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Artigo

DEVELOPMENT OF AN ALTERNATIVE LOW-COST LANDSLIDE MONITORING METHOD USING DATA FROM TUSAGA-AKTIF GNSS NETWORK

Desenvolvimento de um método de monitoramento de deslizamento de terra alternativo de baixo custo usando dados da Rede GNSS TUSAGA-Aktif

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Abstract:

The main objectives of this paper are to develop a kinematic deformation analysis model for landslides using Kalman filtering procedures; and to utilise the observations from TUSAGA-Aktif GNSS Network in Turkey to determine the velocity fields of a landslide study area in the Eastern Black Sea Region of Turkey. Thirty five (35) points were established for the determination of 3-D time dependent velocities of the landslides study area. Point displacements and velocities were determined by single point kinematic model to perform 3-D statistical analysis, and to assess the significance of point displacements and velocities using three periodic observations from TUSAGA-Aktif Network. The determined velocities were used to generate the velocity fields of the landslide area for three epochs using Geographic Information System (GIS). The results obtained indicate that almost all the monitored points showed significant movements, with varying magnitudes of velocities. The directions of movement of the 35 monitored points were also determined. The results show that the dominant trends of landslide movements in the study area are in the northwest and northeast directions. These results are in agreement with the previous results obtained in the same study area about ten years ago.

Keywords: Landslides, TUSAGA-Aktif, Kinematic Deformation Monitoring, Velocity field

Resumo:

Os principais objetivos deste trabalho são desenvolver um modelo cinemático análise de deformação para deslizamentos utilizando procedimentos de filtragem de Kalman; e utilizar as observações de TUSAGA-Aktif Rede GNSS na Turquia para determinar os campos de velocidade de uma área de estudo deslizamento de terra na região do Mar Negro oriental da Turquia. Trinta e cinco foram estabelecidos (35) pontos para a determinação de 3-D em tempo velocidades dependentes da área de estudo deslizamentos de terra. Deslocamentos e velocidades de ponto foram determinadas por ponto único modelo cinemático para realizar a análise estatística 3-D, e para avaliar a importância dos deslocamentos de ponto e velocidades usando três observações periódicas de TUSAGA-Aktif Rede. As determinadas velocidades foram usadas para gerar os campos de velocidade da área de deslizamento de terra por três épocas, utilizando Sistema de Informação Geográfica (GIS). Os resultados obtidos indicam que quase todos os pontos monitorados mostrou movimentos significativos, com diferentes magnitudes de velocidades. Foram também determinados os rumos do movimento dos 35 pontos monitorados. Os resultados mostram que as tendências dominantes dos movimentos de deslizamento de terra na área de estudo estão nas direções noroeste e nordeste. Estes resultados estão de acordo com os resultados anteriores obtidos na mesma área de estudo cerca de dez anos atrás.

Palavras-chave: Deslizamentos de terra, TUSAGA-Aktif, Monitoramento Cinemático de Deformação, Campo de velocidade

1. Introduction

Landslide is defined as ‘‘the movement of a mass of rock, debris, or earth down a slope’’ (Cruden, 1991). The main factors responsible for the occurrence of landslides include - prolonged precipitation, earthquakes, volcanic eruptions, rapid snow melting, and various anthropogenic activities. Landslide is difficult to predict in time and in space. This is because landslide occurrence depends on complex interaction of many factors, namely slope, soil properties, elevation, land cover, and lithology, among others (Dai and Lee, 2002). Also, the relationship and interaction between these factors are uncertain. Guzzetti (2005) identified a large spectrum of the landslide phenomena, which are diverse and complex in nature. This spectrum includes: landslide length, landslide area/volume, landslide velocity, total number of landslides, triggering time, and landslide lifetime. These diverse and complex factors make it practically difficult to adopt a particular technique and instrumentation to map and monitor landslides.

One of the main challenges in landslide monitoring is how to reduce the cost of the monitoring scheme. The cost of monitoring includes the costs of RTK GPS receivers, power supply, communication, logistics, personnel, etc. Several authors have proposed the use of low-cost GPS L1-only monitoring receivers (Cina and Piras, 2014; Cina et al. 2013; Yu, 2011; Verhagen et al. 2010; Brown et al. 2006). The short-coming of this approach is the potential degradation of the position solution due to the effects of ionospheric delay, and the challenges in the ambiguity resolution. Recently, Eyo et al. (2014) proposed a low cost landslide monitoring approach based on Reverse Real-Time Kinematic (RRTK) technique. The main features of this technique are that: low-cost receiver hardware can be utilized for real-time streaming of raw GPS measurements, thus eliminating complex algorithms and computations at the user end. This will drastically reduce the costs and tasks of the landslide monitoring scheme. Many low-cost landslide monitoring systems have been developed over the years (e.g. Lei et al. 2011; Glabsch et al. 2009; Aguado et al. 2006).

Globally, there is an upsurge in landslide occurrence, which could be attributed to the increasing human activities on the environment (Glade, 2003; Sidle et al. 2004) and the impact of climate change (Geertsema et al. 2006). The consequences of landslides are enormous. Recent landslide disasters in many regions of the world have destroyed infrastructure, killed thousands of people, and resulted in heavy economic losses. The continuous occurrence of disastrous landslide events has increased the demand for new and improved techniques for landslide monitoring.

The Global Navigation Satellite Systems (GNSS) - GPS, GLONASS, Galileo, Compass, QZSS and IRNSS are now being utilized as global infrastructure for a wide range of applications, including landslide monitoring. Continuously Operating Reference Stations (CORS) of Global Navigation Satellite Systems (GNSS) are being established in many regions of the world to provide valuable infrastructure for real-time kinematic positioning and applications in areas such as surveying, mapping, navigation and environmental monitoring. The use of RTK networks of reference stations has become the best solution for high precision positioning using Global Navigation Satellite Systems (GNSS). Compared to the standard RTK GPS, network RTK technique provides significant savings in the cost of infrastructure.

The main focus of this paper is to develop an alternative low-cost landslide monitoring technique using TUSAGA-Aktif - a Real Time Kinematic Geodetic GNSS Network in Turkey. TUSAGA-Aktif provides the users in the field instantaneous position solution with centimetre accuracy; and eliminates the cost of deploying two receivers (at base and rover stations), and also the need for post-processing of GNSS observations. The main objectives of this study are to develop a kinematic deformation analysis model for landslides using the Kalman filter; and to utilize the TUSAGA-Aktif measurements for determining the velocity fields of a landslide study area in the Eastern Black Sea Region of Turkey, in order to make realistic interpretations of the landslide evolution.

2. TUSAGA-Aktif Network

The development of GPS-RTK technique in the mid-1990 heralded the cm-level accuracy positioning in real-time, and gave impetus to carrier phase-based GPS technology. The standard RTK method employs radio links to transmit reference receiver data (or observation corrections) to the rover receiver. The user or rover unit utilizes this data together with its own raw measurements to resolve the ambiguity of the differenced carrier phase data and to estimate the rover's position. The main problem in single-base RTK surveying is that the accuracy of the position solutions is compromised with increase in baseline length, especially with relatively short occupation periods.

The problem in standard RTK GPS can be overcome by extending RTK GPS positioning from a single to a multi-base system, where a network of reference stations with baseline lengths of less than 100 km is used. The network RTK technique uses the Continuously Operating Reference Stations (CORS) to acquire a large amount of data, over a wide geographical scale, for the determination of the position solutions. The network RTK allows the separation between the reference stations at significantly longer baseline lengths (> 100 km), and has been able to address the baseline length restriction of the single-base RTK technique.

Continuously Operating Reference Stations (CORS) of Global Navigation Satellite Systems (GNSS) are being established in many regions of the world to provide valuable infrastructure for real-time kinematic positioning and applications in areas such as surveying, mapping, navigation and environmental monitoring. The initial motivations for the establishment of CORS were for scientific applications, to capture the occurrence of an earthquake and other geohazards in real-time. Government agencies were mainly in the fore-front of the establishment CORS infrastructure, basically to maintain and expand their existing geodetic network. CORS infrastructure has been installed in many countries. Some of the examples include: US National Geodetic Survey CORS, Canadian Active Control System (CACS), Malaysia Real-Time Kinematic GNSS Network (MyRTKnet), Singapore Satellite Positioning Reference Network (SiReNT), and many other CORS system in Australia, Germany, Japan, Switzerland, Belgium, United Kingdom, etc. One of the main advantages of CORS network is that the cost of operating the reference, including the cost of hardware is eliminated. These Network of RTK services have proven to be an efficient tool for landslides monitoring in real-time (Lui, 2010).

TUSAGA-Aktif is a Real Time Kinematic Geodetic GNSS Network in Turkey, established to provide infrastructure for strategic research in areas such as atmosphere, meteorology, earthquake early warning and accurate positioning, among others (Yildirim et al. 2011). This network consists of 147 Continuously Operating Reference Stations, as shown in Figure 1 (Yildirim et al. 2011). The Master and Auxiliary control stations of TUSAGA-Aktif are established in Ankara, the capital city of Turkish Republic (Mekik et al. 2011). TUSAGA-Aktif has the capability to provide cm-level accurate position solution throughout Turkey (Mekik et al. 2011, Eren, 2009).

Figure 1: Locations of TUSAGA-Aktif reference stations

3. Landslide Study Area and Data Collection

Kutlugün (Hacımehmet) Village in Maçka County in the Province of Trabzon in Eastern Black Sea Region of Turkey (see Figure 2) was selected as the study area where landslides are the most serious natural hazards. The Northeastern Black Sea Region of Turkey is characterized by steep mountainous terrain, complex lithology and high precipitation, which makes this region susceptible to landslide occurrence.

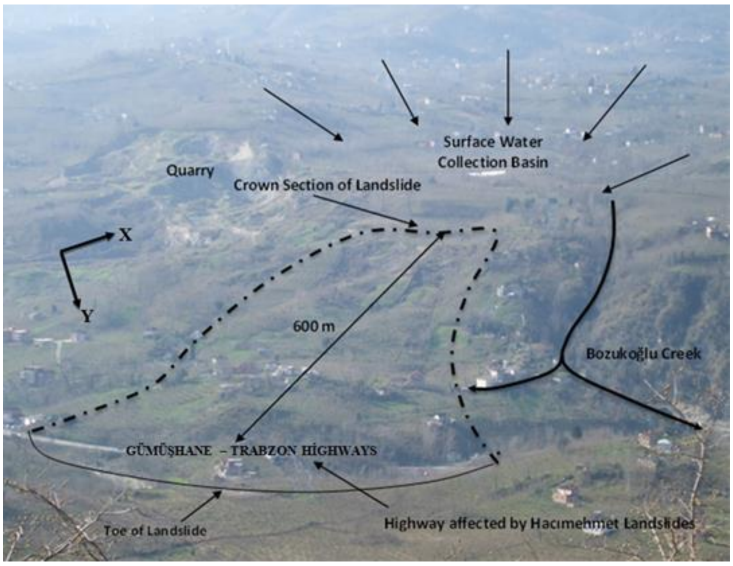

Figure 2: A view of Kutlugün (Hacımehmet) landslides

In order to monitor landslides in the study area, 35 points covering the whole landslide area and its surroundings were established to acquire periodic measurements. The measurements were made in August 2012, November 2012, and February 2013. Measurement time was very short for one point (about 2 minutes), and about 3 hours was used in acquiring data from the 35 points. 10-epochs of measurements were made at each point for every three months using real-time TUSAGA-Actif Network.

4. Kalman Filter Model for Kinematic Deformation Analysis

The adjusted coordinates of the points were used to evaluate the kinematic deformation analysis of the landslide area. Point displacements and velocities were determined by kinematic single point model to perform 3-D statistical analysis, and to inspect the significance of point displacements coming from three repeated TUSAGA-Actif surveys. Kalman filtering technique was used in the solution of the kinematic model on Microsoft Excel. The determined velocities were used to generate the velocity fields of the landslide area for three epochs using Geographic Information System (GIS).

Ten epochs of real time measurements and their Root Mean Square (RMS) values were observed separately in a point at period k. These observed values were adjusted. Adjusted coordinates X_k, Y_k, Z_k and their RMS values $(m_{X_k}, m_{Y_k}, m_{Z_k})$ were determined for the object point. Coordinates differences between two periods were obtained as Equation 1 for the object point as follows (Turan et al. 2012):

$$\begin{aligned} \Delta X_{k,k+1} &= X_{k+1} - X_k \\ \Delta Y_{k,k+1} &= Y_{k+1} - Y_k \\ \Delta Z_{k,k+1} &= Z_{k+1} - Z_k \end{aligned} \tag{1}$$

Error propagation rule was applied to Equation 1 and given as follows (Turan et al. 2012):

$$\begin{aligned} d\Delta X_{k,k+1} &= \frac{\partial \Delta X_{k,k+1}}{\partial X_k} \cdot dX_k + \frac{\partial \Delta X_{k,k+1}}{\partial X_{k+1}} \cdot dX_{k+1} \\ d\Delta Y_{k,k+1} &= \frac{\partial \Delta Y_{k,k+1}}{\partial Y_k} \cdot dY_k + \frac{\partial \Delta Y_{k,k+1}}{\partial \Delta Y_{k+1}} \cdot dY_{k+1} \\ d\Delta Z_{k,k+1} &= \frac{\partial \Delta Z_{k,k+1}}{\partial Z_k} \cdot dZ_k + \frac{\partial \Delta Z_{k,k+1}}{\partial \Delta Z_{k+1}} \cdot dZ_{k+1} \end{aligned} \tag{2}$$

Equation 2 can be re-written in matrix form as follows (Turan et al. 2012):

$$\begin{bmatrix} d\Delta X_{k,k+1} \\ d\Delta Y_{k,k+1} \\ d\Delta Z_{k,k+1} \end{bmatrix} = \begin{bmatrix} -1 & 0 & 0 & 1 & 0 & 0 \\ 0 & -1 & 0 & 0 & 1 & 0 \\ 0 & 0 & -1 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} dX_k \\ dY_k \\ dZ_k \\ dX_{k+1} \\ dY_{k+1} \\ dZ_{k+1} \end{bmatrix} \tag{3}$$

The variance and co-variance matrix of functional model can be obtained as follows (Turan et al. 2012):

$$K_{XYZ} = \begin{bmatrix} m^2_{X_k} & 0 & 0 & 0 & 0 & 0 \\ 0 & m^2_{Y_k} & 0 & 0 & 0 & 0 \\ 0 & 0 & m^2_{Z_k} & 0 & 0 & 0 \\ 0 & 0 & 0 & m^2_{X_{k+1}} & 0 & 0 \\ 0 & 0 & 0 & 0 & m^2_{Y_{k+1}} & 0 \\ 0 & 0 & 0 & 0 & 0 & m^2_{Z_{k+1}} \end{bmatrix} \tag{4}$$

Equations 3 and 4 were used in matrix operations of kinematic single point models. In the recommended method, Kalman filtering technique was used for the solution of the kinematic model. A time-dependent kinematic model consisting of displacements and their velocities can be formed as follows (Holdahl and Hardy, 1979; Yalçinkaya and Bayrak, 2005; Acar et al. 2008):

$$\begin{aligned} X_{k+1} &= X_k + (t_{k+1} - t_k)V_{X_k} \\ Y_{k+1} &= Y_k + (t_{k+1} - t_k)V_{Y_k} \\ Z_{k+1} &= Z_k + (t_{k+1} - t_k)V_{Z_k} \\ V_{X_{k+1}} &= V_{X_k} \\ V_{Y_{k+1}} &= V_{Y_k} \\ V_{Z_{k+1}} &= V_{Z_k} \end{aligned} \tag{5}$$

Where:

X_k, Y_k, Z_k: Adjusted point coordinates at period k

$V_{X_k}, V_{Y_k}, V_{Z_k}$: Velocities of point coordinates

Two periods of measurements are sufficient to solve model parameters using Kalman filtering technique in Equation 5. Equation 5 can be re-written as Equation 6 in matrix form and with a shorter form in Equation 7. Equation 6 is the functional model for the kinematic single point model (Yalçinkaya and Bayrak, 2005; Acar et al. 2008).

$$\overline{Y}_k = \begin{bmatrix} X \\ Y \\ Z \\ V_X \\ V_Y \\ V_Z \end{bmatrix}_{k+1} = \begin{bmatrix} I & I(t_{k+1} - t_k) \\ 0 & I \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ V_X \\ V_Y \\ V_Z \end{bmatrix}_k \tag{6}$$

$$\overline{Y}_k = T_{k,k+1}\hat{Y}_k \tag{7}$$

Where:

$\overline{Y}_k$: Prediction status (displacements and velocities at period k)

$\hat{Y}_k$: Status vector at period k

$T_{k,k+1}$: Prediction matrix

I: Unit matrix

Prediction status vector at period k and its covariance matrix can be written as Equations 8 and 9 (Yalçinkaya and Bayrak, 2005; Acar et al. 2008).

$$\overline{Y}_k = T_{k,k+1}\hat{Y}_k + N_{k,k+1}w_k \tag{8}$$

$$Q_{\overline{Y}\overline{Y},k} = T_{k,k+1}Q_{\hat{Y}\hat{Y},k}T^T_{k,k+1} + N_{k,k+1}Q_{ww,k}N^T_{k,k+1}, \tag{9}$$

Where:

$N_{k,k+1}$ is the system noise matrix; w_k is the random noise vector at period k; $Q_{\overline{Y}\overline{Y},k}$ is cofactor matrix of status vector and $Q_{ww,k}$ is cofactor matrix of system noises.

The adjustment of the kinematic model can be expressed in matrix form in Equation 10 and Equation 11. Equation 11 is the functional model for the Kalman filtering technique. The stochastic model for the Kalman filtering technique can be written as Equation 12 (Yalçinkaya and Bayrak, 2005; Acar et al. 2008).

$$L_k + V_l = A_k \hat{Y}_k \tag{10}$$

$$\begin{bmatrix} \bar{Y} \\ L_k \end{bmatrix} = \begin{bmatrix} L \\ A_k \end{bmatrix} \hat{Y}_k - \begin{bmatrix} V_{\bar{Y},k} \\ V_{L,k} \end{bmatrix} \tag{11}$$

$$Q_k = \begin{bmatrix} Q_{\bar{Y}\bar{Y},k} & 0 \\ 0 & Q_{LL,k} \end{bmatrix} \tag{12}$$

Where:

V is the innovation vector; L_k is the actual observation; $A_k \hat{Y}_k$ is the predicted observation.
The kinematic model using Equations 11 and 12 were solved and their displacements and velocities are computed with two periods of measurements.

5. Results and Analysis

In the model, movement parameters are point displacements and their velocities. They were solved using Kalman filtering technique on Microsoft Excel, using two periods of measurements, which was sufficient to solve movement parameters using the model. Kinematic analysis was performed between August 2012-November 2012, and August 2012-February 2013. Results for velocities are given in Table 1 for August 2012-November 2012, and Table 2 for August 2012-February 2013.

In the solution, the velocity parameters were divided by the square-mean errors and test values (T) were computed. These values were compared with the t-distribution table values (q) to evaluate whether velocities were significant or not in Table 1 and Table 2. If velocity parameters have significantly changed, a (+) sign is given in Table 1 and Table 2; otherwise, a (-) sign is given.

In order to view the 3-D time dependent velocity fields of the landslides area, velocity field maps were drawn using Table 1 and Table 2 data. ArcGIS was utilized in drawing the maps, data interpolation were done using the Kriging method. Figure 3, 4, and 5 show the velocity fields of the landslides area in direction of X, Y and Z, respectively, between August 2012 and February 2013 measurement periods. Tables 1 and 2, and Figures 3, 4, and 5 indicate that almost all the points showed significant movements, with varying magnitudes of velocity.

The directions of the landslide movement of the 35 points are shown in Figures 6 and 7. The landslide between August 2012 and November 2012 (shown in Figure 6) shows the following trends in the direction of movement – northwest, 23 points (65.7%); northeast, 7 points (20%); southeast, 3 points (8.6%); and southwest, 2 points (5.7%). The landslide between August 2012 and February 2013 (shown in Figure 7) shows the following trends in the direction of movement – northwest, 30 points (85%); and northeast, 5 points (15%). Thus, the dominant trends of landslide movements in the study area are in the northwest and northeast directions. These trends in the direction of the landslide movements agree with the previous results obtained in the same study area about ten years ago (Yalçinkaya and Bayrak, 2005).

Table 1: Significance test of velocities computed with kinematic model between August 2012 and November 2012

PN	Velocities (mm/3Months)			Test Values for velocities and decisions (q = 2.04)					
	V_{X_k}	V_{Y_k}	V_{Z_k}	T_{X_k}	Decision	T_{Y_k}	Decision	T_{Z_k}	Decision
1	-0.17	0.51	-4.24	2.36	+	6.85	+	38.58	+
2	-0.01	0.45	-2.33	0.20	-	7.05	+	22.79	+
3	-0.22	0.05	-1.61	4.26	+	1.00	-	15.05	+
4	-0.42	-0.27	-1.51	3.26	+	2.12	+	6.46	+
5	-0.70	0.85	-1.70	14.41	+	17.46	+	13.14	+
6	-0.33	0.47	-0.23	5.07	+	7.07	+	2.35	+
7	-0.11	0.31	-1.05	2.49	+	6.38	+	10.29	+
8	-0.02	0.11	-0.10	0.63	-	2.36	+	1.45	-
9	0.13	0.12	1.05	2.56	+	2.35	+	7.04	+
10	1.23	0.25	-5.03	29.13	+	6.00	+	50.17	+
11	-0.10	0.35	-4.18	1.12	-	3.53	+	26.73	+
12	1.79	0.29	-1.08	39.30	+	6.63	+	11.40	+
13	6.70	0.57	-6.63	86.72	+	7.45	+	30.45	+
14	-2.20	00.00	1.62	29.37	+	0.09	-	10.31	+
15	0.56	-0.81	0.56	8.18	+	11.65	+	4.27	+
16	0.67	-0.48	-6.19	8.67	+	6.30	+	45.97	+
17	0.87	0.37	0.43	9.21	+	3.99	+	3.03	+
18	0.10	-0.23	0.00	1.60	+	3.59	+	0.05	+
19	-2.85	0.30	-3.25	9.15	+	0.99	-	5.75	+
20	-2.89	0.19	-4.21	3.55	+	0.25	-	2.99	+
21	-4.06	1.47	-1.92	57.22	+	20.69	+	14.88	+
22	0.57	0.50	-0.11	6.85	+	6.01	+	1.12	-
23	-0.45	-0.38	-1.25	7.65	+	6.52	+	6.99	+
24	-0.13	0.88	-0.73	3.03	+	17.29	+	14.25	+
25	-0.42	-0.11	-1.03	6.92	+	1.89	-	10.28	+
26	-0.15	0.56	-0.86	2.28	+	7.71	+	6.56	+
27	-0.95	2.41	-2.07	18.42	+	46.59	+	12.69	+
28	-0.30	1.52	-1.55	5.32	+	26.15	+	11.35	+
29	-1.01	1.02	0.18	16.87	+	17.03	+	1.61	-
30	-0.16	6.02	-1.75	3.02	+	106.39	+	13.75	+
31	1.12	0.73	0.74	14.58	+	9.53	+	4.75	+
32	-0.16	1.64	-1.11	2.03	-	19.51	+	5.92	+
33	-0.45	1.62	-1.23	10.47	+	37.66	+	12.78	+
34	0.24	0.71	0.30	3.86	+	11.05	+	1.81	+
35	-0.22	1.21	-1.84	4.83	+	24.76	+	15.69	+

Table 2: Significance test of velocities computed with kinematic model between August 2012 and February 2013

PN	Velocities (mm/6months)			Test Values for velocities and decisions (q = 2.04)					
	V_{X_k}	V_{Y_k}	V_{Z_k}	T_{X_k}	Decision	T_{Y_k}	Decision	T_{Z_k}	Decision
1	-1.04	0.70	-2.77	24.49	+	16.50	+	44.17	+
2	-0.7	1.3	-5.4	7.66	+	5.99	+	13.82	+
3	-0.72	0.75	-2.31	5.30	+	8.18	+	7.42	+
4	-0.85	0.41	-3.54	8.93	+	4.82	+	17.23	+
5	-1.73	1.17	-2.87	33.21	+	22.31	+	21.27	+
6	-0.52	1.42	-2.54	3.95	+	10.70	+	14.19	+
7	-1.18	1.25	-2.07	9.99	+	9.15	+	6.87	+
8	-0.26	0.85	-0.73	3.20	+	7.01	+	4.21	+
9	-0.57	0.69	-1.30	4.53	+	5.56	+	3.30	+
10	1.46	0.50	-7.09	11.90	+	4.23	+	24.30	+
11	-0.49	0.63	-7.56	4.97	+	4.72	+	30.33	+
12	0.48	1.09	-3.95	4.54	+	10.80	+	17.93	+
13	6.12	1.93	-7.83	74.85	+	24.19	+	40.66	+
14	-3.85	0.77	0.00	12.94	+	7.54	+	0.00	-
15	-1.29	3.24	-1.27	10.61	+	26.41	+	5.61	+
16	-0.49	3.19	-8.94	3.05	+	19.97	+	34.30	+
17	-0.47	3.22	-2.06	2.16	+	15.71	+	6.30	+
18	-1.49	2.79	-1.52	6.32	+	9.55	+	4.90	+
19	-5.09	2.46	-6.17	14.55	+	11.25	+	9.33	+
20	-3.45	1.75	-6.78	8.11	+	14.59	+	7.40	+
21	-7.09	4.28	-3.65	45.01	+	27.29	+	11.19	+
22	-2.08	6.28	-0.77	9.59	+	29.25	+	3.53	+
23	-4.47	6.72	-2.88	20.86	+	31.71	+	3.94	+
24	0.19	2.04	-0.34	1.21	-	9.96	+	1.69	-
25	-0.88	0.68	-2.67	5.87	+	5.45	+	9.02	+
26	-0.61	1.43	-2.14	6.03	+	11.49	+	8.21	+
27	-3.06	5.42	-4.44	42.31	+	74.57	+	22.07	+
28	-1.86	3.61	-3.28	18.29	+	33.94	+	13.28	+
29	-2.67	2.14	0.63	28.44	+	22.81	+	3.66	+
30	-3.61	3.91	-3.53	18.36	+	17.54	+	7.21	+
31	0.56	1.85	-0.79	5.47	+	18.12	+	3.52	+
32	-0.63	3.50	-2.41	7.95	+	37.48	+	9.62	+
33	-1.31	3.56	-3.53	12.68	+	33.96	+	13.54	+
34	0.04	1.59	-0.48	0.40	-	14.35	+	1.61	-
35	-0.09	0.25	-0.36	5.50	+	14.05	+	9.33	+

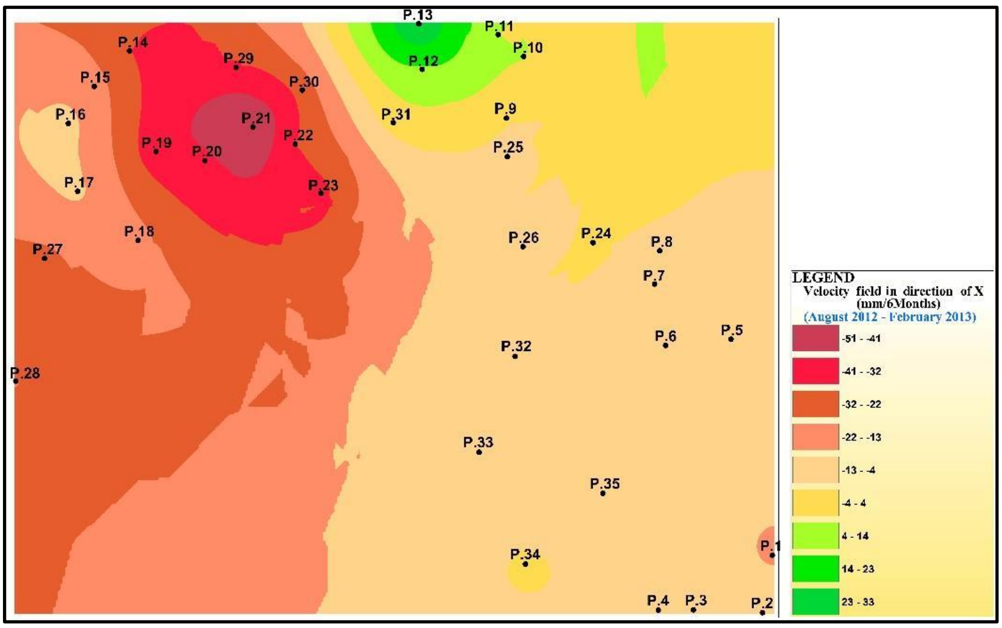

Figure 3: Velocity field in Direction of X

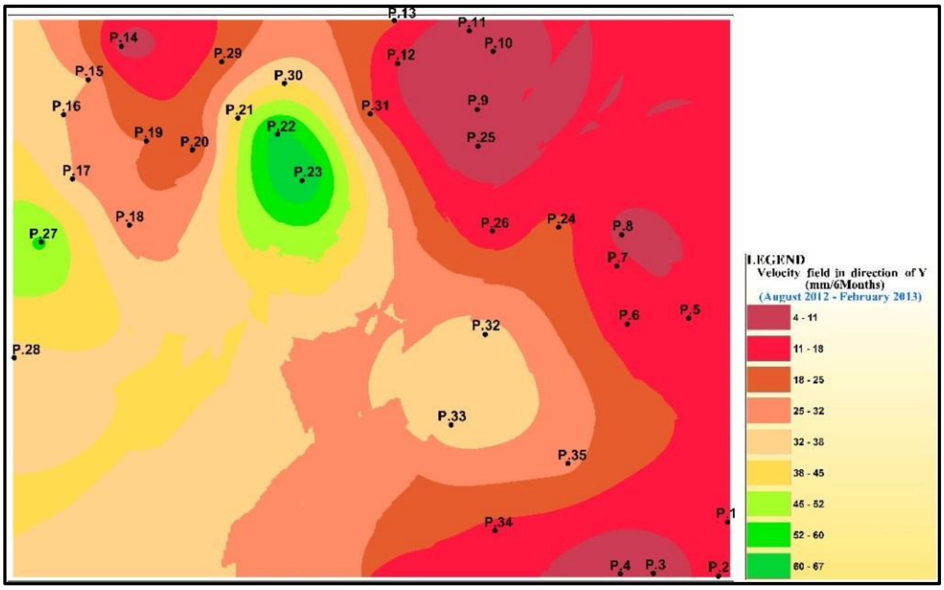

Figure 4: Velocity field in Direction of Y

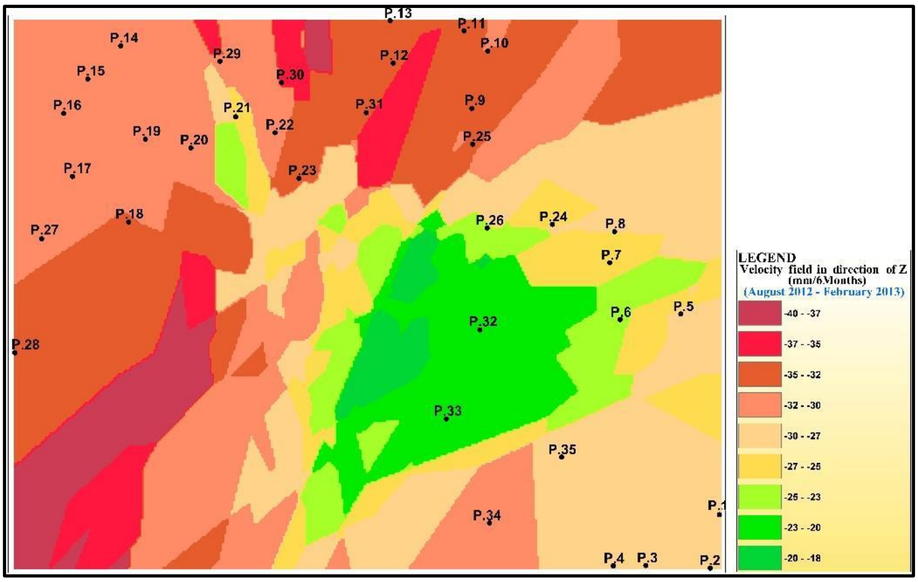

Figure 5: Velocity Field in Direction of Z

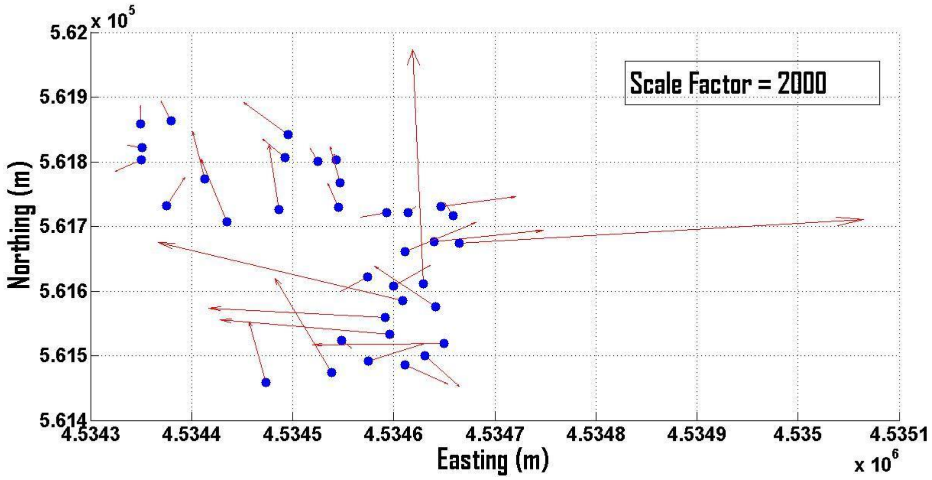

Figure 6: 2-D Landslide Movements (Aug. 2012 – Nov. 2012)

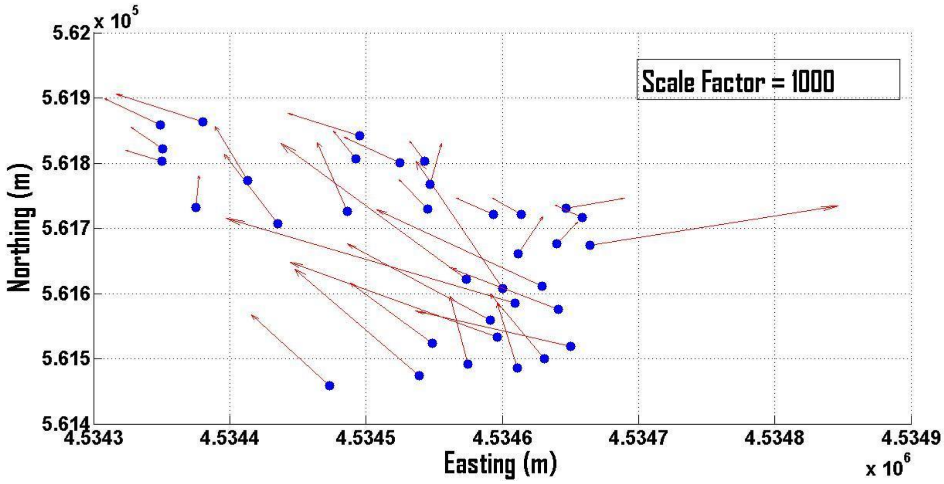

Figure 7: 2-D Landslide Movements (Aug. 2012 – Feb. 2013)

6. Conclusion

In this paper, a methodology is presented for an alternative low-cost landslide monitoring using periodic data collected from TUSAGA-Aktif GNSS Network. The landslide site used for this study is located in Kutlugün (Hacımehmet) Village, Trabzon Province, Eastern Black Sea Region of Turkey. In order to monitor landslides in the study area, 35 points covering the whole landslide area and its environ were established to acquire periodic GPS observations at 3 months interval (on August 2012, November 2012, and February 2013). 10-epochs of GPS observations were acquired on each of the 35 points to generate 3-D coordinates for all the points.

The coordinates were adjusted and used to perform kinematic deformation analysis of the landslide study area, using kinematic single point model developed based on Kalman filtering technique. Using the kinematic model, displacements and velocities were computed for all the monitored points; and 3-D statistical analysis was performed to determine the significance of point displacements and velocities. In the statistical analysis, the computed test values (T) were compared with the t-distribution table values (q) to assess whether the velocities were significant or not.

Using the ArcGIS tool in Geographic Information System (GIS), the velocities determined by the kinematic model were used to generate the velocity fields of the landslide study area. The results obtained indicate that almost all the monitored points showed significant movements, with varying magnitudes of velocities.

The directions of movement of the 35 monitored points were also determined. The landslide between August 2012 and November 2012 shows the dominant trends in the direction of northwest (65.7%) and northeast (20%). Also, the landslide between August 2012 and February 2013 shows the dominant trends in the direction of northwest (85%) and northeast (15%). These trends in the direction of the landslide movements agree with the previous results obtained in the same study area about ten years ago (Yalçinkaya and Bayrak, 2005).

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