

# LANDSLIDE MONITORING THROUGH KALMAN FILTERING: A CASE STUDY IN GÜRPINAR

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## ABSTRACT:

Many regions in Turkey are located on earthquake zones. The latest major earthquakes that hit eastern Marmara on August 17th and November 12th 1999 left tens of thousands of deaths. Another natural disaster that is a common in Turkey, mostly in Black Sea region and in some particular locations, is the landslides. In recent years several landslides happened after heavy rains and the resulting floods. This makes the landslide monitoring and mitigation techniques an important study subject for the related professional disciplines in Turkey. In the periphery of Istanbul, which is a metropolis with a population of more than 10 million, there are also some landslide regions. In this study, a landslide monitoring project in such a landslide area and the results obtained are discussed. The area is near Gürpınar village, located along the Marmara Sea coast to the northwest of Istanbul. The area that had been formerly an agricultural place was opened up for the settlements starting from the mid 80's. After than, several houses, mostly designed as weekend houses, were built. However, the effects of the landslides on the buildings were terrible. Many of the constructed buildings were damaged. The landslide monitoring project was carried out to identify the characteristics of the landslides and their potential risks. The geodetic measurement campaigns consist of two phases. In the first part of the monitoring, terrestrial geodetic observations were done in 6 epochs between 1990 and 1991. By the time, some network points were lost. In the second phase, the remaining network points were measured using the GPS technique in 4 epochs between 1996 and 1998. The results of the terrestrial works had been published before. In this study, only the campaigns with GPS observations are evaluated. The deformation analysis procedure applied is based on the Kalman Filtering technique. The results indicate the seriousness of the landslides. The displacements detected reach up to 5 meters. In the study, the approach for the deformation analysis and the overall displacements are presented.

## 1. INTRODUCTION

The basic objective of the science of geodesy is to determine the shape of the Earth and its gravity field. Besides, it deals with many applications related to positioning and surveying. One of these fields is the determination of crustal movements. Crustal movements or ground movements sometimes suddenly happen and these sudden movements are generally caused by earthquakes or landslides. The actual crustal movements, however, are slow that are difficult to be determined. Due to the slowness of these movements and the differences between the reference systems chosen for comparison, direct determination of these movements is normally impossible. Therefore, relative movements are determined using repeated observations (Yalçınkaya, 1994). The advances in measurement technology in the last three decades have made great contributions to deformation monitoring studies. As a result of these developments, deformation monitoring on large structures like dams, bridges, towers and the areas subjected to landslides and earthquakes have become widely applied.

For the analysis and the interpretation of deformations, different deformation models have been developed. These models consist of static, kinematic and dynamic models. Static model that is not dependent on time provides the determination of deformations on the characteristic points of the area or the structure, which is monitored. In time and position dependent

kinematic model, the movements of the characteristic points and the motion of these movements are investigated. In dynamic model, in addition to the kinematic model, the relation between deformations and the influencing factors are also taken into consideration.

Different deformation analysis algorithms have been applied so far. One of these mathematical approaches is the Kalman filtering technique. In this study, a deformation analysis procedure that has been carried out through a kinematic deformation model based on Kalman filtering technique is discussed. The geodetic data used for the analysis had been collected in a landslide area. In the following sections, characteristics of the landslide area, deformation analysis procedure and numerical applications are given.

## 2. CHARACTERISTICS OF LANDSLIDE AREA

The study area is a landslide region located nearby Gürpınar village that is to the northwest of Istanbul. In the area, without doing proper geotechnical investigations some buildings, mostly weekend houses had been built. But after the construction work had completed, many damages on the constructions took place as a result of landslides. In order to investigate the effects of landslides in and around the settlement area, a multidisciplinary project has been realised. Throughout the project geotechnical investigations and geodetic

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deformation measurements and analysis were done (Acar et al., 2003).

According to the geotechnical investigations, excluding the artificial disturbance of natural equilibrium, the reason of soil movements depends upon the changes in conditions related to underground water, seismic forces arising after earthquakes and the decrease in sliding strength in fissured (capilar fissures) and heavily consolidated clays. The area where the study was carried out is an old landslide region where slope equilibrium was formed gradually. As a result of movements in the form of small-sized flows due to surface water and the settlement in the area, the equilibrium was disturbed, causing mass movements (Fig.1). In order to prevent soil movements, drainage was performed (Altan et al, 1994).

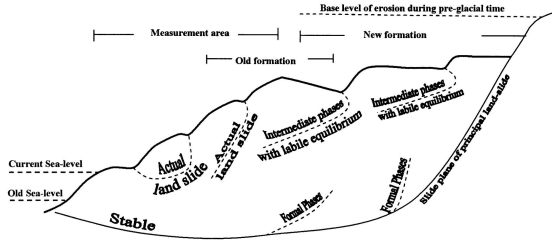


Figure 1 The landslide model of the Büyükçekmece region (Altan et al., 1994)

### 3. KINEMATIC DEFORMATION MODEL

Time-dependent 3D kinematic model that contains position, velocity and acceleration can be expressed by the following formula:

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

where

- $X_j^{(k+1)}, Y_j^{(k+1)}, Z_j^{(k+1)}$  : coordinate of point j at time  $(t_{k+1})$ . period
- $X_j^{(k)}, Y_j^{(k)}, Z_j^{(k)}$  : coordinate of point j at time  $(t_k)$ . period
- $v_{xj}, v_{yj}, v_{zj}$  : velocities of X, Y, Z coordinates of point j
- $a_{xj}, a_{yj}, a_{zj}$  : accelerations of X, Y, Z coordinates of point j
- $k = 1, 2, \dots, i$  (i: measurement period number)
- $j = 1, 2, \dots, n$  (n: number of points)

Kalman filtering technique is employed for the prediction of present state vector using state vector information of known motion parameters at period  $t_k$  and the measurements collected at period  $t_{k+1}$ . The state vector of motion parameters consists of position, motion and acceleration variables. The motion and acceleration parameters are the first and the second derivations

of the position with respect to time. Matrix form of the motion model used for the prediction of motion parameters by Kalman filtering technique in 3D networks can be given as follows:

$$\bar{Y}_{k+1} = \begin{bmatrix} x \\ y \\ z \\ v_x \\ v_y \\ v_z \\ a_x \\ a_y \\ a_z \end{bmatrix}_{k+1} = \begin{bmatrix} I & I(t_{i+1} - t_i) & I \frac{(t_{i+1} - t_i)^2}{2} \\ 0 & I & I(t_{i+1} - t_i) \\ 0 & 0 & I \end{bmatrix}_{k+1,k} \begin{bmatrix} x \\ y \\ z \\ v_x \\ v_y \\ v_z \\ a_x \\ a_y \\ a_z \end{bmatrix}_k \quad (2)$$

$$\bar{Y}_{k+1} = T_{k+1,k} Y_k^- \quad (3)$$

where

- $\bar{Y}_{k+1}$  : 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  $t_{k+1}$
- $I$  : unit matrix

Eq. 3 is the basic prediction equation of Kalman Filtering. The system noise is considered as the noise matrix  $S$  that consists of the terms of the last column given in Eq. (3). The noise matrix  $S$  is given below in Eq. (6).

$$\bar{Y}_{k+1} = T_{k+1,k} Y_k^- + S_{k+1,k} + \alpha_k \quad (4)$$

$$Q_{\bar{Y}\bar{Y}, k+1} = T_{k+1,k} Q_{Y^- Y^-, k} T_{k+1,k}^T + S_{k+1,k} Q_{ww, k} S_{k+1,k}^T \quad (5)$$

$$S_{k+1,k}^T = \begin{bmatrix} I \frac{(t_{k+1} - t_k)^2}{2} & I & I(t_{k+1} - t_k) \end{bmatrix} \quad (6)$$

where

- $\alpha_k$  : the random noise vector between periods  $t_{k+1}$  and  $t_k$
- $Q_{Y^- Y^-, k}$  : the cofactor matrix of state vector at time  $t_k$
- $Q_{ww, k}$  : the cofactor matrix of system noises at time  $t_k$

The random noise vector  $\alpha$  is uncertain and as a rule it cannot be measured. Therefore, for  $\alpha$ , pseudo observation vector can be used as  $\alpha=0$ . The effect of noise on positions can be determined from former experiences. Its effect on the motion and acceleration, however, can be hardly predicted. The covariance of noise effect acceleration can be derived using noise matrix  $S$  as given below (Bayrak, Yalçınkaya 2002).

$$Q_{\alpha\alpha,k} = 4(t_{k+1} - t_k)^{-4} Q_{SS,k} \quad (7)$$

where,

$Q_{SS}$  : covariance matrix for the noise components of positions at period k.

The residual vector for the observations at period k+1 is formed as follows:

$$l_{k+1} + v_{l,k+1} = A_{k+1} Y_{k+1}^- \quad (8)$$

$l_{k+1}$  : measurements at time  $t_{k+1}$   
 $v_{l,k+1}$  : residuals  
 $A_{k+1}$  : coefficients matrix  
 $Y_{k+1}^-$  : state vector at time  $t_{k+1}$

The matrix form of functional and stochastic models of Kalman filtering technique can be obtained by combining Eq. 4 and Eq. 8 as follows:

$$\begin{bmatrix} \bar{Y}_{k+1} \\ l_{k+1} \end{bmatrix} = \begin{bmatrix} I \\ A_{k+1} \end{bmatrix} Y_{k+1}^- - \begin{bmatrix} v_{\bar{Y},k+1} \\ v_{l,k+1} \end{bmatrix}, \quad Q_i = \begin{bmatrix} Q_{\bar{Y},k+1} & 0 \\ 0 & Q_{ll,k+1} \end{bmatrix} \quad (9)$$

By this model, motion parameters and cofactor matrix are computed. Kalman gain matrix is given as follows:

$$\begin{aligned} G_{k+1} &= Q_{\bar{Y},k+1} A_{k+1}^T (Q_{ll,k+1} + A_{k+1} Q_{\bar{Y},k+1} A_{k+1}^T)^{-1} \\ &= Q_{\bar{Y},k+1} A_{k+1}^T D_{k+1}^{-1} \end{aligned} \quad (10)$$

Using the equations above, innovation vector  $d_{k+1}$ , state vector filtered at time  $t_{k+1}$ ;  $Y_{k+1}^-$ , predicted state vector;  $v_{\bar{Y},k+1}$ , residual vector of observations at time  $t_{k+1}$  can be computed by the following equation:

$$\begin{bmatrix} d_{k+1} \\ Y_{k+1}^- \\ v_{\bar{Y},k+1} \\ v_{l,k+1} \end{bmatrix} = \begin{bmatrix} -A_{k+1} & I \\ I - G_{k+1} A_{k+1} & G_{k+1} \\ -G_{k+1} A_{k+1} & G_{k+1} \\ Q_{ll,k+1} D_{k+1}^{-1} A_{k+1} & Q_{ll,k+1} D_{k+1}^{-1} \end{bmatrix} \begin{bmatrix} \bar{Y}_{k+1} \\ l_{k+1} \end{bmatrix} \quad (11)$$

Actually, the filtering phase is based on classical least squares adjustment. The most important difference from the classical adjustment procedure is that, contrary to the classical approach, in the filtering the number of observations can be less than the number of unknowns. Through the filtering, adjusted values of state unknowns are computed using weighted combination of measurements and a priori estimations (Gülal, 1999; Bayrak and Yalçınkaya, 2002).

#### 4. NUMERICAL APPLICATION

In order to determine the point displacements in the landslide area, a deformation network consisting of 13 points was set up. The control points were established in stable areas out of the landslide region. The locations of the deformation points were determined according to the geotechnical investigations in the landslide region. The geodetic measurements used in the project were GPS measurements that were carried out in four periods between July 1996 and March 1998. In this study, the measurements of periods March 1997, October 1997 and March 1998 have been evaluated. The GPS data was collected in rapid static mode using 6 Leica SR399 and 4 Trimble SSI receivers. In all periods 2 sessions of GPS observations (10 minutes at each point) were realised. The data has been processed using commercial Leica SKI-Pro software. The measurements in each period have been adjusted through free network adjustment procedure and their adjusted values and variance-covariance matrix have been computed (Acar et al., 2003).

As a first step, static deformation analyses were carried out through the evaluation of adjusted coordinates and their variance-covariance information. In the analysis, Codeka3D deformation analysis software was used.

In the second part of the study, the kinematic deformation analysis procedure based on Kalman filtering technique as described in the previous section has been applied. By the application of this model, the motion parameters of network points have been computed. Afterwards, whether or not the obtained results are statistically significant have been tested. The maximum values of the velocities and accelerations of the points found after the kinematic analysis are given below in Table 1.

Position	Velocities (cm/month)	Accelerations (cm/month <sup>2</sup> )
X	41.75	2.663
Y	-42.66	-2.787
Z	-23.32	-1.506

Table 1 Maximum velocities and accelerations

As the final step, the solutions obtained through the kinematic model have been compared with the static deformation analysis results. The comparison showed that both models give almost identical results. The horizontal and vertical displacements obtained through kinematic deformation analysis are given in Table 2. As seen from the table, on 4 network points, horizontal and vertical displacements took place. Despite having no vertical displacement, Point 9 has horizontal movements. This is the only difference from the static deformation analysis where this point has been found stable.

Point	dx (cm)	dy (cm)	dz (cm)
9	0.58	3.65	1.11
1886	4.30	-9.39	-12.12
1996	116.99	-110.17	-112.83
2396	367.74	-363.98	-202.01
2496	150.43	-147.74	-140.834

Table 2 Point displacements

## 5. CONCLUSION

In this study, a Kalman filtering technique based kinematic deformation analysis procedure has been applied on a data set collected in a landslide area by GPS. In addition to this technique, the data has also been analyzed by static deformation analysis. Two different approaches produced identical results. However, the kinematic model has some clear advantages. For example, in kinematic model time dependent motion parameters of each point can be determined. Stepwise computation of motion parameters eases the control of the computations and the interpretation of the results.

It is obvious that, for the computation of motion parameters or in other words for modelling the motion, more measurements are required. This is actually the main drawback of kinematic deformation model approach. In this study, in order to overcome this problem, Kalman filtering technique has been conducted for the computation of motion parameters. The main advantage of Kalman filtering technique is that it requires less measurement period. However, since the Kalman filtering technique employs prediction, the kinematic behaviours should not be extended unlimitedly by extrapolation.

The study area discussed in this paper is a landslide area where a multi-disciplinary project had been conducted. The project partners are geodesists, civil engineers and earth scientists. However, this study focused only on the geodetic deformation monitoring process. It is clear that, through the combination of different data sets, a more realistic deformation model for the landslides would be produced.

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