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Research paper

Structural damage detection of elevated circular water tank and its supporting system using geodetic techniques

Zaki Zeidan[1], Ashraf A.A. Beshr[2*], Sara Sameh[3]

[1,2]Mansoura University, Faculty of Engineering, Mansoura city – Egypt-Postal code 35516, Egipt
[1]e-mail: zmze283@yahoo.com
[2]e-mail: eng.aaabeshr@yahoo.com

[3]Badr University in Cairo, Faculty of Engineering, Egipt
e-mail: sarasameh724@gmail.com

[*]Corresponding author: Ashraf A.A. Beshr

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Abstract: Water is the main source of daily life for everyone and everywhere in the world. Sufficient water distribution depends on the place and design of water tank in certain areas. Water storage tanks are relatively flexible structures and they can tolerate greater settlements than other engineering structures. Deformation of tanks may cause severe damages to tank or even loss of life and injury to people, so monitoring the structural deformation and dynamic response of water tank and its supporting system to the large variety of external loadings has a great importance for maintaining tank safety and economical design of man-made structures. This paper presents an accurate geodetic observations technique to investigate the inclination of an elevated circular water tank and the deformation of its supporting structural system (supporting columns and circular horizontal beams) using reflector-less total station. The studied water tank was designed to deliver water to around 55000 person and has a storage capacity about 750 m^3. Due to the studied water tank age, a non-uniform settlement of tank foundation and movement of pumps and electric machines under tank's body will cause stress and strain for tanks membrane and settlement of sediments. So the studied water tank can tend to experience movement vertically, horizontally or both. Three epochs of observations were done (July 2014, September 2014 and December 2014). The results of the practical measurements, calculations and analysis of the interesting deformation of the studied elevated tanks and its supporting system using least squares theory and computer programs are presented. As a results of monitoring the water storage tank, circular reinforced concrete beams and columns at three monitoring epochs. The body of water storage tank has an inclination to the east direction and the value of inclination is increased with the time.

Keywords: water tank, deformation, inclination, accuracy, total station

1. Introduction

Water storage tanks are widely used in both residential and commercial areas. Based on the location of the tank, the tanks can be named as elevated, on ground or underground. The tanks can be made in different shapes usually circular and rectangular shapes are mostly used (Beshr, 2012). Elevated concrete water tanks (such as the studied water tank) are mainly used for water supply and fire protection. One of the major problems that may lead to failure of these structures is settlements of foundation. Deformation may be attributed to several reasons, such as incomplete investigation of foundation soil properties, improper construction of the foundation system, insufficient knowledge of the operating conditions, earthquakes etc. (Beshr, 2014). So, continuous monitoring of the behavior of the elevated water tank and its supporting structural system is important and vital because observations and deformation history recording don't present only scientific interest for the geotechnical engineers, but they are also indications of the long-term behavior of that type of structure and can be an useful guide to predict the expected movements and failure of it which have gradually gained greater importance in tank maintenance programs (American Concrete Institute, 2014; Pukanská, et al., 2014). Up to now, there are hundreds of available models of various geodetic and non geodetic instruments for deformation measurements. The decision on which instruments should be used and where they should be located leads to the need for a proper design and optimization of a proposed measuring scheme which should be based on the best possible combination of all the available measuring instrumentation (Beshr, 2014).

Therefore, the design of a monitoring scheme should satisfy not only the best geometrical strength of the network of the observation stations, as is the case in geodetic positioning surveys, but should primarily satisfy the needs of the subsequent physical interpretation of the monitoring results, i.e., should give optimal results when solving for the deformation parameters of the selected deformation model (Beshr, 2012). Reflectorless total stations are widely used nowadays for several applications in geodetic engineering due to its highly accurate and fast measurements (Gairns, 2008; Lutes, 2002). The data, resulted from advanced total stations, is corrected for atmospheric conditions, instrument offsets and then processed through a rigorous least-squares station adjustment, followed by data reduction algorithms to remove random errors.

Achieving the required accuracy for geodetic monitoring technique of structure is based on the following factors:

1. The used instruments specifications (Instrument specifications, data collection options and the proper operating instructions).
2. The field observing and modeling procedures. Measurements and adjustment techniques of the network have direct influence on the detection of monitoring point's displacements and consequently the accuracy of monitoring and setting out process.

Monitoring of the water tank settlement and deformation has gradually gained greater importance in tank maintenance programs. So, in this paper, the following objectives will be covered:

1. Develop an accurate geodetic monitoring technique for monitoring the deformation of elevated circular water storage tank.

2. Analysis and processing the geodetic field observations using the suitable mathematical model and least square adjustment technique to investigate the inclination of an elevated circular water tank and the deformation of its supporting structural system (supporting columns and circular horizontal beams).

2. Description of the studied water tank and site

The studied elevated water tank is located in the residential area of Meet EL-Qureshy village at Meet Ghamer city, about 65 km south west of Mansoura city, Egypt. The studied reinforced concrete tank was designed to serve many villages, located in the local governmental area of Meet Ghamer, Dakhlia Governorate, Egypt. The water storage tank, which was constructed to deliver water to more than 55,000 person, is part of water station. The water station, as shown in Figure 1, includes the water storage tank and also six wells to supply the water to tank, and two small rooms; one for the electrical

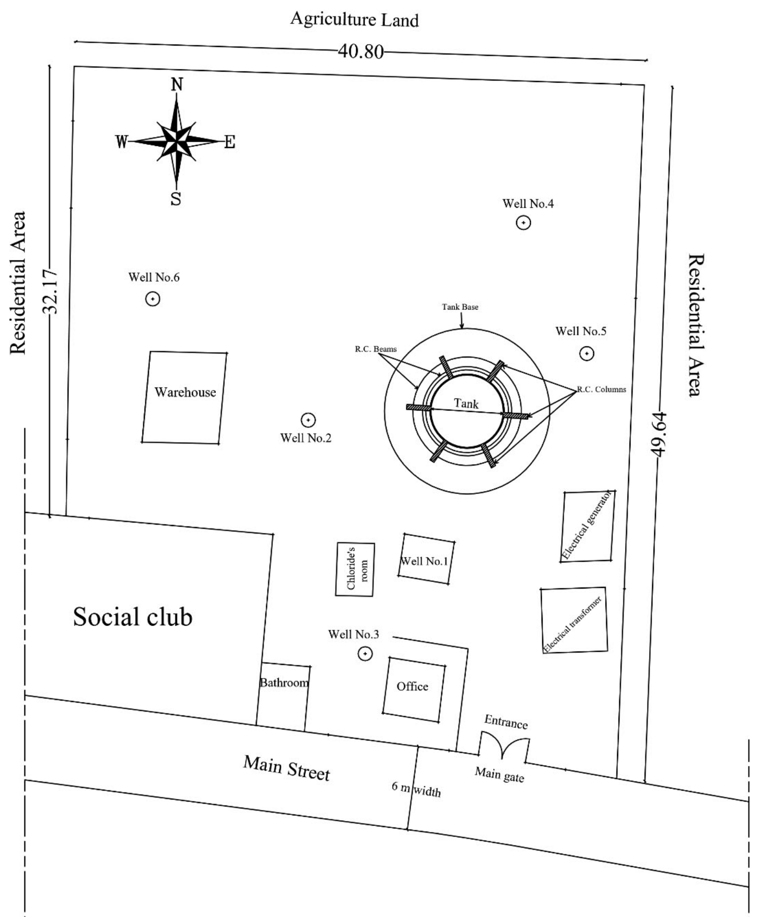

Fig. 1. Layout of water station and studied water storage tank area at Meet El-Qurashy village, Mansoura, Egypt (Sketch is not to scale)

generator and the other contains an electrical transformer beside a small office with a bathroom and room for a chloride and warehouse. This water station was established on an approximate area 1,717 m^2 and forms a common boundary from the east direction, a residential area with a common brick wall with a length of 49.65 m and from the west direction, with crowded populated area without any wall, as in the north direction, there is an agricultural land and from the south side, the entrance of water station (Figure 1).

The studied water tank was elevated and has cylindrical shape and circular cross section. Studied tank was made from reinforced concrete which was covered with bricks from outside (Figure 2). The water tank was supported on six concrete columns connected with four horizontal circular beams with various diameters at different heights and ground floor. The ground floor walls are made of bricks extending under ground

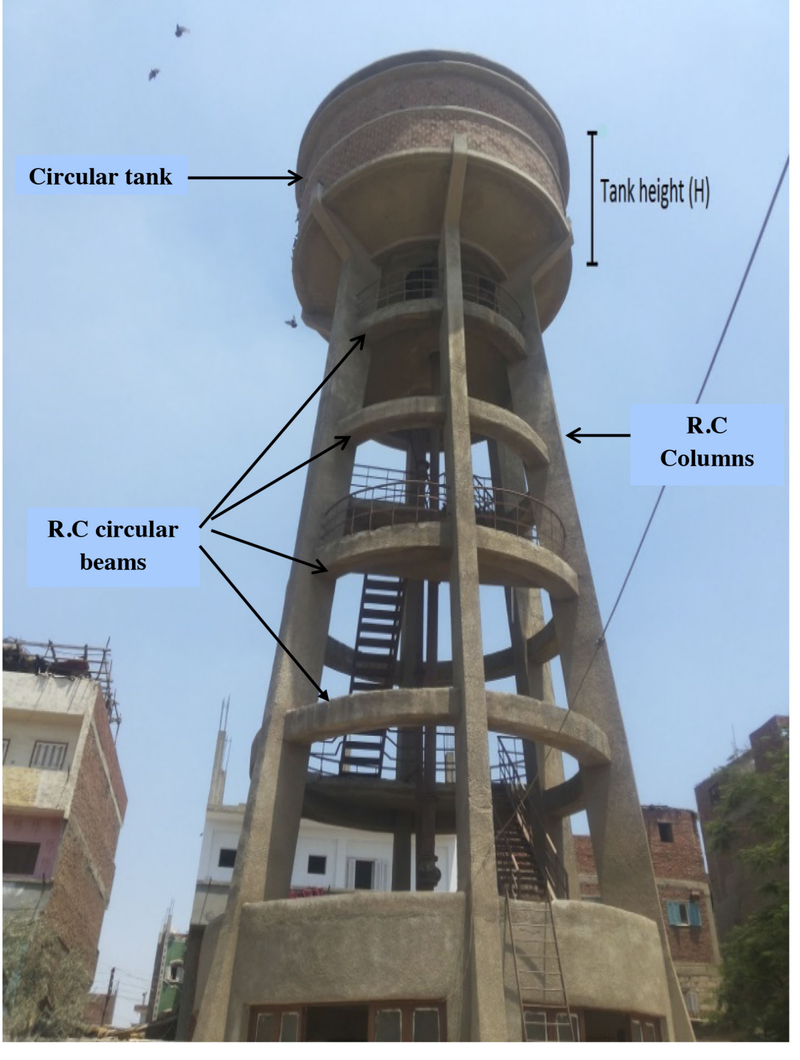

Fig. 2. The studied water storage tank at Meet El-Qurashy village, Meet Ghamer city, Egypt

level because it stores mechanical equipments which used to supply and pump water (Figure 2). From the visual inspection at the time of the first observations epochs (July 2014), it was noted that there were clear cracks in the floor of the tank, which led to cracks in the floor tiles used in the ground base of the tank and there were a clear cracks in the wall located in the eastern side of the water station, especially in the near part of the tank as shown in Figure 3. There are also small cracks in supporting columns and horizontal beams.

Fig. 3. Cracks in the water storage tank and surrounding wall (July 2014). a) Cracks near a pump; b) Cracks in the base of the tank; c) Cracks in base of the tank; d) Cracks in the base near the skeleton; e) Cracks in the concrete structure; f) Cracks in a common brick wall

After two months (The second observations epoch; September 2014), the cracks of water tank surface and base were clearer than in the first observations epoch (July 2014). New cracks have been found also in water tank slab, floor near the skeleton and near a pump, so monitoring the deformation of the water storage tank is vital and necessary.

Due to the tank age, a non-uniform settlement of tank foundation and movement of pumps and electric machines under tank's body will cause stress and strain for tanks membrane and settlement of sediments. So the studied water tank can tend to movement vertically, horizontally or both. So accurate geodetic observations and analysis methods must be carried out to detect the deformation and inclination of elevated tank and its supporting system and this is the aim of this research. Monitoring the deformation of the studied elevated tank, in the presented paper, depends mainly on comparison the deformed shape of tank axis and wall inclinations between three observations epochs. The comparison of coordinates of monitoring points of the the studied tank is old technique and difficult to apply in the case of elevated tank.

3. Study the accuracy of the used reflector-less total station observations

The effectiveness, cost, and reliability of any monitoring observations technique are the most important factors to take the decision to carry out a certain monitoring system over other. An important step in the process of monitoring the structural deformation of engineering structures is the selection of geodetic instrument and its measurements accuracy (Beshr, 2014; Vanatwerp, 1994). The used instruments must be calibrated to confirm the specified accuracy for measuring angles and distances. So some experiments using the used instrument must be done before the process of collecting deformation data.

The equipment used was reflectorless total station (Geomax) with accessories which its manufacturer quotes a standard deviation $0.5''$ to $1''$ for angle measurements, $\pm(2\text{ mm} + 2\text{ ppm})$ for EDM measurements with reflector and $\pm(3\text{ mm} + 3\text{ ppm})$ for EDM measurements without reflector.

Accuracy of reflector less total station observations depends mainly on the power of the signal, which is reflected from the reflecting surface. The intensity of the returning signal depends on the distance from total station, and reflectivity of reflecting surface which have different color and made from various materials. Increasing the distance between instrument and target, the horizontal and vertical angles increase in reflector less total station measurement errors.

The following test was carried out to determine the performance of the reflector-less total station under conditions comparable to those expected during construction of the actual detectors. The suggested test measures the accuracy of the instrument within a reference frame established with a set of highly accurate control measurements. As known, the expected vertical and horizontal movements of monitoring points for any monitored structure or building are few millimeters or centimeters. To detect point movement successfully and with confidence, it was imperative that the sensitivity of the reflector-less total station in detecting the motion of deforming targets was assessed. In this section, a subsiding object was simulated to examine the reflector-less total station aptitude at detecting the motion of several targets. For achieving that goal; the following test was carried out.

Four targets were fixed on vertical wall. The distances between marks are shown in Figure 4. The distance between targets was measured with high accurate instrument (Vernier with accuracy 0.02 mm) before the test. For all observations epochs, the specified reflector-less total station was positioned approximately 5 meters away from the wall and fixed in the same position for all observations epochs. The two marks A and B will be fixed during all observation epochs. These two fixed targets were included as a measure of control against the two deforming targets.

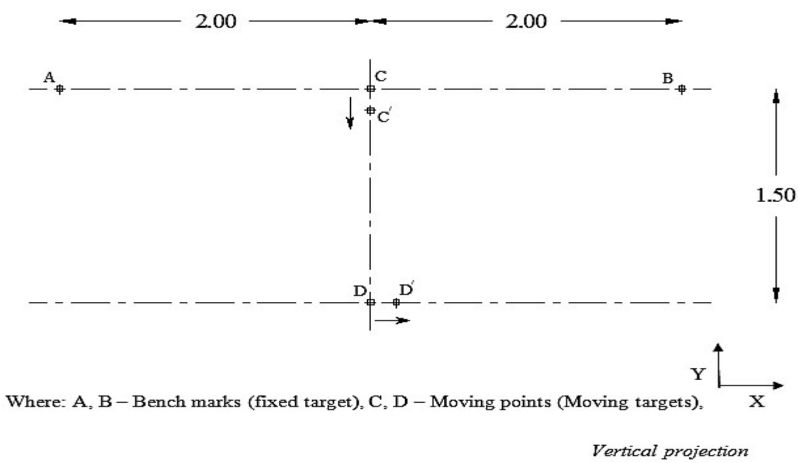

Fig. 4. The distribution of marks for testing reflector-less total station observations for deformation monitoring

The main idea of the experiment is that the two targets at points C, D (Figure 4), will be moved by known several distances in the directions X and Y by different values while the two marks A, B will be fixed without any movements. Point C will be moved in vertical direction but point D will be moved in horizontal direction (Figure 4). The vertical and horizontal displacements must be measured by high accurate instrument (Vernier with accuracy 0.02 mm). The first deformation analysis involved moving the targets by large increments approximately 100 mm, 80 mm, 50 mm, and 30 mm for point C (as vertical movement, direction Y (Figure 4) and approximately 90 mm, 75 mm, 60 mm, and 35 mm for point D (horizontal movement, direction X, Figure 4). On the other hand, the targets were moved by small increments 20 mm, 15 mm, 8 mm, 5 mm for point C and by 18 mm, 14 mm, 7 mm and 4 mm for point D (The values of increments were chosen random to simulate the real expected deformation values). for each targets movements (simulated as observations epoch), the four targets were observed by the specified reflector-less total station and the distance between targets were measured by Vernier.

The accuracy of total station with reflector-less ability can be determined by comparing the accuracy of the calculated distance between observed targets resulted from coordinates measured by total station and the calculated distance from other accurate instrument (vernier with accuracy 0.02 mm). The length of side (D), from its end coordinates (points i and j) can be calculated by:

$$D = \sqrt{(X_j - X_i)^2 + (Y_j - Y_i)^2 + (Z_j - Z_i)^2} \tag{1}$$

By differentiating equation (1) and using propagation law [4], the accuracy of the side length between two points can be determined depending on the accuracy of distance and angles and by using the following formula:

$$m_D^2 = \left(\frac{X_j - X_i}{D}\right)^2 m_{X_j}^2 + \left(\frac{X_i - X_j}{D}\right)^2 m_{X_i}^2 + \left(\frac{Y_j - Y_i}{D}\right)^2 m_{Y_j}^2 + \left(\frac{Y_i - Y_j}{D}\right)^2 m_{Y_i}^2 + \left(\frac{Z_j - Z_i}{D}\right)^2 m_{Z_j}^2 + \left(\frac{Z_i - Z_j}{D}\right)^2 m_{Z_i}^2 \tag{2}$$

where: m_X, m_Y, m_Z – the standard deviations (accuracy) of observed point coordinates (X, Y, Z).

The deformation of each point (C and D) for all epochs (distances CC′ and DD′) were calculated using formulae (1), and their accuracies were determined using eq. (2). The final results are listed in Table 1. From Table 1, it is deduced that the difference of mea-

Table 1. Comparison of deformation values resulted from reflector-less total station and vernier

Distance		Proposed movements, (mm)	Distance measured by Vernier, (mm)	Calculated distance from Total Station observations, (mm)	Difference of distances between Vernier and Total Station observations, (mm)	Relative error (Diff./Dist.)
C – C′ Vertical movement	large increments	100	100.34	101.01	−0.67	1 : 151
		80	79.86	79.22	0.64	1 : 124
		50	50.12	51.16	−1.04	1 : 49
		30	30.3	30.95	−0.65	1 : 48
	small increments	20	19.94	20.65	−0.71	1 : 29
		15	15.18	15.49	−0.31	1 : 50
		8	8.82	8.04	0.78	1 : 10
		5	4.8	5.66	−0.86	1 : 7
D – D′ Horizontal Movements	large increments	90	90.54	90.98	−0.44	1 : 207
		75	74.92	74.44	0.48	1 : 155
		60	60.18	58.81	1.37	1 : 43
		35	35.84	36.46	−0.62	1 : 59
	small increments	18	18.26	17.75	0.51	1 : 35
		14	13.88	14.28	−0.4	1 : 36
		7	8.16	7.74	0.42	1 : 18
		4	4.22	3.6	0.62	1 : 6

sured distance between the two points (simulated as deformation value) resulted from vernier and total station with the ability of reflector-less is small. Maximum difference value is 1.37 mm and minimum value 0.31 mm.

4. Monitoring observations technique of elevated water tank

The main idea behind the selected monitoring system is to create a set of measurements relative to a specified grid of monitoring points fixed on the surface of the studied elevated circular tank. These selected points distributed around the tank to ensure complete coverage of the tank surface. These points locations must be measured with high accuracy. To achieve this goal, a network created around the studied water tank. Any movements of the position of the monitoring points fixed on the monitoring studied tank (and thus its deformation) can be exposed by safeguarding the same point locations over time and by observing them at specific time (Beshr, 2012).

In order to ensure the reliability of the monitoring points of tank body and its supporting system, they were tied to accurate control points established on presumed stable ground and some distances away from the tank. The total station instrument, used for the measurement, was mounted on these control fixed points and observations taken to the monitoring points in the tank face. The suggested monitoring scheme of the studied elevated circular tank consists of a small quadrlateral geodetic network around the tank area and the selected monitoring points distributed on the outer surface covering the whole circular cross section of elevated tank at different heights and its structural supporting system. The main objective of the selected network is to provide a number of stations whose relative and absolute positions, are accurately established. The network contains six lines, eight horizontal angles and twelve vertical angles. Each line distance was measured ten times and each horizontal angle was measured on four arcs. Then, the network was solved using least square theory as a combined system of measuring distances and angles represents the strongest network for creating the horizontal control to find the coordinates of its stations and accuracy.

As though, it is important to note that the monitoring station, surrounding the tank, were first established in July 2014. The observations of the geodetic network were done only one time at the first epoch of monitoring observations (July 2014). All stations of geodetic networks were fixed in stable positions. A clear mark made of the nail was set at the center of each concrete filled pipe for point identification. The pipes were painted red for easy identification. The point number were finely marked and embedded in each concrete.

4.1. Monitoring the water storage tank body

The elevated water storage tank was divided into five horizontal cross sections at different height. Each circular cross section of tank was divided into 16 monitoring points at the outer surface every one meter high as shown in Figure 5. These points are distributed at equal distaces and located by fixing sheet prism with diameter 1 cm. These points will be observed from total station instrument.

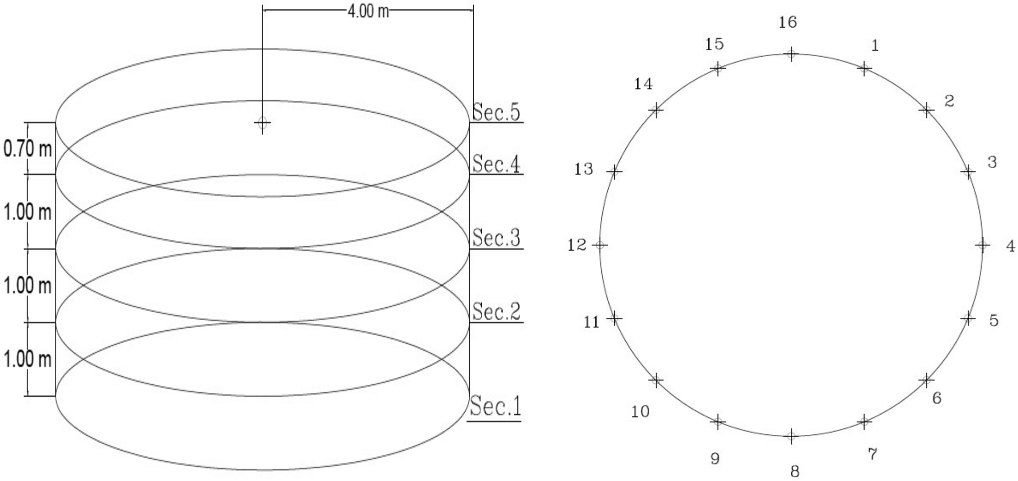

Fig. 5. Circular water tank cross sections and distribution of monitoring points on each cross section

4.2. Monitoring the reinforced concrete beams

The circular cross section of each circular R.C. beam (four beams) of the water storage tank was divided into 12 monitoring points distributed on equal distance to cover the whole perimeter of the beam cross section. Two monitoring points were fixed between every two columns at equal intervals on the outer face of the circular beam. These monitoring stations are fixed using sheet prisms and set out at equal distance at fixed height from the beam base (Figure 6).

a) b)

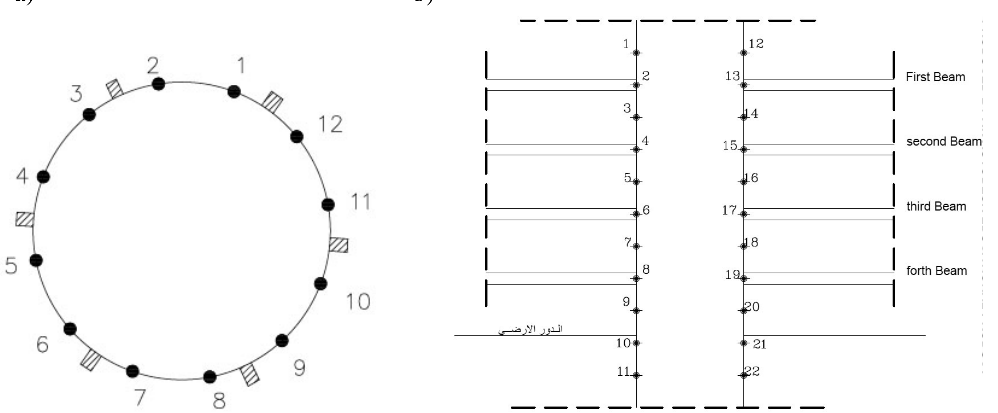

Fig. 6. Cross section of R. C. beams, columns and distribution of its monitoring points. a) Distribution of monitoring points on horizontal R.C. beam; b) Distribution of monitoring points on Supporting R.C. column

4.3. Monitoring the reinforced concrete columns

The six supporting R.C. columns, on which the upper water tank restraint on, are connected with horizontal beams with variable diameter. At each column there are 22 monitoring point divided into 11 point on each edge of the column. The 11 monitoring points on each edge of column distributed as: point at each intersection between a horizontal beam and the column, point between each two beams and two points observed at the ground floor as shown in Figure 6.

4.4. Determine the coordinates of center and the radius of circular tank cross section

There are many techniques to define the radius of circular section of cylindrical structure. Some of these techniques are done by applying geodetic methods and others by using invar and steel tapes. The simplest method to determine radius by invar or steel tape is measuring the length of water tank circular section perimeter. This length of perimeter equals $2\pi r$, and then radius r can be calculated.

The following section explains the methodology for calculating the radius r from coordinates of vertical circular tank from (n) surface points (more than three points) on the perimeter of circular section. From coordinates of several points (more than three points) on the circumference of circular section, the radius of the tank r and coordinates of center (X_C, Y_C) can be determined using the least square method as following: $(X_i - X_C)^2 + (Y_i - Y_C)^2 - r^2 = 0$.

For any monitoring point on circular section of tank surface (X_i, Y_i) must be fulfilled the equation of a circle:

$$(X_i - X_C)^2 + (Y_i - Y_C)^2 - r^2 = 0 \tag{3}$$

in which X_C, Y_C, and r are the unknown coordinates and radius respectively, of the circular cross section. When redundant points $i = 1, 2, \ldots, n$ are available, then n equations (3) may be written as follows:

$$\left.\begin{array}{l}(X_1 - X_C)^2 + (Y_1 - Y_C)^2 - r^2 = 0\\(X_2 - X_C)^2 + (Y_2 - Y_C)^2 - r^2 = 0\\\ldots\\(X_n - X_C)^2 + (Y_n - Y_C)^2 - r^2 = 0\end{array}\right\} \tag{3a}$$

These equations (Equations (3a)) can be written in the form:

$$\left.\begin{array}{l}f_1 = (X_1 - X_C)^2 + (Y_1 - Y_C)^2 - r^2 = 0\\f_2 = (X_2 - X_C)^2 + (Y_2 - Y_C)^2 - r^2 = 0\\\ldots\\f_n = (X_n - X_C)^2 + (Y_n - Y_C)^2 - r^2 = 0\end{array}\right\} \tag{3b}$$

In equations (3a), (3b), the observables and parameters are not separable, so the general (combined) method of least square must be used to solve this equation. The used general form of least square as following:

$$\underset{(n,u)}{A}\ \underset{(u,1)}{\delta} + \underset{(n,m)}{B}\ \underset{(m,1)}{V} + \underset{(n,1)}{L} = \underset{(n,1)}{0} \tag{4}$$

in which:

n – number of equations; in this case n equals the number of monitoring points;
u – number of unknowns; in this case $u = 3$; radius r and coordinates X_C, Y_C;
m – number of observations; $m = 2n$ for this case;
A – matrix of partial differentials of equations (3a) with respect to (X_C, Y_C, r);
δ – column matrix of unknowns (X_C, Y_C, r);
B – matrix of partial differentials of Equations (3a) with respect to $(X_1, Y_1, X_2, Y_2, \ldots, X_n, Y_n)$;
L – column matrix of constant terms associated with each of equations (3);
V – vector of residuals $(V_1, V_2, \ldots, V_n)$ of the observed coordinates.

For applying least square theory, approximates values of unknowns (radius r_0 and coordinates of center (X_0, Y_0) must be assumed or calculated. And approximated value of radius r^0 can be taken from documents of tanks or by using three points on the perimeter of tank. The matrices can be formed by the following methods:

$$\underset{(n,3)}{A} = \begin{bmatrix} \frac{\partial f_1}{\partial X_C} & \frac{\partial f_1}{\partial Y_C} & \frac{\partial f_1}{\partial r} \\ \frac{\partial f_2}{\partial X_C} & \frac{\partial f_2}{\partial Y_C} & \frac{\partial f_2}{\partial r} \\ \cdots & \cdots & \cdots \\ \frac{\partial f_n}{\partial X_C} & \frac{\partial f_n}{\partial Y_C} & \frac{\partial f_n}{\partial r} \end{bmatrix} = \begin{bmatrix} -2(X_1 - X_C^0) & -2(Y_1 - Y_C^0) & -2r \\ -2(X_2 - X_C^0) & -2(Y_2 - Y_C^0) & -2r \\ \cdots & \cdots & \cdots \\ -2(X_n - X_C^0) & -2(Y_n - Y_C^0) & -2r \end{bmatrix}, \tag{5}$$

$$\underset{(n,1)}{L} = \begin{bmatrix} (X_1 - X_C^0)^2 + (Y_1 - Y_C^0)^2 - (r^0)^2 \\ (X_1 - X_C^0)^2 + (Y_1 - Y_C^0)^2 - (r^0)^2 \\ \cdots \\ (X_1 - X_C^0)^2 + (Y_1 - Y_C^0)^2 - (r^0)^2 \end{bmatrix}, \tag{6}$$

$$\underset{(n,m)}{B} = \begin{bmatrix} \frac{\partial f_1}{\partial X_1} & \frac{\partial f_1}{\partial Y_1} & 0 & 0 & 0 & 0 & \ldots \\ 0 & 0 & \frac{\partial f_2}{\partial X_2} & \frac{\partial f_2}{\partial Y_2} & 0 & 0 & \ldots \\ \ldots \\ \ldots \\ \ldots \\ 0 & 0 & 0 & 0 & \ldots & \frac{\partial f_n}{\partial X_n} & \frac{\partial f_n}{\partial Y_n} \end{bmatrix}. \tag{7}$$

Then, the steps of the least square method must be applied to find the corrected values of radius, coordinates of the center and their accuracy.

4.5. The inclination of circular water tank from center coordinates and radius

The suggested technique for investigating the inclination of water tank walls from coordinate of center and radius contains the following steps:

1. The height of water storage tank was divided into five horizontal sections at every 1 m from the bottom of the tank to get the actual deformation shape of the water storage tank inclination. Each horizontal section was divided into 16 monitoring points that chosen at equal distances to cover the whole perimeter of the cross section of tank as mentioned above.
2. From the previous presented technique, the coordinates of the monitoring points at each sections were calculated and its accuracy.
3. By using the least square methods, the coordinates of center for each horizontal section (X_{C_j}, Y_{C_j}) and the value of radius r_j were calculated from the coordinates of the monitoring points.
4. The values and direction of the inclinations of axis of the water storage tank (Q_x, Q_y) were calculated by subtract the coordinates of section (j) from coordinates of first section as following:

$$\left.\begin{aligned} Q_{X_J} &= X_{C_J} - X_{C_1} \\ Q_{Y_J} &= Y_{C_J} - Y_{C_1} \end{aligned}\right\} \tag{8}$$

   where X_{C_J}, Y_{C_J} – coordinates of any section j along the tank height; X_{C_1}, Y_{C_1} – coordinates of the first section of the tank.
5. The values and direction of the tank wall inclination $(q_x,\ q_y)$ were calculated by the following formulae:

$$\left.\begin{aligned} q_{X_J} &= Q_{X_J} \pm (r_j - r_1) \\ q_{Y_J} &= Q_{Y_J} \pm (r_j - r_1) \end{aligned}\right\} \tag{9}$$

6. Drawing the actual deformation shape of the wall water tank.

4.6. The inclination of reinforce concrete circular beams

In horizontal direction each point on the perimeter of horizontal beam cross section of oil tanks must fulfill the equation of circle. By using the resulted values of radius r_{act} and coordinates of center (X_C, Y_C), the distortion of each monitoring point can be determined by using the following formula (10):

$$f_i^{\text{dist}} = \sqrt{(X_i - X_C)^2 + (Y_i - Y_C)^2} - r_{\text{act}}, \tag{10}$$

where: X_i, Y_i – coordinates of any point of 12 points, X_C, Y_C – calculated coordinates of center of circular beam, r_{act} – computed radius of circular beam.

By determining the distortion of each point on the circular cross section, the actual deformed shape of circular cross section can be determined for each horizontal beam.

In vertical direction for each beam, all 12 points have been observed at the same elevation using total station. By comparing the vertical coordinates component (Z) of each point in the beam, the values of the settlement are determined because all the points on the same beam are supposed to be on the same level and height. So the increase or decrease in height of any point (i) is calculated by:

$$\Delta Z = Z_i - Z_1\,, \tag{11}$$

where: Z_i – the elevation of any point (11 points) on the circular beam, Z_1 – the elevation of first point on the circular beam.

The inclination of reinforced concrete columns, the six columns, that the elevated tank based on, are connected with each other by horizontal reinforced concrete beams with variable diameter with the height of the columns, as shown in Figure 2. In this paper, the observations and analysis technique for determining the inclination and deformation of R.C. columns is new and different. Each edge of column was observed by 11 monitoring points fixed using sheet prism (Figure 7). Then all 22 monitoring points on the two outer edges of each column were observed from the four control points of the designed network with total station.

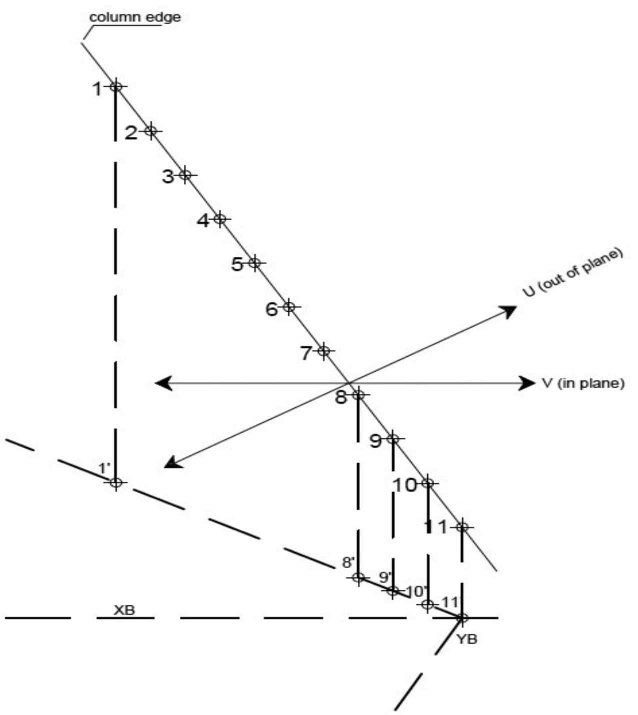

Fig. 7. The projection of the monitoring points of each column edge

When studying the vertical inclination of any structure, the value of inclination and the horizontal displacement of each corner of the building must be defined in two directions; the first direction is the perpendicular direction to the building and the other is the parallel direction of the building. For convenience, it was assumed that the perpendicular direction on the concrete column is the (U) axis (out of plane) and the parallel direction of the column is the (V) axis (in plane) (Figure 7). Therefore, it is necessary to determine the value and direction of the displacement for each monitoring point in both directions for each column.

Inclination of column out of plane, each point of the edge of the concrete column has coordinates (X, Y, and Z). To study the distortion of any observed point on the edge of the column out of plane, the following procedure must be done. The projection of all observed 11 points on the horizontal plane (only X, Y coordinates from observations) must be located at one straight line and thus projection fulfills the equation of straight line. So the equation of line, which has more than two points, using least square theory must be determined. Then, the distortion of any monitoring point (Δ_i) on column edge can be determined using the following equation (12):

$$\Delta_i = \frac{|ax + by|}{\sqrt{a^2 + b^2}} \tag{12}$$

where: a, b – the parameters of line equation $(y = ax + b)$.

Inclination of column in Plane, the projection of all observed 11 points on vertical plane (only X, Z coordinates from observations) must be located at one straight line and thus projection fulfills the equation of straight line. So, all the observed 11 monitoring points in each edge of the column must fulfill the straight line equation in vertical projection. As previously, the distortion in plane was determined using equation (12).

5. Analysis of observations and results

The applied monitoring techniques in observing the monitoring points can be summarized as mentioned above in several group of monitoring points distributed on the outer circumference of the circular water storage tank at several sectional with different elevations through its height besides many monitoring points distributed on the four horizontal reinforced concrete beams and inclination vertical columns.

The coordinates of monitored points, resulted from total station observations, were converted into meaningful engineering values by applying the suggested analysis method as following.

5.1. Calculating the radius r and center coordinates of water tank sections

With the discussed technique of calculating radius and coordinates of the circular section center, the adjusted values of radii and coordinates of center for all epochs of observations and its accuracy were calculated using MATLAB program and least square theory as presented in Table 2.

Table 2. Calculation of the tank radius and center of coordinates for water tank sections at all three observations epochs

a) First epoch July 2014

Observation Date		July 2014				
Number of monitoring points in circular cross section		16 monitoring points covering the whole perimeter of water tank cross section				
Number of cross sections observed		Five cross sections (this observations done when the tank was full of water)				
		section 1	section 2	section 3	section 4	section 5
Radius	r, m	4.0126	4.0138	4.0143	4.0133	4.0138
	σ_r, mm	2.67	2.35	2.58	1.67	1.81
coordinates of center	X, m	9.2236	9.2227	9.2274	9.2285	9.2294
	σ_x, mm	2.49	2.07	2.45	1.85	1.82
	Y, m	−8.4658	−8.4684	−8.4672	−8.4706	−8.4714
	σ_y, mm	2.15	1.97	1.48	2.13	1.82

b) Second epoch September 2014

Observation Date		July 2014				
Number of monitoring points in circular cross section		16 monitoring points covering the whole perimeter of water tank cross section				
Number of cross sections observed		Five cross sections (this observations done when the tank was full of water)				
		section 1	section 2	section 3	section 4	section 5
Radius	r, m	4.0167	4.0173	4.0161	4.0178	4.0187
	σ_r, mm	1.93	2.01	2.09	1.54	1.22
coordinates of center	X, m	9.2307	9.2291	9.2328	9.2352	9.2348
	σ_x, mm	2.02	2.18	2.15	2.88	1.89
	Y, m	−8.4598	−8.4613	−8.4622	−8.4633	−8.4649
	σ_y, mm	1.93	2.04	1.87	2.34	1.97

c) Third epoch December 2014

Observation Date		July 2014				
Number of monitoring points in circular cross section		16 monitoring points covering the whole perimeter of water tank cross section				
Number of cross sections observed		Five cross sections (this observations done when the tank was full of water)				
		section 1	section 2	section 3	section 4	section 5
Radius	r, m	4.0185	4.0201	4.0185	4.0191	4.0201
	σ_r, mm	2.36	2.15	1.92	2.88	2.47
coordinates of center	X, m	9.2308	9.2316	9.2345	9.2356	9.2364
	σ_x, mm	3.08	2.04	3.11	2.78	3.45
	Y, m	−8.4613	−8.4611	−8.4651	−8.4647	−8.4631
	σ_y, mm	1.64	1.58	2.06	2.34	1.78

d) Differences in tank radius and center coordinates for all observations epochs

Section	Differences for all observations epochs for all sections					
	For tank radius, mm		For center Coordinates, mm			
	Value, mm $(r_{\text{Sept. 2014}} - r_{\text{July 2014}})$	Value, mm $(r_{\text{Dec. 2014}} - r_{\text{July 2014}})$	Value, mm $(X_{\text{Sept. 2014}} - X_{\text{July 2014}})$	Value, mm $(X_{\text{Dec. 2014}} - X_{\text{July 2014}})$	Value, mm $(Y_{\text{Sept. 2014}} - Y_{\text{July 2014}})$	Value, mm $(Y_{\text{Dec. 2014}} - Y_{\text{July 2014}})$
Section 1	4.1	5.9	7.1	7.2	6.0	4.5
Section 2	3.5	6.3	6.4	8.9	7.1	7.3
Section 3	1.8	4.2	5.4	7.1	5.0	2.1
Section 4	4.5	5.8	6.7	7.1	7.3	5.9
Section 5	4.9	6.3	5.4	7.0	6.5	8.3

From Table 2 (a, b, c and d) the following remarks can be summarized:

1. The radius of elevated water tank cross sections is varied from 4.01265 m to 4.01435 m in July 2014 but from 4.0161 m to 4.0187 m at September 2014 and from 4.0141 m to 4.0171 m at December 2014.
2. The accuracy of radius calculation is varied from 1.67 mm to 2.67 mm in July 2014 but from 1.22 mm to 2.09 mm at September 2014 and from 1.92 mm to 2.88 mm at December 2014.
3. The center coordinates of each circular sections were also calculated for all epochs and its accuracy. The results show that the maximum standard deviation for X direction is 2.49 mm and the minimum is 1.82 mm in July 2014, the maximum standard deviation is 2.88 mm and the minimum is 1.89 mm in September 2014, the maximum standard deviation is 3.45 mm and the minimum is 2.04 mm in December 2014 but in Y direction the maximum standard deviation is 2.15 mm and the minimum is 1.48 mm in July 2014, the maximum standard deviation is 2.34 mm and the minimum is 1.87 mm in September 2014, the maximum standard deviation is 2.34 mm and the minimum is 1.58 mm in December 2014.

5.2. Calculating the radius r and center coordinates for the four reinforced concrete beams

By the same way using the least square theory and Matlab programming, the radius and center coordinates for all four circular reinforced concrete beams and its accuracy were calculated for all epochs as following in Table 3.

Table 3. The radius and center of coordinates and its accuracy for all concrete reinforced beams for all observations epochs

a) Reinforced concrete beam no. 4

Beam no. 4								
Number of monitoring points in circular cross section	12 monitoring points covering the whole perimeter of reinforced concrete beam							
First epoch of observation July 2014			Second epoch of observation September 2014			Third epoch of observation December 2014		
Radius	r, m	2.5964	Radius	r, m	2.5943	Radius	r, m	2.5919
	σr, mm	1.96		σr, mm	2.85		σr, mm	2.27
coordinates of center	X, m	9.2323	coordinates of center	X, m	9.2348	coordinates of center	X, m	9.2337
	σx, mm	1.11		σx, mm	3.45		σx, mm	2.78
	Y, m	–8.4483		Y, m	–8.4576		Y, m	–8.4613
	σy, mm	2.4		σy, mm	3.61		σy, mm	3.25

b) Reinforced concrete beam no. 3

Beam no. 3								
Number of monitoring points in circular cross section	12 monitoring points covering the whole perimeter of reinforced concrete beam							
First epoch of observation July 2014			Second epoch of observation September 2014			Third epoch of observation December 2014		
Radius	r, m	2.6648	Radius	r, m	2.6626	Radius	r, m	2.6601
	σr, mm	2.57		σr, mm	3.87		σr, mm	1.33
coordinates of center	X, m	9.2346	coordinates of center	X, m	9.2362	coordinates of center	X, m	9.2328
	σx, mm	3.24		σx, mm	1.41		σx, mm	2.18
	Y, m	–8.4257		Y, m	–8.4372		Y, m	–8.4432
	σy, mm	3.52		σy, mm	2.31		σy, mm	3.02

c) Reinforced concrete beam no. 2

Beam no. 2								
Number of monitoring points in circular cross section	12 monitoring points covering the whole perimeter of reinforced concrete beam							
First epoch of observation July 2014			Second epoch of observation September 2014			Third epoch of observation December 2014		
Radius	r, m	2.9617	Radius	r, m	2.9603	Radius	r, m	2.9629
	σr, mm	5.11		σr, mm	2.07		σr, mm	3.48
coordinates of center	X, m	9.2375	coordinates of center	X, m	9.2348	coordinates of center	X, m	9.2325
	σx, mm	1.89		σx, mm	3.15		σx, mm	2.64
	Y, m	–8.4357		Y, m	–8.4482		Y, m	–8.4491
	σy, mm	3.21		σy, mm	2.61		σy, mm	3.12

d) Reinforced concrete beam no. 1

Beam no. 1								
Number of monitoring points in circular cross section	12 monitoring points covering the whole perimeter of reinforced concrete beam							
First epoch of observation July 2014			Second epoch of observation September 2014			Third epoch of observation December 2014		
Radius	r, m	3.1975	Radius	r, m	3.1952	Radius	r, m	3.1984
	σr, mm	1.24		σr, mm	4.18		σr, mm	2.48
coordinates of center	X, m	9.2321	coordinates of center	X, m	9.2374	coordinates of center	X, m	9.2386
	σx, mm	2.49		σx, mm	2.02		σx, mm	4.38
	Y, m	–8.4254		Y, m	–8.4393		Y, m	–8.6182
	σy, mm	1.67		σy, mm	2.15		σy, mm	3.88

5.3. Inclination of circular water tank from center coordinates and radius of its cross sections

From reflector less total station observations of water storage tank and based on least square theory, the calculated radius and coordinates of tank center for each section at every 1 m through the tank height, the values of inclination in X, Y axes direction and also in walls were calculated as presented in the following Table 4 and Figure 8.

a)

b)

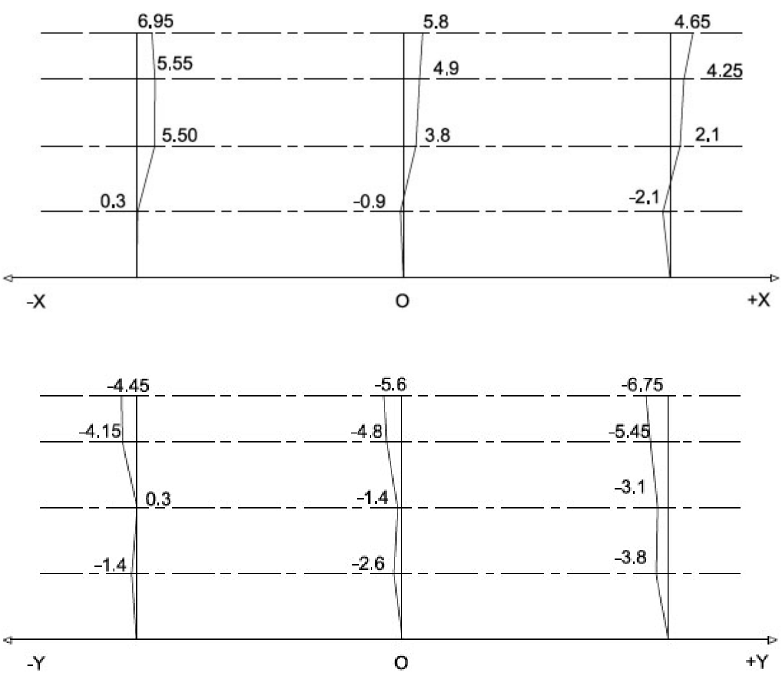

Fig. 8. Inclination in water tank axis and wall for first epoch (July 2014). a) Inclination in X direction (July 2014); b) Inclination in Y direction (July 2014)

Table 4. The values of inclination in X, Y axes direction in tank walls (July 2014)

a) First epoch July 2014

Height of section from tank bottom	Values of inclinations in x,y, mm			Values of inclination of tank walls, mm			
				qx		qy	
	Qx	Qy	Q=	X	–X	Y	–Y
0	0	0	–	0	0	0	0
1	–0.9	–2.6	2.75	–2.1	0.3	–3.8	–1.4
2	3.8	–1.4	4.05	2.1	5.50	–3.1	0.3
3	4.9	–4.8	6.86	4.25	5.55	–5.45	–4.15
3.7	5.8	–5.6	8.06	4.65	6.95	–6.75	–4.45

b) Second epoch September 2014

Height of section from tank	Values of inclinations in x,y, mm			Values of inclination of tank walls, mm			
				qx		qy	
	Qx	Qy	Q=	X	–X	Y	–Y
0	0	0	–	0	0	0	0
1	–1.6	–1.5	2.19	–2.2	–1	–2.1	–0.9
2	2.1	–2.4	3.19	2.7	1.50	–1.8	–3
3	4.5	–3.5	5.70	3.4	5.6	–4.6	–2.4
3.7	4.1	–5.1	6.54	2.1	6.1	–7.1	–3.1

c) Third epoch December 2014

Height of section from tank	Values of inclinations in x, y, mm			Values of inclination of tank walls, mm			
				qx		qy	
	Qx	Qy	Q=	X	–X	Y	–Y
0	0	0	–	0	0	0	0
1	0.8	0.2	0.82	2.2	–0.6	1.6	–1.2
2	3.7	–3.8	5.30	2.8	4.60	–4.7	–2.9
3	4.8	–3.4	5.88	3.2	6.4	–5	–1.8
3.7	5.6	–1.8	5.88	5.8	5.4	–1.6	–2

5.4. The Inclination of reinforce concrete circular beams

5.4.1. According to horizontal direction

By determining the distortion of each point on the circular reinforced concrete beam cross section,the actual deformed shape of circular cross section was determined and drawn as shown in Table 5 and Figure 9 for example.

Table 5. The distortion of all monitoring points on circular beam no. 4

Monitoring points on the beam no. 4	Distortion, mm		
	July 2014	September 2014	December 2014
1	−6.90	−6.21	−6.42
2	5.42	5.80	5.43
3	−25.17	−23.61	−27.96
4	17.42	17.51	17.69
5	31.27	23.11	27.44
6	17.58	17.76	17.51
7	35.44	37.83	33.29
8	32.42	32.03	30.47
9	33.70	36.38	41.24
10	−27.64	−42.50	−27.80
11	−40.83	−30.64	−48.32
12	−1.59	−1.51	−1.59
Maximum distortion value, mm	35.44	37.83	41.24
Minimum distortion value, mm	−40.83	−42.50	−48.32

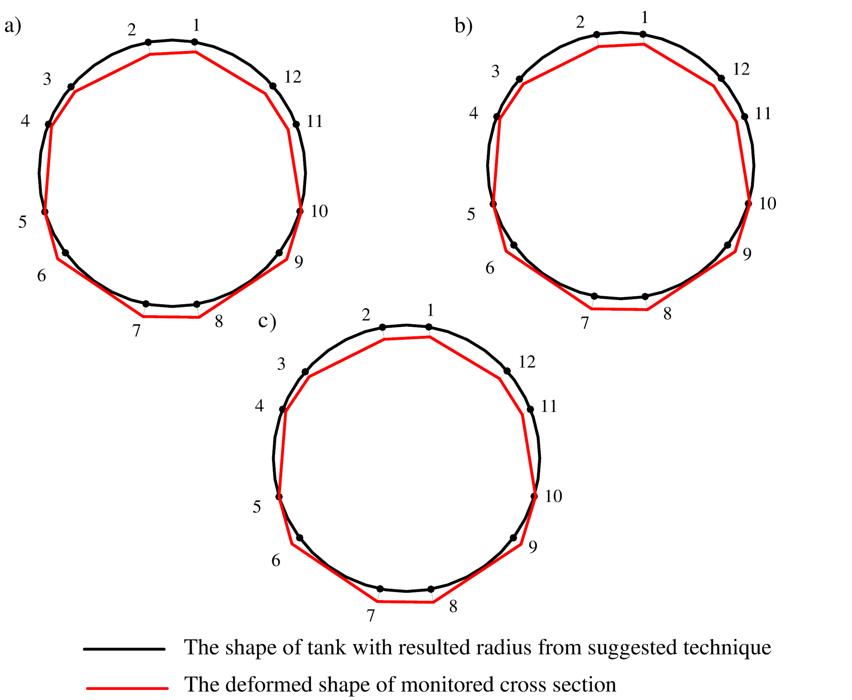

Fig. 9. The deformed shape of the monitored cross section of beam no. 1 at all epochs.
a) First epoch (July 2014); b) Second epoch (September 2014); c) Third epoch (December 2014)

5.4.2. According to vertical direction (Z)

By determining the height and drop of each point on the reinforced concrete beam circular cross section, the actual settlement of circular cross section can be determined as shown in Table 6.

Table 6. The difference between the level of each monitoring point on the beam and the first one

Monitoring points on the circular beam	Different in level value (Z coordinates) (cm)			
	Beam no. 1 Average level = 16.82 m	Beam no. 2 Average level = 20.25 m	Beam no. 3 Average level = 23.73 m	Beam no. 4 Average level = 27.49 m
2	−0.5	0.5	0.8	1.2
3	0.8	0.2	0.9	1.2
4	1.6	0.9	1.5	1.2
5	1.2	1.5	1.4	1.6
6	1.8	1.6	1.9	2.1
7	1.1	1.6	1.6	2.2
8	−1.1	−0.9	−0.2	−0.9
9	−0.2	−0.9	−1.3	−1.8
10	−0.3	−0.5	−1.2	−2.2
11	−1.2	−1.7	−2.1	−2.3
12	−1.1	−1.8	couldn't observed	couldn't observed

5.5. Inclination of concrete columns in vertical plane

The value of inclination and horizontal displacement of each edge of monitoring column was determined as presented using only X, Z coordinates from observations. The results are presented in Table 7 and Figure 10.

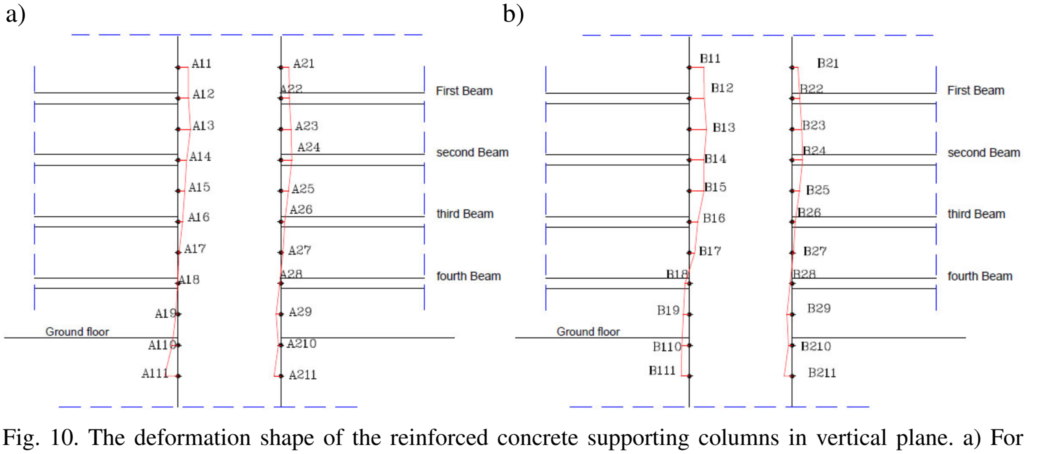

Fig. 10. The deformation shape of the reinforced concrete supporting columns in vertical plane. a) For column (A); b) For column (B)

Table 7. Distortion in each edge of reinforced concrete columns (mm) in vertical plane

		Column A		Column B		Column C	
		Edge A1	Edge A2	Edge B1	Edge B2	Edge C1	Edge C2
Distortion in each edge of R.C. columns, mm	1	12.68	9.98	17.83	7.15	15.28	6.61
	2	13.12	10.21	18.23	9.30	16.61	8.35
	3	15.04	12.49	20.10	11.76	15.92	12.37
	4	10.34	13.33	17.87	12.83	16.22	10.54
	5	8.00	9.20	10.19	8.76	11.23	8.87
	6	5.34	4.65	9.63	3.81	8.52	4.93
	7	1.08	2.51	2.54	1.45	−3.93	0.25
	8	−0.67	−1.54	−5.42	−2.54	−4.39	−2.36
	9	−2.84	−5.98	−7.32	−6.45	−9.98	−7.03
	10	−7.58	−3.13	−9.87	−4.56	−11.55	−9.28
	11	−12.66	−8.39	−10.10	−9.77	−13.56	−10.25

		Column D		Column E		Column F	
		Edge D1	Edge D2	Edge E1	Edge E2	Edge F1	Edge F2
Distortion in each edge of R.C. columns, mm	1	10.02	4.09	11.34	8.76	9.60	6.54
	2	13.57	5.85	14.19	9.14	11.65	4.77
	3	16.89	9.27	15.64	10.35	10.96	0.83
	4	17.40	6.13	9.46	7.71	9.45	−4.55
	5	10.26	7.16	3.85	4.18	5.12	−8.91
	6	7.30	4.50	−2.47	−2.27	−1.48	−9.99
	7	−4.10	−2.45	−1.90	−8.22	−2.65	−11.86
	8	−5.35	−4.43	−0.63	−7.27	−6.74	−20.72
	9	−7.25	−9.69	2.54	−4.19	−5.63	−16.76
	10	−8.11	−2.66	5.66	−3.78	−4.40	−6.56
	11	−10.67	3.65	8.16	2.93	−1.12	7.54

6. Conclusions

Depending on the previous experimental and field works, analysis and numerical results obtained, the following conclusions can be summarized:

1. The proposed surveying monitoring (observations and data analysis) technique can provide valuable data for the structural members and settlements of elevated circular tank and its supporting system, so the presented technique in monitoring

the elevated water storage tank and the reinforced concrete beams and inclination columns is active and vital technique.

2. As a results of monitoring the water storage tank, circular reinforced concrete beams and vertical inclination reinforced concrete columns at three monitoring epochs (July 2014, September 2014, December 2014), it is found that:
   a) The body of water storage tank has inclination to the east direction at average value 3.48 cm.
   b) The circular reinforced concrete beams are inclined to the east direction at average value 5.32 cm.
   c) The inclination reinforced concrete columns are leaning to the east direction at average value 4.34 cm.

   The value of inclination of the body of water storage tank is increased with the time.
3. The least squares method is very appropriate for adjusting the geodetic observations of the surface of storage tanks to get its actual deformed shape by determining the adjusted radius and center coordinates of the circular cross section.

It is recommended to find suitable structural engineering solution to the water tank deformation and its supporting system where as the values of distortion for monitoring the water tank at three different epochs are almost large.

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