Implementation of Condition Equation Model in Geodetic Observation: A Case Study of Circular Reservoir Structure

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ABSTRACT

In engineering projects involving the construction of aboveground storage tank big enough to retain and/or accommodate large quantities of petroleum products such as crude oil and condensate, mathematical reduction of obtained field data using condition equation method is always appropriate for an onward monitoring of those structures. This paper demonstrates how condition equation method can be used to adjust geodetic surveying measurements in relation to aboveground storage tank. Accuracy is in the order of $\sigma_a = 5.66e-4$ and $\sigma_b = 1.113e-3$ while σ_{smax} and σ_{smin} are 0.0522 and -0.0511 respectively. The results obtained revealed that the method can be satisfactorily implemented for aboveground circular reservoir storage tank structural modelling and monitoring for a similar scenario.

Keywords: Crude oil, Condition equation, Observation, Storage tank

1.0. Introduction

Aboveground storage tanks (ASTs), are commonly used to store large quantities of petroleum products such as crude oil or condensate. Reservoirs used by oil companies in Nigeria are basically cylindrical in shape. In most cases due to age, non-uniformity of foundation, geological conditions loading and offloading, crude oil temperature, primary and secondary settlement of sediments results in radial deformation or out of roundness (Ehigiator-Irughe *et al.*, 2012).

Aboveground storage tanks (ASTs) situated at the Forcados terminal were constructed between 1967 and 1970. Ten (10) of these crude oil storage reservoirs each spanning around 22m in height and of diameter 76.2m are presently in operation. Figures 1 and 2 show the study area and a typical example of the kind of cylindrical tank about which data collection were made.

Periodic monitoring of these tanks has been suggested by Ehigiator-Irughe and Ehigiator (2010). The structural integrity of these reservoirs has been of major concern to both local community and environmentalists especially in Niger delta area of the country. Although API 653 remain the industry standard relative to reservoir inspection and maintenance, the frequency of testing and inspection can also be affected by various State and Local regulations (Ehigiator-Irughe and Ehigiator, 2010).

The schedule of this inspection process depend on a number of factors as noted by Ehigiator-Irughe *et al.* (2011) which include the age of tank, their proximity to groundwater, the leak records, the date of the last integrity test, the construction material used, the product stored, soil condition, among others. Storage tanks (reservoirs) at Forcados farm are bounded with a bound wall measuring 250m by 150m and at a height of 12m respectively. These bound walls are intended to accommodate as well as contain any accidental spill that may result from failure of any of the reservoir as a temporary remedial means.

The objective of this paper is to determine the vertical movement or shift in the position of the tanks using a precise geodetic levelling instrument DL101C and to establish horizontal controls around the monitoring site by adopting a Total station (Sokkia SET1130R) instrument. Prior to the period of

carrying out this work, no such equipment and monitoring operation exercise of that nature has been adopted for the same purpose at the study area.

2.0. Materials and Methods

2.1. Study area

The study area (Forcados) terminal is located in Burutu Local Government Area of Delta State, Nigeria, forming boundary with the Bight of Benin by the Atlantic Ocean with coordinates (759624.59 m E, 591614.74 m N and 760885.71 m E, 590242.51 m N) in UTM Zone 31 (Figures 1 and 2).

Figure 1: Location of the study area and a typical crude oil tank

Figure 2: Screen shot of the study area.

2.2. Materials

The materials used in this work include steel tape, Total station (Sokkia SET1130R), precise geodetic level DL101C, Staff, Computer set and accessories, etc. The circular cross section of each storage tanks was divided into 16 monitoring points distributed around the tanks. These monitoring points were fixed at equal intervals on the outer face of the tanks and placed at 2m high from the tanks base. These monitoring points were established in such a way that they remained fixed throughout the period of observation.

In order to ensure the reliability of the monitoring points, they were tied to higher order control points established in some stable ground and some distances away from the tanks. The total station instrument used for the measurement was mounted on these control points and observation taken to the monitoring station in the tank face. Measurements were made using a combination of angular and linear intersection with the aid of the total station instrument to reflectors held on the studs.

3.0. Results

Figure 3 is a typical model of the levelling networks adopted for the measurement of the height/elevation of the 16 studs, while Table 1 shows the difference in elevation obtained during the exercise.

Figure 3: Levelling observation networks

Table 1: Differences in elevation before adjustment

STUDS	Diff. Elev. (m)
STUD1	$\Delta h_1=1.02036$
STUD2	$\Delta h_2=0.01157$
STUD3	$\Delta h_3=-0.00026$
STUD4	$\Delta h_4=0.00432$
STUD5	$\Delta h_5=-0.00363$
STUD6	$\Delta h_6=0.00352$
STUD7	$\Delta h_7=0.00482$
STUD8	$\Delta h_8=0.00406$
STUD9	$\Delta h_9=-0.00143$
STUD10	$\Delta h_{10}=0.00085$
STUD11	$\Delta h_{11}=-0.00238$
STUD12	$\Delta h_{12}=0.00209$
STUD13	$\Delta h_{13}=-0.00615$
STUD14	$\Delta h_{14}=-0.00290$
STUD15	$\Delta h_{15}=-0.00524$
STUD16	$\Delta h_{16}=-0.00151$
BM_1A	-1.02469

3.1. Implementation of condition equation

The method of condition equations otherwise known as the method of correlates was described by (Ayeni, 2001; Ghilani, 2006) as one which establishes a set of equations which must be satisfied by the true values of observations, given certain geometrical conditions or physical laws of nature imposed by the configuration of the problem. This is because the true values of observations exist only in the metaphysical/supernatural world. It is only practicable to set up condition equations which relate together some adjusted (that is, most probable value of observations). Using the condition equation as follows:

$$BM_1A + (V_1 + \Delta h_1) + (V_2 + \Delta h_2) + (V_3 + \Delta h_3) + (V_4 + \Delta h_4) + (V_5 + \Delta h_5) + (V_6 + \Delta h_6) + (V_7 + \Delta h_7) + (V_8 + \Delta h_8) + (V_9 + \Delta h_9) + (V_{10} + \Delta h_{10}) + (V_{11} + \Delta h_{11}) + (V_{12} + \Delta h_{12}) + (V_{13} + \Delta h_{13}) + (V_{14} + \Delta h_{14}) + (V_{15} + \Delta h_{15}) + (V_{16} + \Delta h_{16}) + (V_{17} + \Delta h_{17}) = BM_1A \quad (1)$$

Substituting the value of the BM height we have:

$$2.43418 + (V_1 + \Delta h_1) + (V_2 + \Delta h_2) + (V_3 + \Delta h_3) + (V_4 + \Delta h_4) + (V_5 + \Delta h_5) + (V_6 + \Delta h_6) + (V_7 + \Delta h_7) + (V_8 + \Delta h_8) + (V_9 + \Delta h_9) + (V_{10} + \Delta h_{10}) + (V_{11} + \Delta h_{11}) + (V_{12} + \Delta h_{12}) + (V_{13} + \Delta h_{13}) + (V_{14} + \Delta h_{14}) + (V_{15} + \Delta h_{15}) + (V_{16} + \Delta h_{16}) + (V_{17} + \Delta h_{17}) = 2.43418. \quad (2)$$

By substituting the values of (Δh_i) we have the following:

$$\begin{aligned} V_1 + V_2 + V_3 + V_4 + V_5 + V_6 + V_7 + V_8 + V_9 + V_{10} + V_{11} + V_{12} + V_{13} + V_{14} + V_{15} + V_{16} + V_{17} = \\ 2.43418 - 2.43418 - 1.02036 - 0.01157 + 0.00026 - 0.00432 + \\ 0.00363 - 0.00352 - 0.00482 - 0.00406 + 0.00143 - 0.00085 + \\ 0.00238 - 0.00209 + 0.00615 + 0.0029 + 0.00524 + 0.00151 + 1.02469 \\ V_1 + V_2 + V_3 + V_4 + V_5 + V_6 + V_7 + V_8 + V_9 + V_{10} + V_{11} + V_{12} + V_{13} + V_{14} + V_{15} + V_{16} + V_{17} \\ = 0.00340 \end{aligned} \quad (3)$$

Note; V_i = Residual, Δh_i = Difference in elevation, BM_1A = Reference elevation.

The general form of condition equation is given as:

$$[B] \times [V] = [\Delta] \quad (4)$$

where $[B]$ is the design Matrix and is given as:

$$B = [111111111111111111], \text{ and } V = \text{the vector of Residuals; } [\Delta] = 0.00340$$

$$V = \begin{bmatrix} V1 \\ V2 \\ V3 \\ V4 \\ V5 \\ V6 \\ V7 \\ V8 \\ V9 \\ V10 \\ V11 \\ V12 \\ V13 \\ V14 \\ V16 \\ V17 \end{bmatrix}$$

The solution of the normal equation:

$$M = [B] \times [B]^T \quad (5)$$

$$M = [1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1] \times \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} = [17]$$

The solution of Lagrange Multiplier [K]:

$$\left. \begin{aligned} K &= [M]^{-1} \times \Delta \\ K &= [17]^{-1} \times [0.00340] \\ K &= [2.0 \times 10^{-04}] \end{aligned} \right\} \quad (6)$$

The residuals:

$$[V_i] = [B]^T \times [K] \quad (7)$$

$$[V_i] = \begin{bmatrix} 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \end{bmatrix} \times 10^4$$

The variance:

$$\sigma^2 = \left\{ \frac{[V_i]^T \times [V]}{r} \right\} \quad (8)$$

Numbers of unknowns = 16, numbers of observations = 18.

Therefore, redundancy (degree of freedom) = 2,

$$\sigma^2 = \left\{ \frac{[V_i]^T \times [V]}{2} \right\}$$

$$\left\{ \begin{bmatrix} 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \end{bmatrix}^T \times \begin{bmatrix} 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \\ 2.00 \end{bmatrix} \times 10^4 \right\} \times 10^4$$

2

$$\sigma^2 = \left[3.4 \times 10^{-7} \right]$$

Table 2 shows the adjusted elevations for the sixteen tanks (studs) using condition equation model method respectively.

Table 2: The adjusted elevations

Station No	Staff Set - Up	Staff Readings		Prov. Rise (+)	Corr.	Final Rise (+)	Final Elev. (m)
		Back	Fore	Prov. Fall (-)	mm	Final Fall (-)	Datum-----
	BM_1A	1.49409					2.43418
P1	STUD1	0.46644	0.47373	1.02036	0.00020	1.02056	3.45474
P2	STUD2	0.55877	0.45487	0.01157	0.00020	0.01177	3.46651
P3	STUD3	0.56466	0.55903	-0.00026	0.00020	-0.00006	3.46645
P4	STUD4	0.54440	0.56034	0.00432	0.00020	0.00452	3.47103
P5	STUD5	0.59716	0.54803	-0.00363	0.00020	-0.00343	3.46760
P6	STUD6	0.37493	0.59364	0.00352	0.00020	0.00372	3.47475
P7	STUD7	0.62290	0.37011	0.00482	0.00020	0.00502	3.47605
P8	STUD8	0.63397	0.61884	0.00406	0.00020	0.00426	3.47529
P9	STUD9	0.32043	0.63540	-0.00143	0.00020	-0.00123	3.46980
P10	STUD10	0.37890	0.31958	0.00085	0.00020	0.00105	3.47208
P11	STUD11	0.45879	0.38128	-0.00238	0.00020	-0.00218	3.46885
P12	STUD12	0.49455	0.45670	0.00209	0.00020	0.00229	3.47332
P13	STUD13	0.26153	0.50070	-0.00615	0.00020	-0.00595	3.46508
P14	STUD14	0.39577	0.26443	-0.00290	0.00020	-0.00270	3.46833
P15	STUD15	0.81228	0.40101	-0.00524	0.00020	-0.00504	3.46599
P16	STUD16	0.50664	0.81379	-0.00151	0.00020	-0.00131	3.46468
	BM_1A		1.53133	-1.02469	0.00020	-1.02449	2.43418

Table 3 is showing the studs and their adjusted difference in elevation in relation to the bench (reference) station used for the observation.

Table 3: Studs and their respective adjusted difference in elevation

STUDS	Adjusted Diff. Elev. (m)
STUD1	$\Delta h_1 = 1.02056$
STUD2	$\Delta h_2 = 0.01177$
STUD3	$\Delta h_3 = -0.00006$
STUD4	$\Delta h_4 = 0.00452$
STUD5	$\Delta h_5 = -0.00343$
STUD6	$\Delta h_6 = 0.00372$
STUD7	$\Delta h_7 = 0.00502$
STUD8	$\Delta h_8 = 0.00426$
STUD9	$\Delta h_9 = -0.00123$
STUD10	$\Delta h_{10} = 0.00105$
STUD11	$\Delta h_{11} = -0.00218$
STUD12	$\Delta h_{12} = 0.00229$
STUD13	$\Delta h_{13} = -0.00595$
STUD14	$\Delta h_{14} = -0.00270$
STUD15	$\Delta h_{15} = -0.00504$
STUD16	$\Delta h_{16} = -0.00131$
BM_1A	-1.02469

$$\begin{aligned}
 \text{Adjusted_Eve.} &= \begin{matrix} STUD 1 \\ STUD 2 \\ STUD 3 \\ STUD 4 \\ STUD 5 \\ STUD 6 \\ STUD 7 \\ STUD 8 \\ STUD 9 \\ STUD 10 \\ STUD 11 \\ STUD 12 \\ STUD 13 \\ STUD 14 \\ STUD 15 \\ STUD 16 \end{matrix} = \begin{bmatrix} 2.43418 + \Delta h1 \\ 3.45474 + \Delta h2 \\ 3.46651 + \Delta h3 \\ 3.46645 + \Delta h4 \\ 3.47103 + \Delta h5 \\ 3.46760 + \Delta h6 \\ 3.47475 + \Delta h7 \\ 3.47605 + \Delta h8 \\ 3.47529 + \Delta h9 \\ 3.46980 + \Delta h10 \\ 3.47208 + \Delta h11 \\ 3.46885 + \Delta h12 \\ 3.47332 + \Delta h13 \\ 3.46508 + \Delta h14 \\ 3.46833 + \Delta h15 \\ 3.46599 + \Delta h16 \\ 3.46468 + BM - 1.4 \end{bmatrix} \begin{bmatrix} 2.43418 + 1.02056 \\ 3.45474 + 0.01177 \\ 3.46651 - 0.00006 \\ 3.46645 + 0.00452 \\ 3.47103 - 0.00343 \\ 3.46760 + 0.00372 \\ 3.47475 + 0.00502 \\ 3.47605 + 0.00426 \\ 3.47529 - 0.00123 \\ 3.47208 + 0.00105 \\ 3.47208 - 0.00218 \\ 3.46885 + 0.00229 \\ 3.47332 - 0.00595 \\ 3.46508 - 0.00270 \\ 3.46599 - 0.00504 \\ 3.46599 - 0.00131 \\ 3.46468 - 1.02449 \end{bmatrix} \\
 &= \begin{bmatrix} 3.45474 \\ 3.46651 \\ 3.46645 \\ 3.47103 \\ 3.46760 \\ 3.47475 \\ 3.47605 \\ 3.47529 \\ 3.46980 \\ 3.47208 \\ 3.46885 \\ 3.47332 \\ 3.46508 \\ 3.46833 \\ 3.46599 \\ 3.46468 \\ 2.43418 \end{bmatrix} \\
 \text{Adjusted_Elevation}(m) &= \begin{bmatrix} 3.45474 \\ 3.46651 \\ 3.46645 \\ 3.47103 \\ 3.46760 \\ 3.47475 \\ 3.47605 \\ 3.47529 \\ 3.46980 \\ 3.47208 \\ 3.46885 \\ 3.47332 \\ 3.46508 \\ 3.46833 \\ 3.46599 \\ 3.46468 \\ 2.43418 \end{bmatrix}
 \end{aligned}$$

The Variance Covariance (V-C) matrix is given as:

$$\left. \begin{aligned} C_L &= \sigma^2 [1 - T] W^{-1} \\ T &= W^{-1} B^T M^{-1} B \\ C_L &= \sigma^2 [1 - B^T M^{-1} B] \end{aligned} \right\} \quad (9)$$

Since $W^{-1} = 1$

first 3 columns on both V-C Matrix and the Jacobian Matrix, will be used for post adjustment V-C matrix as presented below;

$$C_H = J_H C_L J_H^T s \quad (11)$$

Where:

$$J_H = \frac{\partial G(L)}{\partial L} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & -1 & 0 & 0 & 0 \\ 1 & 1 & -1 & 1 & 0 & 0 \\ 1 & 1 & -1 & 1 & -1 & 0 \\ 1 & 1 & -1 & 1 & -1 & 1 \end{bmatrix}$$

$$C_L = \begin{bmatrix} 3.20 & 3.20 & 3.20 & 3.20 & 3.20 & 3.20 \\ 3.20 & 3.20 & 3.20 & 3.20 & 3.20 & 3.20 \\ 3.20 & 3.20 & 3.20 & 3.20 & 3.20 & 3.20 \\ 3.20 & 3.20 & 3.20 & 3.20 & 3.20 & 3.20 \\ 3.20 & 3.20 & 3.20 & 3.20 & 3.20 & 3.20 \\ 3.20 & 3.20 & 3.20 & 3.20 & 3.20 & 3.20 \end{bmatrix} \times 10^{-7}$$

The V-C matrix C_H of the adjusted benchmarks H is then computed thus;

$$C_H = \begin{bmatrix} 0.0320 & 0.0640 & 0.0320 & 0.0640 & 0.0320 & 0.0640 \\ 0.0640 & 0.1280 & 0.0640 & 0.1280 & 0.0640 & 0.1280 \\ 0.0320 & 0.0640 & 0.0320 & 0.0640 & 0.0320 & 0.0640 \\ 0.0640 & 0.1280 & 0.0640 & 0.1280 & 0.0640 & 0.1280 \\ 0.0320 & 0.0640 & 0.0320 & 0.0640 & 0.0320 & 0.0640 \\ 0.0640 & 0.1280 & 0.0640 & 0.1280 & 0.0640 & 0.1280 \end{bmatrix} \times 10^{-5}$$

$$accuracy : (\sigma_a) = \sqrt{0.032 \times 10^{-5}} = 5.66 \times 10^{-4}$$

$$accuracy : (\sigma_b) = \sqrt{0.128 \times 10^{-5}} = 1.113 \times 10^{-3}$$

and

$$(\sigma_{ab}) = 0.0640 \times 10^{-5}$$

$$2t = \tan^{-1} \left\{ \frac{2\sigma_{ab}}{\sigma_b^2 - \sigma_a^2} \right\} \quad (12)$$

$$2t = \tan^{-1} \left\{ \frac{2 \times 0.0640}{0.1280 - 0.0320} \right\} \times 10^{-5}$$

$$2t = 1.333$$

$$2t = 53^{\circ}07'46''$$

$$t = 26^{\circ}33'53''$$

The problem now is to develop a new covariance matrix from existing Q matrix which removes correlation between the unknowns; and the determination of semi-major axis and the semi-minor axis of error ellipse, from which we have:

$$\left. \begin{aligned} C_{zz} &= R \times C_{LL} \times R^T \\ R &= \begin{bmatrix} \sin(t) & \cos(t) \\ -\cos(t) & \sin(t) \end{bmatrix} \\ C_{zz} &= \begin{bmatrix} \sin(t) & \cos(t) \\ -\cos(t) & \sin(t) \end{bmatrix} \begin{bmatrix} \sigma_a^2 & \sigma_{ab} \\ \sigma_{ba} & \sigma_b^2 \end{bmatrix} \begin{bmatrix} \sin(t) & -\cos(t) \\ \cos(t) & \sin(t) \end{bmatrix} \end{aligned} \right\} \quad (12a, 12b, 12c)$$

$$C_{LL} = \begin{bmatrix} \sigma_a^2 & \sigma_{ab} \\ \sigma_{ba} & \sigma_b^2 \end{bmatrix} = \begin{bmatrix} 0.0320 & 0.0640 \\ 0.0640 & 0.1280 \end{bmatrix} 10^{-5}$$

$$\sigma^2 = \left[3.4 \times 10^{-7} \right]; \sigma = 5.83 \times 10^{-4}$$

$$\left. \begin{aligned} \sigma_{s\max}^2 &= \sigma \left(\sin^2(t)\sigma_a + 2\cos(t)\sin(t)\sigma_{ab} + \cos^2(t)\sigma_b \right) = 5.85 \times 10^{-7} \\ \sigma_{s\min}^2 &= \sigma \left(\cos^2(t)\sigma_a - 2\cos(t)\sin(t)\sigma_{ab} + \sin^2(t)\sigma_b \right) = 3.93 \times 10^{-7} \end{aligned} \right\} \quad (13a, 13b)$$

The semi-major axis of error ellipse was obtained as $\sigma_{s\max} = 7.65 \times 10^{-4}$, while the semi-minor axis was obtained as $\sigma_{s\min} = 6.27 \times 10^{-4}$

4.0. Discussion

The method of condition equation adopted in this work showed a promising result and can be adopted in similar scenarios. Accuracy obtained is in the order of $\sigma_a = 5.66 \times 10^{-4}$ and $\sigma_b = 1.113 \times 10^{-3}$ before $\sigma_{ab} = 0.0640 \times 10^{-5}$ for the adjusted bench marks heights while the error ellipse are $\sigma_{s\max} = 7.65 \times 10^{-4}$ and $\sigma_{s\min} = 6.27 \times 10^{-4}$ respectively, representing insignificant error and acceptable values. However, the values were obtained after the application of new covariance matrix from existing Q matrix which removes correlation between the unknowns. The determination of semi-major axis and the semi-minor axis error ellipse gave $\sigma = 5.83 \times 10^{-4}$ which is a way to ascertain the magnitude of error at a station.

5.0. Conclusion

In this work, attempt has been made to implement condition equation method in circular reservoir structures (above ground tanks) relying on geodata acquired and further preparation for onward analysis of the shift experienced by these structures at the Forcados crude oil tank farm. Since each condition equation must satisfy certain geometric conditions or physical laws. Suggestion is to adopt the process in similar scenarios across the country where such structures exist in order to buttress on the safety of lives of the inhabitants living close to their location.

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