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Evaluation of Inclinometer Errors and Their Impacts on Data Accuracy (Case Study: Karkheh Dam & Galabar Dam)

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ABSTRACT

Inclinometers are usually utilized to attain the horizontal deformation profile of embankment dams. Moreover, they can be used to measure the velocity and displacement direction of different points of the dam. Measuring with inclinometer probes seems to be easy. However, in most cases the attained displacement profile does not adapt with the real dam displacement and needs to be corrected. Hence, the errors detection and correction methods are of great importance. In this paper, using two case studies (Karkheh dam & Galabar dam) the errors of inclinometer data, mostly systematic errors, are investigated. Also, the method of detection and their correction procedure are presented. Finally, the sources of errors and the procedures to minimize or removal errors are discussed.

RÉSUMÉ

Les inclinomètres sont généralement utilisés pour atteindre le profil de déformation horizontale des barrages en remblai. De plus, ils peuvent être utilisés pour mesurer la vitesse et la direction de déplacement de différents points du barrage. Mesurer avec des sondes d'inclinomètre semble être facile. Cependant, dans la plupart des cas, le profil de déplacement obtenu ne s'adapte pas au déplacement réel du barrage et doit être corrigé. Par conséquent, les méthodes de détection et de correction des erreurs revêtent une grande importance. Dans cet article, utilisant deux études de cas (barrage de Karkheh et barrage de Galabar), les erreurs des données de l'inclinomètre, principalement des erreurs systématiques, sont examinées. La méthode de détection et la procédure de correction sont également présentées. Enfin, les sources d'erreurs et les procédures pour minimiser ou supprimer les erreurs sont discutées.

1 INTRODUCTION

The vertical inclinometers are one of the most important instruments that are installed in earth dams in order to monitor dam's horizontal displacement magnitudes and directions.

Complexities of inclinometers, both in data processing and extraction of the correct results rather than other monitoring instruments, has made the inclinometers different from other instruments.

The issue that is currently posed between earth dam's designers and instrumental experts and able to challenge them is to extract the correct results from the inclinometers data.

In this paper, with a case study of installed inclinometers in the Karkheh and Galabar earth dams, the errors in inclinometer's data were investigated. By introducing their correction method, their influence on the accuracy of the inclinometer's data was determined, and further, appropriate solutions to identify, eliminate or less of such errors are provided.

2 DESCRIPTION OF INCLINOMETERS

The first inclinometer was built in 1952 by Stanley D. Wilson. The inclinometers that are used currently follow the same standard operating principles of Stan Wilson's inclinometer. Actually, the only changes are improved data accuracy and how to manage data due to recent advances (Mirghasemi and Ghasemi 2017).

The mode of inclinometer's operation is that by passing a inclinometer's probe inside the guide casing, the relative horizontal displacement profile of the guide casing is obtained (Dunnicliff and Green 1993).

The inclinometers probes have the force-balanced sensing elements which can detect the change in tilt (from absolute vertical) of the probe that houses the sensors. The probe contains two biaxial servo-accelerometers and is fitted with two sets of spring-pressured wheels to guide the probe along the longitudinal grooves of the guide casing (see Figure1).

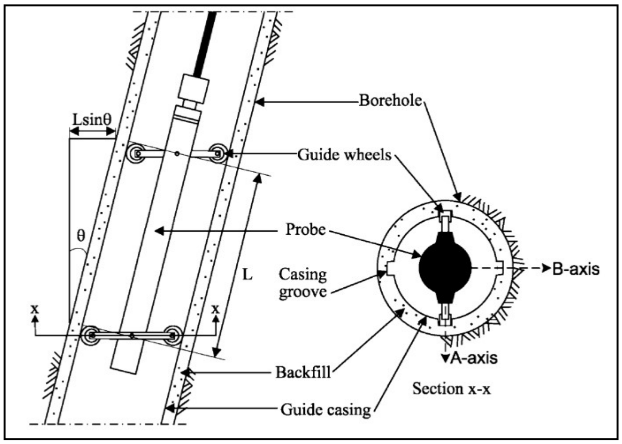

Figure 1. Inclinometer probe within guide casing (Stark and Choi 2008)

One accelerometer is set parallel to the tracking wheels (A+ or A0 direction) of the probe and other is set perpendicular to the wheels (B+ or B0 direction). The accelerometer reads in both positive and negative directions according to which direction the accelerometers are positioned. The positive direction of the A accelerometer is aligned to the upper most wheel of the wheel assembly of the probe. The positive direction of the B accelerometer is positioned 90E clockwise to the A position (Machan and Bennett 2008).

The inclinometer probe is inserted into the guide casing and lowered to the lowest depth to be measured. Incremental readings are made at each 2 ft or 50 cm interval as the probe is pulled up. The sensors record the amount of tilt of the inclinometer probe in the guide casing (Dunnicliff and Green 1993).

The shape of the casing is determined by taking successive 2 ft or 50 cm increment measurements (L), which is the distance between the wheels, providing a continuous profile of the casing. In special applications, measurements could be made at smaller intervals in order to better define the shape of the guide casing and to more accurately define the depth of ground movement (Machan and Bennett 2008).

The inclinometers measurement principle has shown in Figure 2.

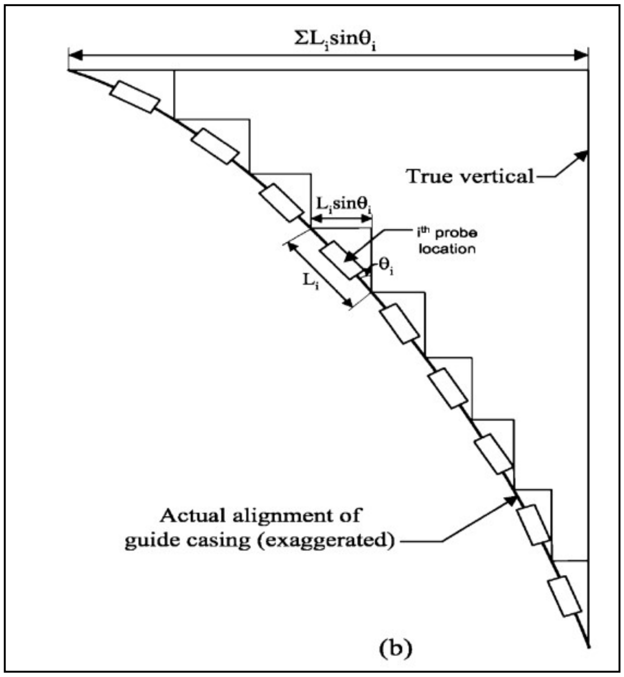

Figure 2. Inclinometer measurement principle (Stark and Choi 2008)

The measurement operation is repeated by rotating the probe 180° and reinserting it into the same groove set of the guide casing. The numerical difference between corresponding readings at each depth is determined.

3 INTRODUCING ERRORS

To understand the nature of errors in inclinometers data and how to correct them, one should be familiar with how to obtain the various profiles that extracted from the inclinometers data. Since the authors have extensively studied how the data is processed (Mirghasemi and Ghasemi 2017), in this article the focus is mostly on the errors and how to correct them. In fact, errors in the inclinometers data are divided into two categories as described below.

3.1 Random Error

Random error refers to errors that do not have specific causes and are not likely to remain constant in a readout set. Also, its effects are less than systematic errors. Random error has a positive relationship with the square root of the number of readout intervals. The random error value measurements for each reading is reported to be approximately 0.16 mm (Mikkelsen 2003). Therefore, for a 30 m guide casing the random error can be estimated 1.24mm (see Eq. 1).

$$RE=0.16\sqrt{N} \qquad [1]$$

Where RE is random error and N is number of reading intervals.

Because of 0.5 m readings interval which is as long as probe length, the number of reading intervals in 30 m guide casing is 60.

3.2 Systematic Error

Systematic error refers to error that nature is known. Basically, this type of error by recognizing performance in inclinometer data can be corrected if necessary. Systematic error is directly related to the number of readings intervals.

Generally, the average systematic error in each read is almost 0.11 mm (Mikkelsen 2003). So, for a 30 m guide casing, the systematic error is 6.6 mm (see Eq. 2).

$$SE=0.11\times N \qquad [2]$$

Where SE is systematic error and N is number of reading intervals.

The total error is the sum of random error and systematic error. As a result, there may normally be 7.8 mm as an error in 30 m guide casing (Mikkelsen 2003).

4 ERRORS DETECTION AND CORRECTION

Systematic errors which have been identified so far, include (1) Bias shift error; (2) Sensitivity drift error; (3) Sensor alignment shift error and (4) Depth positioning error.

4.1 Bias Shift Error

The bias error is one of the most common systematic errors. This error occurs because of shifting calibration value (b) during measurement operation. The bias error is usually very small. If this error detected, then the correction is very easy. One way of identifying it is to detect the movement through the depths in which there is no movement (stable zone). If the relative displacement profile is inclined linearly, then the displacement at the stable zone (where there is no displacement in actual condition) would definitely indicate bias error (Mirghasemi and Ghasemi 2017). To correct it, the bias shift correction per each interval (bs) should be determined by Eq. 3.

$$bs=\frac{BSE}{N} \qquad [3]$$

Where BSE is total bias shift error over zone considered and N is number of reading intervals.

Therefore, by deducting the value of bs from each reading data, this error is corrected.

An example of a bias error that is related to casing No.I3-1 in Karkheh dam is given in the Figure 3. As shown in this figure, the relative displacement profile of 2008/02/09 readings set has bias error characteristics.

More investigations in this casing showed that the stable zone is at least 16.5 m from bottom of casing. Considering the stable zone shown in Figure 3, it can be seen that the total displacement due to bias error at the top of stable zone is -5.115 mm (BSE). In here, stable zone has 33 readings interval (N).

Therefore, by using Eq. 3, the bias error in this readings set is about -0.155 mm (bs) per interval. All of the bias errors of readings sets in Figure 3 are determined by the stable zone and then corrected according to above method. Figure 4 shows the same output after error correction. By analyzing the other inclinometers data from Karkheh dam, the bias shifting error was found around 0.11 mm per readings or intervals on average.

In general, the bias error occurs during measurement operation. In addition, investigations have shown that the effect of operator's skill is so significant in error occurrence and its magnitude. This error is often found in the inclinometer data, but in order to reduce it, the operator must apply the correct measurement methods to inclinometer probe (Mirghasemi and Ghasemi 2017).

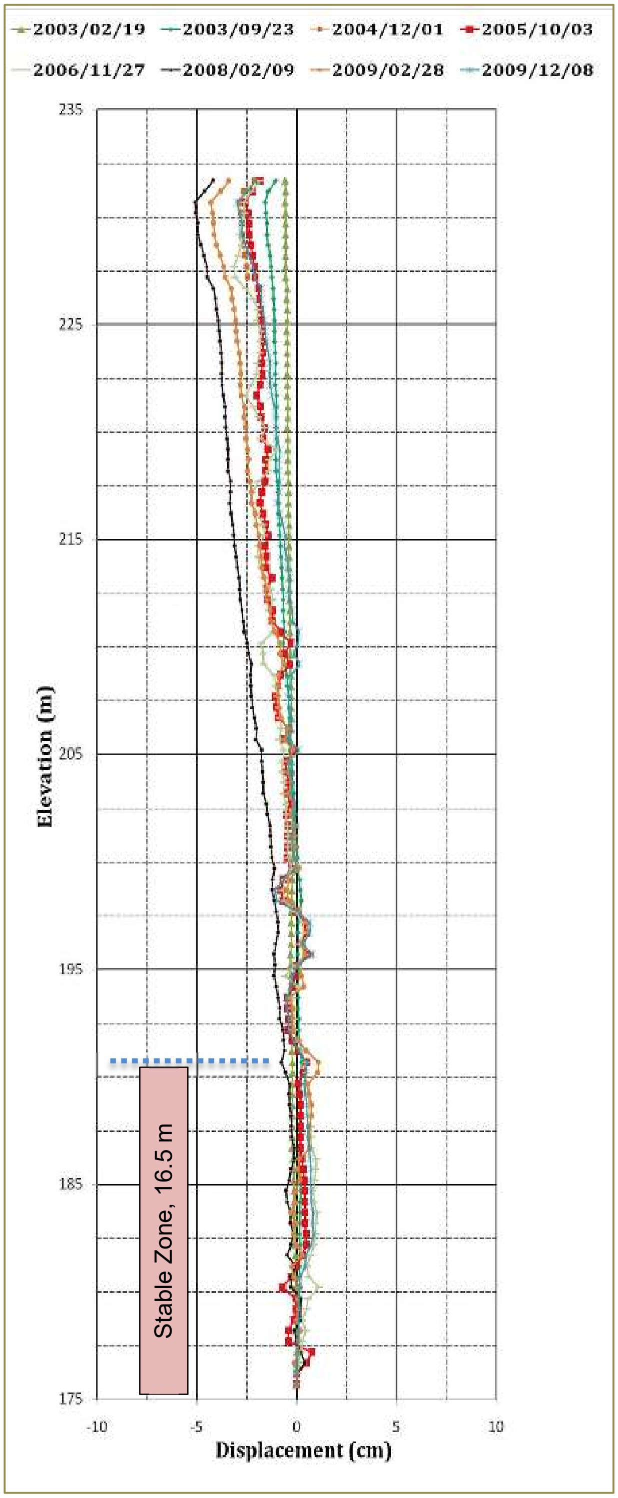

Figure 3. Original relative displacement profiles, A-Axis, casing No.I3-1 in Karkheh dam

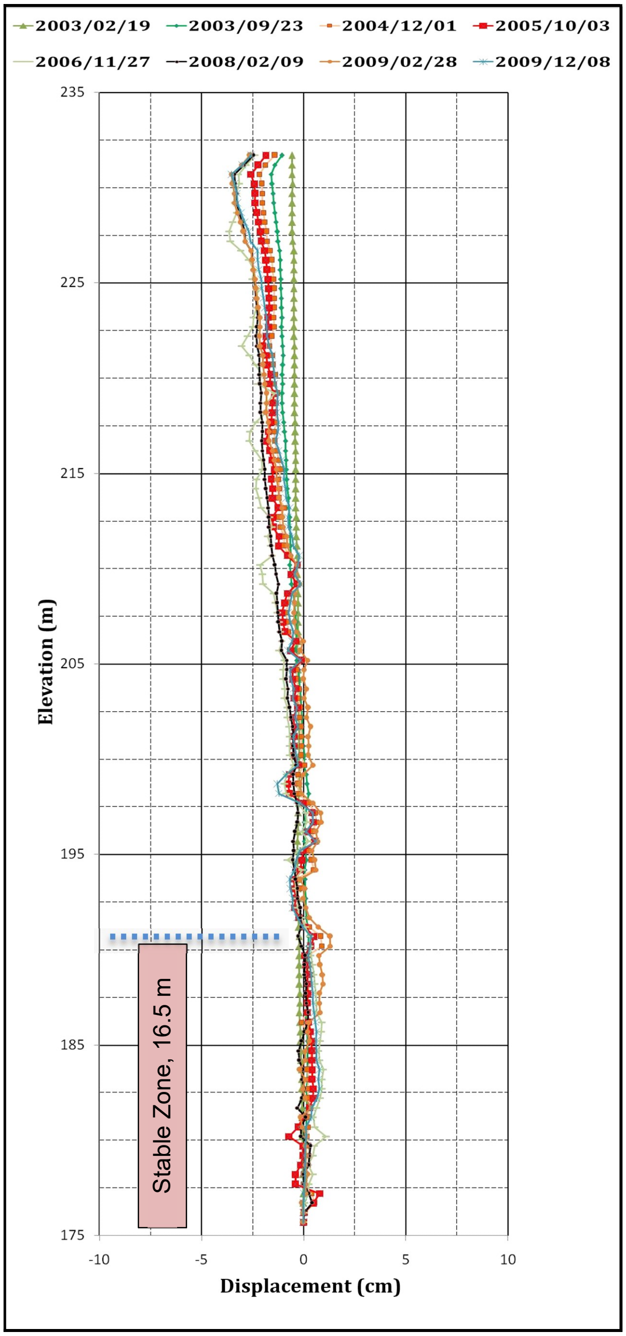

Figure 4. Relative displacement profiles after bias error correction, A-Axis, casing No.I3-1 in Karkheh dam

4.2 Sensitivity Drift Error

The sensitivity drift error occurs due to drift in the operational amplifier. In other words, this error is a kind of diminishing sensitivity and happens rarely. To correct it, should be determined sensitivity drift value of inclinometer probe. After determining the amount of sensitivity drift value, the amount of displacement that is deducted from the data can be added to the data. This value can be determined only by factory calibration. Hence, it is recommended that the inclinometer probe must be sent to the manufacturer at least once a year for re-calibration. According to past experience has seen a few cases where the error is 1 to 2 percent, varying between data sets, but remaining relatively constant for each data set (Mikkelsen 2003).

4.3 Sensor Alignment Shift Error

As the name implies, this error is caused by the rotation of the sensor. The identification of this error is through the incremental deviation profile and the relative displacement profile. If the range of displacement is large enough (more than 1 m), it can be assumed that there is a rotational error in the readout (Mikkelsen 2003). Figure 5 shows an overview of how the rotation error affects the displacement profile.

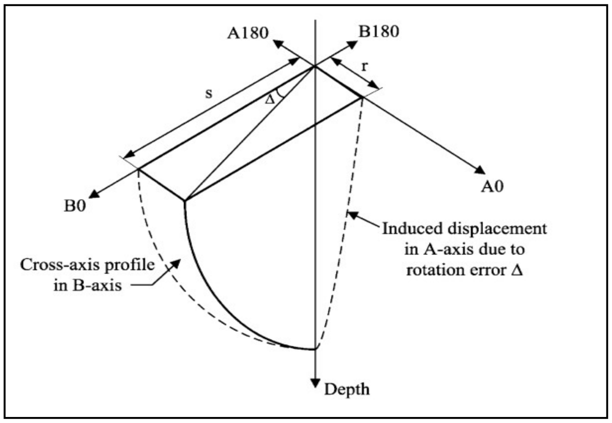

Figure 5. Rotation error overview (Stark and Choi 2008)

One of the ways to correct this error is to use Eq. 4.

$$\tan\Delta = \frac{r}{s} \qquad [4]$$

Where Δ is the rotation angle, r is the induced displacement in A- axis and s is the induced displacement in B- axis.
Eq. 4 is applicable when r and s are completely clear on displacement profiles. However, when r and s are unknown, Δ must be calculated using a relative deviation profile with trial and error (Mirghasemi and Ghasemi 2017). Fig. 6 shows the original relative displacement profile of the reading sets in casing No.I5-1 in Galabar dam. In this figure the displacement range is up to 3 m.

Fig. 7 shows the effect of the rotational error on the original incremental deviation profile of the readings set. In this figure, it is seen that the trend of 5/13/2007 readings set profile (the red color) is different from the trend of other readings sets profile. On the other hand, the trend of the incremental deviation profile of 5/13/2007 readings set has a horizontal shift rather than general trend.

To correct the rotational error in this case the resultant displacement profile of 5/13/2007 readings set should be used. Thus, by back analyzing of resultant displacement profile with a hypothetical Δ, the rotated relative displacement profile is obtained again in A_0 and B_0 directions by Eq. 5 and Eq. 6 (Figures not illustrated).

$$A' = A\cos\Delta - B\sin\Delta \qquad [5]$$

$$B' = A\sin\Delta - B\cos\Delta \qquad [6]$$

Where A′ is the rotated relative displacement A-Axis data, B′ is the rotated relative displacement B-Axis data, A is the original relative displacement A-Axis data and B is the original relative displacement B-Axis data.

Then, by reversing the relationships between deviation data and relative displacement data, the incremental deviation profiles are re-drawn. After this step, we determine Δ that lead to remove shifting from the incremental deviation profiles by try and error. In this case when Δ = 44.9°, shifting is eliminated and the result of this correction have shown in Fig. 8 and Fig. 9.

As it can be seen the actual displacement in casing No.I5-1 in Galabar dam does not exceed 5 cm. The distortion in the Fig. 9 graphs is related to the depth error, which will be discussed in the next section. However, the depth error correction for A-Axis readings sets of I5-1 in Galabar dam has done and the result has shown in Fig. 10.

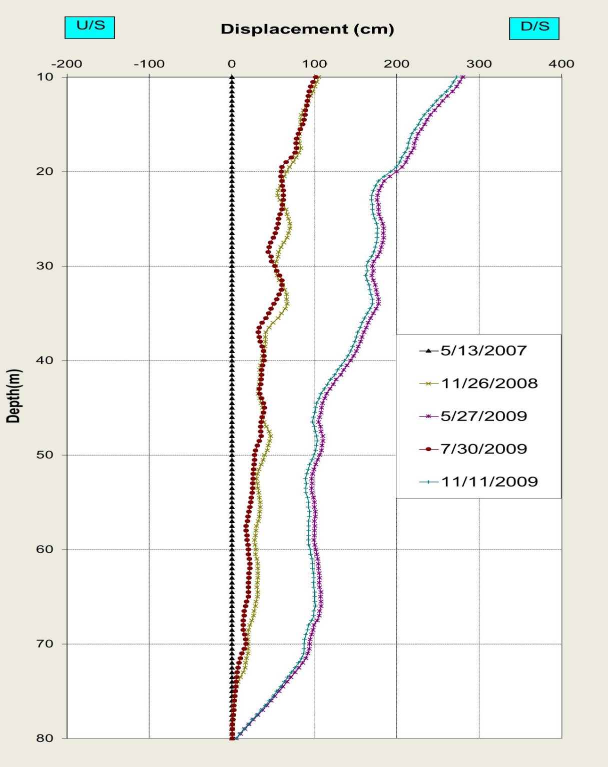

Figure 6. Original relative displacement profiles, A-Axis, casing No.I5-1 in Galabar dam

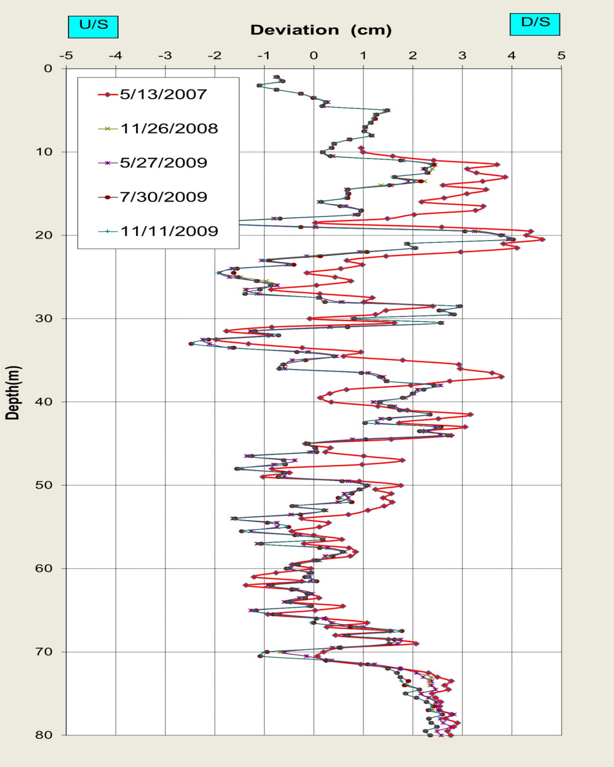

Figure 7. Original incremental deviation profiles, A-Axis, casing No.I5-1 in Galabar dam

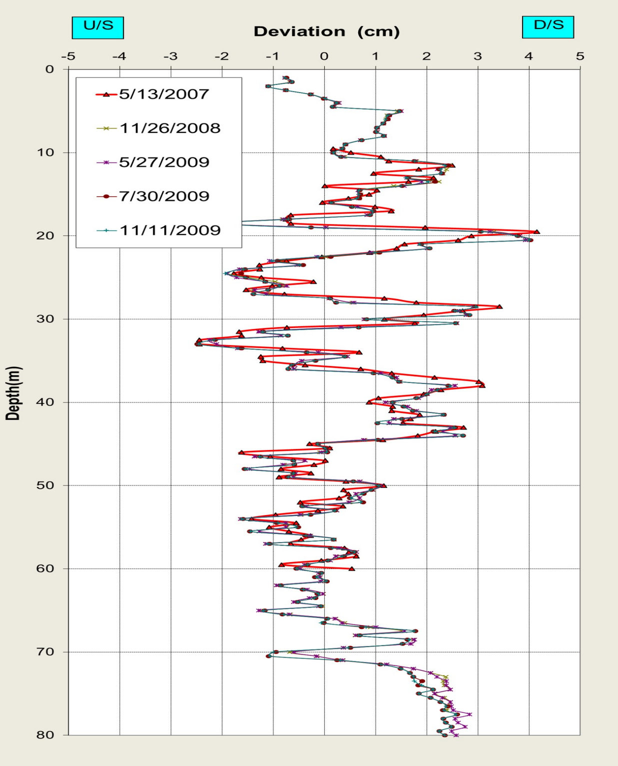

Figure 8. Incremental deviation profiles after rotation correction, A-Axis, casing No.I5-1 in Galabar dam

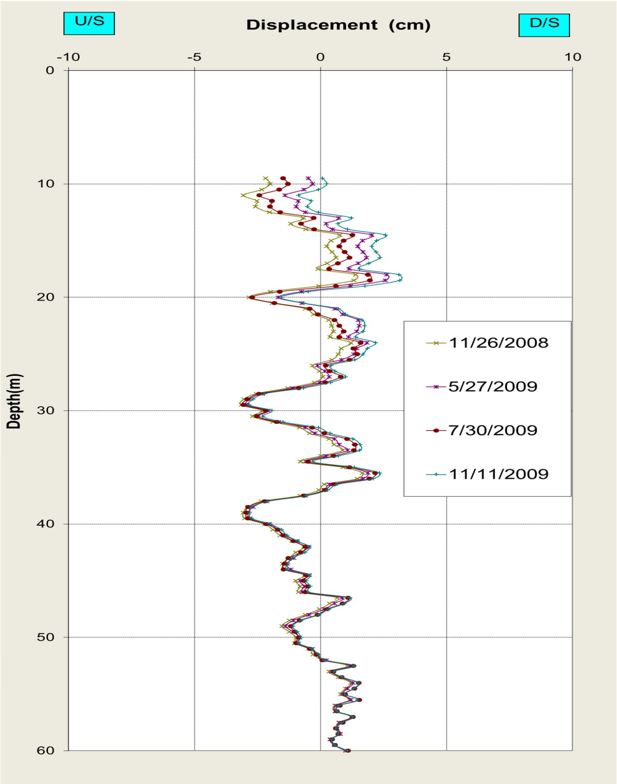

Figure 9. Relative displacement profiles after rotation correction, A-Axis, casing No.I5-1 in Galabar dam

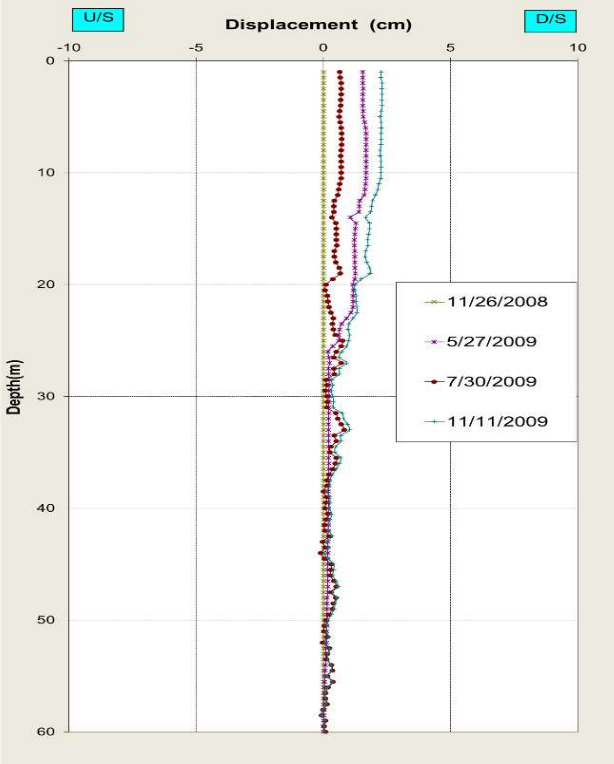

Figure 10. Relative displacement profiles after depth error correction, A-Axis, casing No.I5-1 in Galabar dam

4.4 Depth Positioning Error

The three major factors are involved in causing this error. These factors include: (1) probe position shifting vertically between readings set; (2) having settlement; (3) changing in cable length. If there is a depth error in the inclinometers data, then the relative displacement profile will be distorted (see Fig. 11).

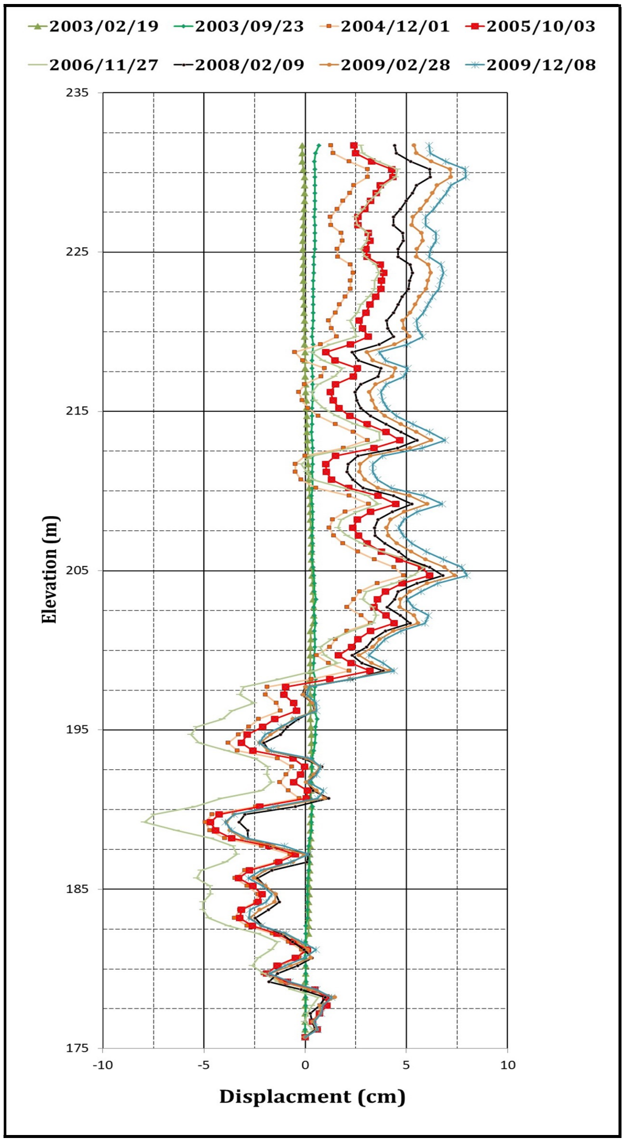

Figure 11. Original relative displacement profiles, B-Axis, casing No.I3-1 in Karkheh dam

To correct depth error, incremental deviation profile is utilized, which is done by shifting data in incremental deviation profile vertically to correct position. If in case generating data for profile adjusting is needed, incremental deviation data should be generated by interpolation or extrapolation rather than correct incremental deviation profile. Considering past experience this error cannot be completely eliminate, yet, it can be only diminished.

Figures 11 and 12 demonstrate the original relative displacement profiles and incremental deviation profiles of B-axis readings which belong to casing No.I3-1 in Karkheh dam have shown respectively. The distortion in both profiles is due to the embankment settlement which it is one of depth error's factors.

According to abovementioned depth error correction method, the depth error in B-axis readings of casing No.I3-1 has been corrected and the corrected profiles have shown in Figures 13 and 14 respectively.

By comparing the relative displacement profiles between Fig. 11 and Fig. 14, we can perceive the effect of the depth error is less than 19mm. Studies show that correcting this error is very time consuming and in some cases impossible.

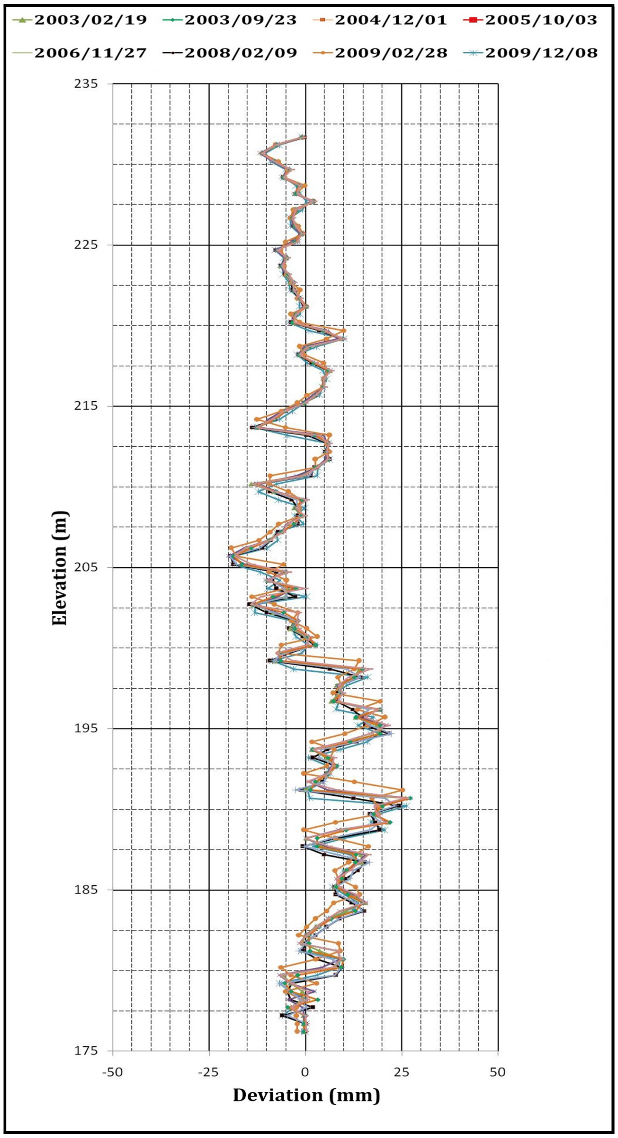

Figure 12. Original incremental deviation profiles, B-Axis, casing No.I3-1 in Karkheh dam

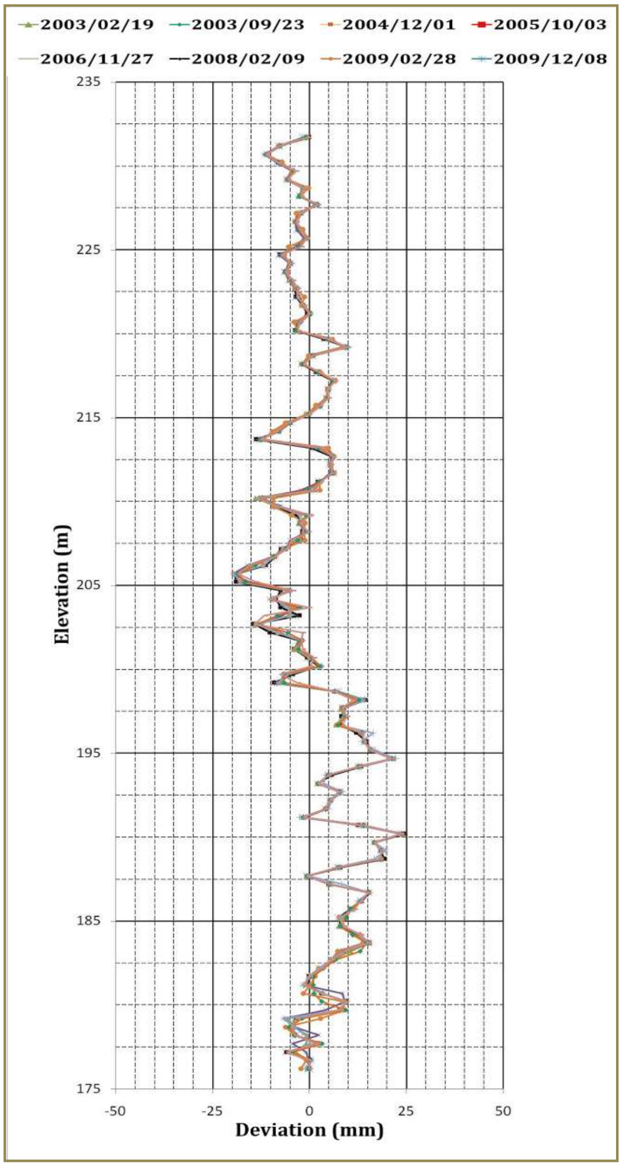

Figure 13. Incremental deviation profiles after depth error correction, B-Axis, casing No.I3-1 in Karkheh dam

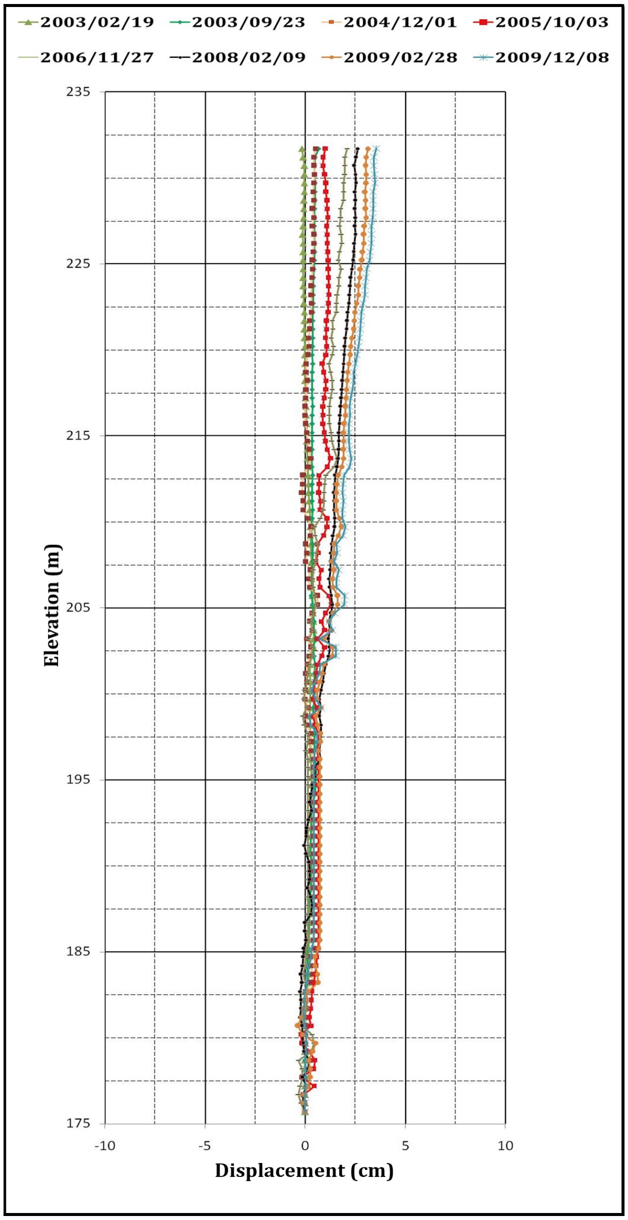

Figure 14. Relative displacement profiles after depth error correction, B-Axis, casing No.I3-1 in Karkheh dam

5 CONCLUSION

The results extracted from this study can be summarized as follows:

The Bias error is one of the most common systematic errors that may exist in the inclinometers data. The evaluation of the inclinometer measurements data in the Karkheh Dam showed 0.11 mm bias error per readings averagely. To prevent or minimize this error, the operator must apply the correct method of measuring and appropriate probe handling procedure. It also needs to have a stable zone that should be considered when guide casings were designing and installing.

When the sensor alignment shift error occurs, significant displacements arise in the displacement profile. The Galabar dam's inclinometers data studying shows that when this error occurs, the displacement range is even up to 3 m.

The depth error is another common systemic error in the earth dams, which exists in the inclinometers data. Correcting this error in most cases should be done manually. This issue causes the correction to be time consuming and impossible. The Karkheh dam's inclinometers data studying shows that in a 100 m inclinometer guide casing, the effect of this error is less than 20 mm.

6 ACKNOWLEDGEMENT

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