Prediction of Dam Deformation Using Kalman Filter Technique

Raphael EHIGIATOR-IRUGHE, Jacob Odeh EHIOROBO and Mabel O. EHIGIATOR, NIGERIA.

Key Words: Kalman Filter, Deformation Monitoring, Kinematic Model, GPS, State Vector

SUMMARY

In Dam Deformation Monitoring repeated observation are carried out to determine either relative or absolute Deformation of the structure. In some cases factors beyond the control of the observer or instrument may make it impossible to obtain reliable results from continuous measurement. In that case other methods of estimation or prediction of the deformation at some future data may be adopted.

Time dependent monitoring of the structures can be carried out using Kinematic and dynamic models in the analysis of the deformation. Such Time and position dependent measurements can be processed using the Kalman Filter equation. The Kalman filter equation estimates measurement parameters using time update and measurement update equations.

The time update equation predicts the results for the next epoch measurement while the measurement update equation serves as a corrector for the next step of the deformation measurement epoch. In this study Kalman filtering technique was used in predicting current estimates of Dam deformation using two previous GPS measurements carried out in 2007 and 2008 respectively. The Kalman filter equation was then used to compute the velocity and acceleration of the Dam object.

From these results coordinates changes were estimated for 2009, 2010, 2011 and 2012 respectively. Analysis of the results for 2008 show a strong correlation between the measurement updates and the predicted coordinates. It can therefore be concluded that the Kalman filtering equation can be used to fill in gaps in deformation measurement where continuous monitoring may not be possible within some epoch.
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1. INTRODUCTION

In analyzing deformation of structures such as Dams various deformation models have been developed. These models consist of static, Kinematic and dynamic models (Acar et al 2000 Lihua 2008). In dynamic deformation models, the deformation as the output signals are a function of time and varying loads.

In the static deformation model, the deformation is function of varying loads only. In Kinematic model, the deformation is described as a function of time. When GPS is used in the measurement of the movement of the Dam from surface measurement, there are no acting forces considered in term of a Kinematic model.

The Kinematic/ dynamic parameters of deformation in a structure such as a Dam can be estimated by use of the Kalma Filter equation. The Kalman filter was designed to estimate the linear dynamic system (Kalma 1960, Kalman and Buocy 1961, cankut and sahin 2000).

Welch and Bishop (2006) defined the Kalman filter as a set of mathematical equations that provides an efficient computational means to estimate the state of a process in a way that minimizes the mean of the square error.

Maybeck (1979) described the Kalma filter as simply an optimal recursive data processing algorithm that blend all available information including measurement outputs, prior knowledge about the system and measuring sensors to estimate the state variables in such a manner that the error is statistically minimized.

Kaplan (1993) on the other hand defined the Kalma filter as a recursive algorithm that provides optimum estimates of user position, velocity and Time based on noise statistics and current measurements. The filter contains a dynamic model of the GPS receiver platform motion and output a set of user receiver Position, Velocity and Time (PVT) state estimates as well as associated error variances.

The filter estimates a process state at some time and then obtain a feedback in the form of noisy measurements. Thus, the equation for the Kalman filter consist of time update equation that projects forward (in time) the current state and error covariances estimates to get a priori estimate for the next time step and the measurement update equation which incorporates new measurements into the priori estimate to get an improved posteriori estimate.
The Kalman filter is very convenient in estimating the state vector of a deformation object (Ince and sahin 2000, Grewal and Andrew 1993). The elements of the state vector in the Kalman filter include position (X Y Z) in the object or deformable body and variation of the position.

The Kalman filter supports estimation of past, present and future states of a dynamic system. Used without stochastic parameters, the kalman filter is regarded as a recursive solution of the Gauss original least-squares problems. In the filtering however, the number or observation can be less than the number of unknowns.

2. DESCRIPTION OF STUDY AREA

The Ikpoba River Dam is located in Benin City, the capital of Edo State of Nigeria. The Dam together with its head works is located about 6km from the city centre (see fig 1).

Fig 1: Location Map of Ikpoba Dam in Benin City, Nigeria.

The Ikpoba Dam water supply scheme was designed to supply 160,000,000 litres of water per day at ultimate capacity. This account for about 60% of the water supply requirement for Benin City with a population of about 1.5 million.
The network for Deformation monitoring consist of eleven control points both around the upstream and downstream are of the dam and Nine monitoring points established on the Dam crest Fig 2.

Fig 2: Layout of Control of Reference Point within the Dam area.

3. METHODOLOGY
3.1 DATA COLLECTION

The data collection of the first GPS campaign took place during the period 11\textsuperscript{th} and 12\textsuperscript{th} of August 2007 and the second campaign on the 17\textsuperscript{th} and 18\textsuperscript{th} of August 2008. Four units of Leica 500 GPS systems and their corresponding accessories including a 12 volt battery were deployed.

The GPS data were collected in static mode and post processed using Leica Ski-PRO software.

3.2 KINEMATIC DEFORMATION MODEL: THE KALMAN FILTER

The Kalman Filter was designed to be a recursive solution to the discrete data linear filtering problem (Kalman 1960, Welch and Bishop 2006). When GPS is used in the determination of Deformation in a dam from surface measurements, there are no acting forces available and the deformation can be considered in terms of a Kinematic model.
Kinematic deformation model determines displacements, velocity and acceleration and is time dependent. A time dependent 3-D Kinematic model that contain position, velocity and acceleration can be expressed using the equation (Acar et al 2000)

$$\begin{align*}
X_j^{k+1} &= X_j^{(k)} + (t_{k+1} - t_k) V_{xj} + \frac{1}{2} (t_{k+1} - t_k)^2 a_{xj} \\
Y_j^{k+1} &= Y_j^{(k)} + (t_{k+1} - t_k) V_{yj} + \frac{1}{2} (t_{k+1} - t_k)^2 a_{yj} \\
Z_j^{k+1} &= Z_j^{(k)} + (t_{k+1} - t_k) V_{zj} + \frac{1}{2} (t_{k+1} - t_k)^2 a_{zj}
\end{align*}$$

In eq (1),

- $X_j^{k+1}, Y_j^{k+1}, Z_j^{k+1}$ - Coordinates of points j at time $(t_{k+1})$ period
- $X_j^{(k)}, Y_j^{(k)}, Z_j^{(k)}$ - Coordinates of points j at time $(t_k)$ period
- $V_{xj}, V_{yj}, V_{zj}$ - Velocities X, Y, Z of points j at time t
- $a_{xj}, a_{yj}, a_{zj}$ - Acceleration of XYZ of points j at time t
- $k=1, 2$ ---- $i$ (i = measurement period number)
- $j=1, 2$ ---- $n$ (= number of points in the network)

In this study, kalman Filtering techniques was used for the prediction of present state vector using state vector parameters of known movement vector at period $t_k$ and measurements carried out at period $t_{k+1}$. The state vector of movement parameter consist of position movements i.e XYZ movements along with acceleration variable.

The movements and acceleration parameters are the first and second derivative of position with respect to the time i.e

$$\frac{\partial (XYZ)}{\partial t} \quad \text{and} \quad \frac{\partial^2 (XYZ)}{\partial t^2}$$

The matrix form of the movement model used for the prediction of movement parameters by the Kalman filter technique in respect of 3D GPS network is given as
\[
Y_{k+1} = \begin{bmatrix}
X \\
Y \\
Z \\
V_x \\
V_y \\
V_z \\
a_x \\
a_y \\
a_z
\end{bmatrix} = \begin{bmatrix}
1 & 1(t_{k+1} - t_k) & \frac{1(t_{k+1} - t_k)^2}{2} \\
0 & 1 & 1(t_{k+1} - t_k) \\
0 & 0 & 1
\end{bmatrix}_{k+1,k}
\begin{bmatrix}
X \\
Y \\
Z \\
V_x \\
V_y \\
V_z \\
a_x \\
a_y \\
a_z
\end{bmatrix}
\]

---

\[Y_{k+1} = T_{k+1,k} Y_k \quad (3)\]

Where

\[Y_{k+1}\] - state vector at time \( t_{k+1} \)

\[Y_k\] - state vector at time \( t_k \)

\[T_{k+1,k}\] - Transition matrix from time \( t_k \) to \( t_{k+1} \)

\[
T_{k+1,k} = \begin{bmatrix}
1 & 1(t_{k+1} - t_k) & \frac{1(t_{k+1} - t_k)^2}{2} \\
0 & 1 & 1(t_{k+1} - t_k) \\
0 & 0 & 1
\end{bmatrix}_{k+1,k}
\]

\( \mathbf{1} \) - unit matrix

Equation (3) is the prediction equation of Kalman filtering. If we include the system matrix \( S \) and random noise vector \( \propto \) between period \( t_{k+1} \) and \( t_k \) then the basic Kalman equation becomes

\[Y_{k+1} = T_{k+1,k} Y_k + S_{k+1,k} + \propto_k \quad (5)\]

The random noise vector \( \propto \) cannot be measured

We can assume its value = 0

In the dynamic model of the filter three states which will be nine variables that are three linear degrees of freedom (position vector) the corresponding velocity variables (velocity vector) and the corresponding acceleration variables (acceleration vector) are considered Iyiade (2000). The state model can be written as
\[ X_k = x, v_x, a_x, y, v_y, a_y, z, v_z, a_z \]  \hspace{1cm} (6)

Using the kalman filter, the velocity and acceleration of the movement of the structure can be written as follows:

for velocity,

\[
\begin{align*}
V_{xj}^{k+1} &= \frac{x_{j}^{k+1} - x_{j}^{k}}{\Delta t_{k+1,k}} \\
V_{yj}^{k+1} &= \frac{y_{j}^{k+1} - y_{j}^{k}}{\Delta t_{k+1,k}} \\
V_{zj}^{k+1} &= \frac{z_{j}^{k+1} - z_{j}^{k}}{\Delta t_{k+1,k}}
\end{align*}
\]  \hspace{1cm} (7)

For the acceleration components

\[
\begin{align*}
a_{xj}^{k+1} &= \frac{x_{j}^{k+1} - x_{j}^{k}}{\Delta t_{k+1,k}^2} \\
a_{yj}^{k+1} &= \frac{y_{j}^{k+1} - y_{j}^{k}}{\Delta t_{k+1,k}^2} \\
a_{zj}^{k+1} &= \frac{z_{j}^{k+1} - z_{j}^{k}}{\Delta t_{k+1,k}^2}
\end{align*}
\]  \hspace{1cm} (8)

### 3.3 NUMERICAL APPLICATION OF THE KALMAN FILTER

In the first instance, static deformation analysis was carried out by evaluating the post adjustment coordinates together with the variance - covariance matrix. Next kinematic deformation analysis based on Kalman filter technique was implemented on a MATALB using
The solution obtained from the Kinematic model using Kalman filter were compared with those obtained from the initial static deformation measurement results. Finally, the velocity and acceleration of the movement for each point in the network was plotted.

4. RESULTS AND DISCUSSIONS

The computed coordinates from the static GPS measurement results along with the velocity and acceleration of motion for each of the points is shown in Table 1.

Fig 3 and 4 presents the graph of the velocity and acceleration of motion for each points in the network in the X, Y, and Z direction. In Table 2, the predicted coordinates using the Kinematic model for each of the points for 2008 to 2013 is presented. A comparison of the measured and predicted coordinates for 2008 is presented in table 3 and represented graphically in figure 5.

Table 1: GPS measurement Results for 2007 and 2008 measurement period with velocity and acceleration.

<table>
<thead>
<tr>
<th>Name</th>
<th>2007 Measurement</th>
<th>Displacement</th>
<th>2008 Measurement</th>
<th>Velocity</th>
<th>Acceleration</th>
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<td>ΔE</td>
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</table>
Figure 3: Graph of velocity

Figure 4: Graph of Acceleration
Table 2: Prediction

<table>
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<tr>
<th>Name</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
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Table 3: Prediction and Correlation

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Prediction of Dam Deformation Using Kalman filter Technique, (6848)
Raphael Ehigiator - Irughe, Jacob Ehiaboru and Mabel Ehigiator (Nigeria)

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10/14
The computed displacements for Kinematic observation i.e ∆N, ∆E, and ∆Z show that all the points in the network moved except point 11SI, which has a vertical displacement of zero and horizontal shift of 0.14mm.

Maximum horizontal movement of 238mm and vertical movement of 82.2mm occurred in point 6S1 followed by reference point RF 7 with horizontal displacement of 113mm and vertical displacement of 113mm.

Maximum velocity and acceleration occurred in point 6SI for vertical and RF 7 for horizontal. Analysis of the results between the measurement update and predicted deformation results for 2008 indicate a correlation between the two, except in the case of 6SI and RF 7 where the correlation were weak.

An evaluation of the quality of the solution of the Kinematic model problem by Kalman filter using test statistics is the subject of discussions in another paper and have not been included here.

5. CONCLUSIONS

In this study, the Kalman filter technique based on Kinematic Deformation analysis was applied to measurement data collection by static GPS at the Ikpoba River Dam in Benin City, Nigeria.

By comparing the predicted and measured displacements, the efficiency of the Kinematic deformation model using Kalman filter was demonstrated. A major advantage in the method is
the ability to carry out step wise computation of structural movement parameters which projects forward the expected deformation at any later time.

This study focused on geodetic deformation prediction process using measurement parameters. The graph of correlation reveals that the accuracy of the predicted deformation compared quite well with the measured deformation for 2008. Further research is on going in order to determine the behavior for longer prediction period based on measured displacement.
REFERENCES


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BIOGRAPHICAL NOTES

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