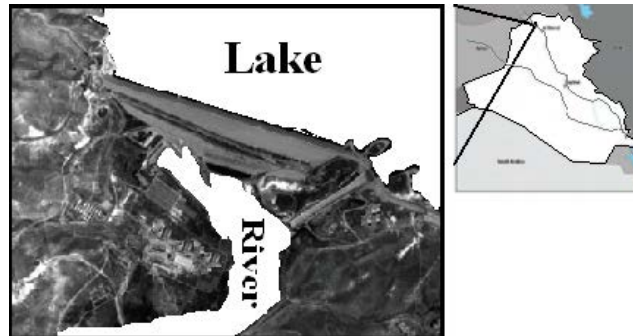


Figure (1) Location of Mosul dam.

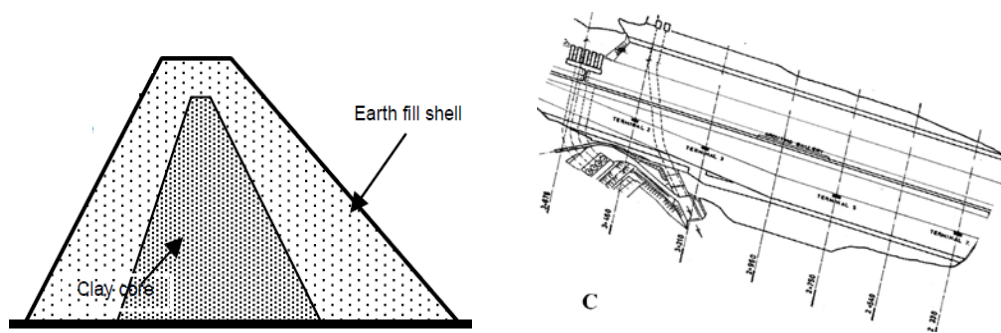


Figure (2) a) Schematic dam cross section [8].

b) Dam plan layout [9].

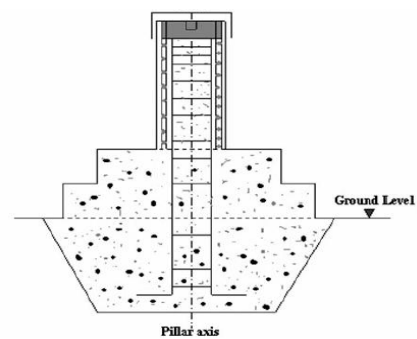


Figure (3) Typical pillar and details used for horizontal control. [10].

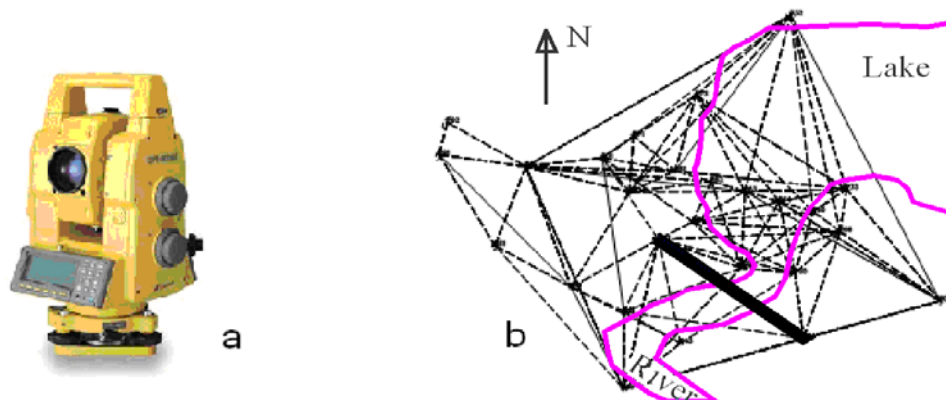


Figure (4) a) Total station. b) Distribution of pillars used for distance and angle measurements. Base line of control is the solid black line.

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MOUSAL DAM PROJECT OBS (36)
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Number of Control Stations      - 2
Number of Unknown Stations     - 24
Number of Distance observations - 153
Number of Angle observations    - 163
Number of Azimuth observations  - 0

*****
Initial approximations for unknown stations
*****
Station      X      Y
-----
P01      468,120.697  49,162.902
P03      470,477.753  47,589.142
*****
*****

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Figure (5) Part of adjustment output.



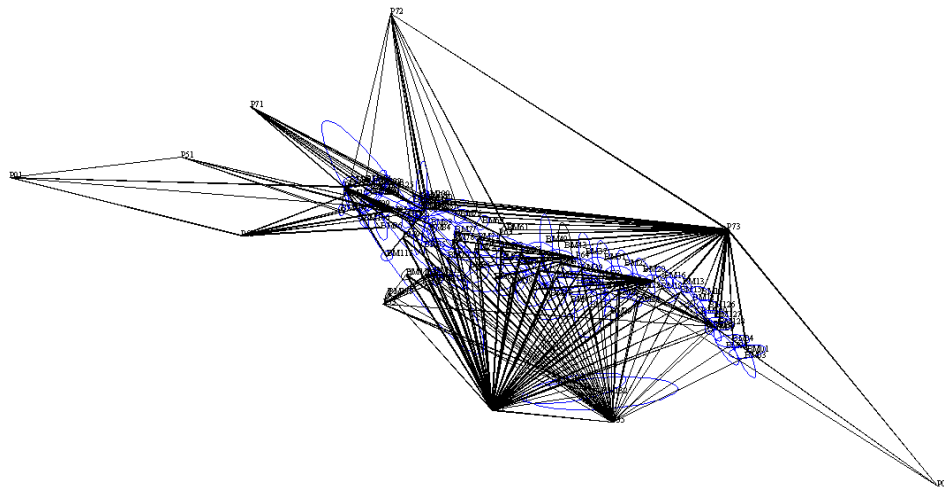


Figure (6) Network of points and error ellipses.

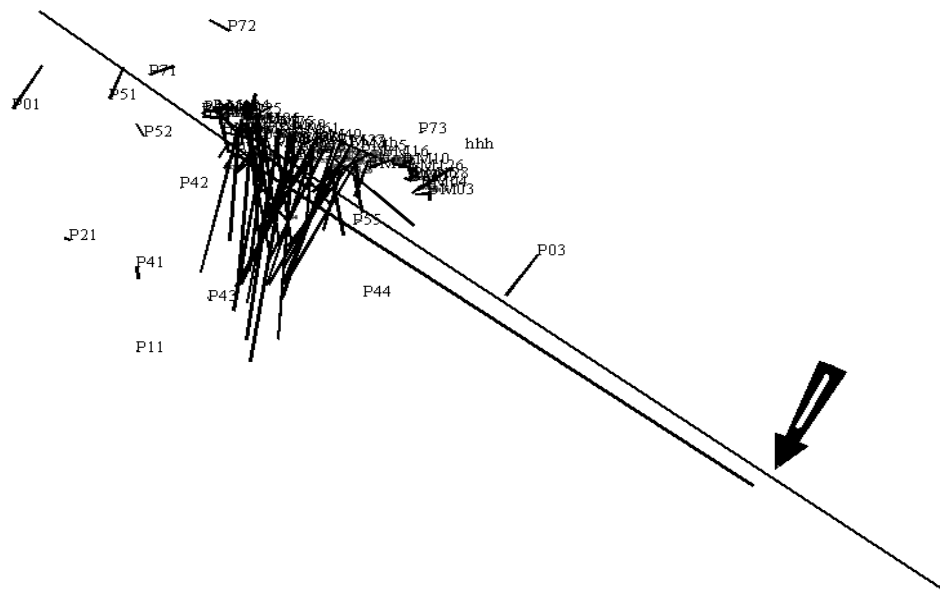


Figure (7) Horizontal movements of points between observations of epochs 9-36.  
Values are exaggerated 10000 times of scale. The solid arrow indicates the  
unusual deformation of BM120 which comes from probable error, see the text.

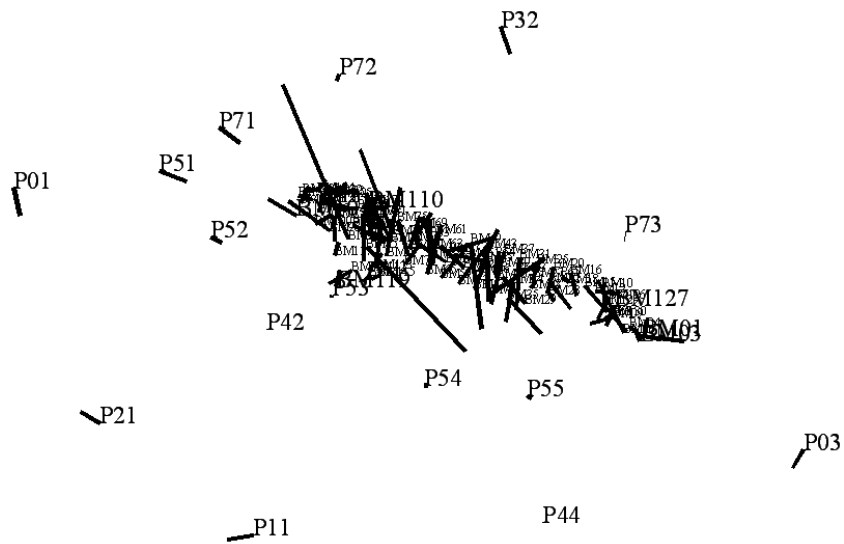


Figure (8) Horizontal deformation between observations of epochs 35-36

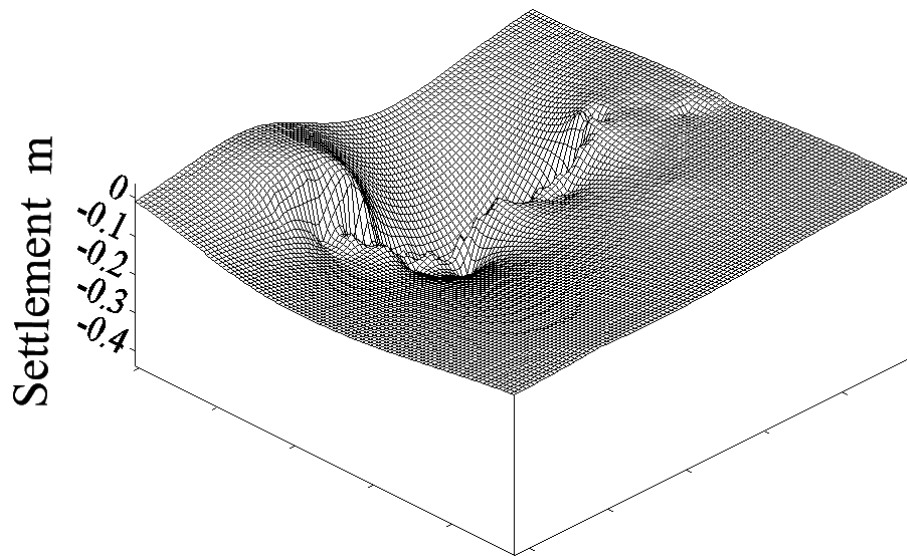


Figure (9) 3D view of vertical settlement between observation epochs 9-36 of selected points.