Proceedings, 11th FIG Symposium on Deformation Measurements, Santorini, Greece, 2003.

A DYNAMIC ANALYSIS METHOD REGARDING GROUNDWATER LEVEL CHANGES AS CAUSATIVE FORCE FOR LANDSLIDES

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Abstract

Landslides are one of the most important natural disasters in Turkey especially in the North Eastern Black Sea Region. Steep mountainous terrain, complex geology and high precipitation in the region all combine to make this region particularly susceptible to landslide activities. In fact, in this Region, the loss of life and damage to property caused by landslides is greater than those caused by other natural hazards. As this region's cities, towns, roads and highways steadily encroach onto steeper slopes and mountainsides, landslide hazards become an increasingly serious threat to life and property. The goal of this study is to investigate relationships between precipitation and landslides, understand slide mechanism of landslides due to large groundwater level changes, determine temporal behavior of creep landslides with a dynamic deformation model regarding groundwater level changes, monitor and control landslides with repeated GPS surveys by a deformation network in a selected test area in this region. This paper describes mathematical and statistical structure of a dynamic deformation model regarding large groundwater changes being the most important one of the causative forces for creep landslides. The model includes computations of displacements, displacement velocities, displacement accelerations and groundwater effect parameters that shows the geometric reflection of groundwater level changes on point movements. Finally, acceleration effects of large groundwater changes on landslides were investigated, results were interpreted and advantages and disadvantages of dynamic deformation model for landslide studies were brought up.

1. Introduction

Kutlugün landslide is only one of the landslide activities that have occurred in North Eastern Black Sea Region. A long history of ground movements together with road construction at toe and changes in groundwater regime over time within the slope created the preconditions for Kutlugün landslide. Preliminary investigations indicated that Kutlugun landslide was active and unstable. Active Kutlugün landslide damaged Trabzon-Maçka Highway and Water Pipe Line supplying drinking water to Trabzon city. Besides, a lot of houses were affected during slow sliding. To prevent possible damages, a retaining wall was constructed at the toe of slide area. However, it was not strong enough to stop mass movement. Thus, it was deemed necessary to monitor the landslide to help reduce the damages that could possibly be caused by it. To do this, Kutlugün Village in Maçka County in the Province of Trabzon in Eastern Black Sea Region of Turkey was selected as the study area (Fig. 1). In this area, in 1995, geological and geophysical investigations were made by INSITU (Geology Geotechnics Drilling Co. Ltd.) and geological structure and causative forces of Kutlugün landslides were determined (İller Bankası Raporları, 1995). In 1999, geological and geophysical structure of Kutlugün landslide were also investigated by scientists of Karadeniz Technical University, Department of Geology and Geophysics, and the current border of the landslides was determined. According to these investigations, groundwater level changes were the most important causative factor for Kutlugün landslide. In the process of building the dynamic model, the groundwater level changes were considered the causative. The Kutlugün landslide was determined with static, kinematic and dynamic models. The results were compared and used to infer conclusions about model suitability.

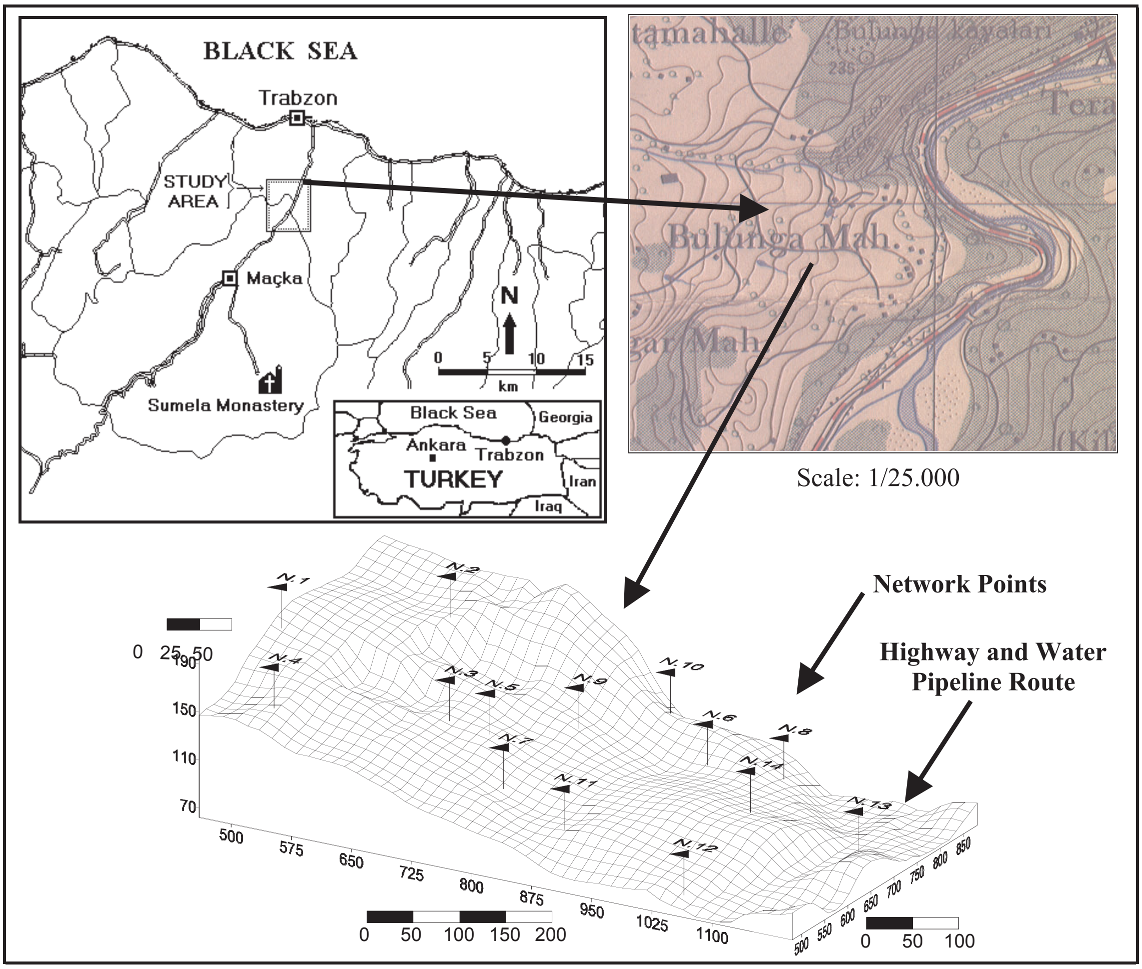

Figure 1. Location map of study area and 3D-view of slide area

2. Mathematical theory of the developed dynamic analysis method

In monitoring applications, three analysis methods are used. These are static, kinematic and dynamic models. Hypothesis test in static model being independent from time and causative forces is formed like in Eq.(1) and tested statistically. Thus, significant changes are determined (Mierlo, 1978; Pelzer, 1985; Koch, 1999).

$$x_j^{(i)} = x_j^{(i-1)} \tag{1}$$

Where, $x_j^{(i)}$ and $x_j^{(i-1)}$ are vectors of point coordinates at times t_i and t_{i-1}, j=1,2,...,p*n, n is number of points in network, p is number of coordinates at one network point. The kinematic deformation model that determines the movement with a function dependent on time and position is formed in Eq.(2).

$$x_j^{(i)} = f(x_j^{(i-1)}, \Delta t) \tag{2}$$

Where, T t is the difference between t_i and t_{i-1} observation times. If Eq.(2) consists of a Taylor series until the 2nd degree Eq (2) can be written as follows,

$$x_j^{(i)} = x_j^{(i-1)} + v_j^{(i-1)}(t_i - t_{i-1}) + \frac{1}{2}a_j^{(i-1)}(t_i - t_{i-1})^2 \quad ... \tag{3}$$

In Eq.(3) named as kinematic single point model, points moved over time in network, point displacements, velocity (v) and acceleration (a) of moving points are determined according to time. Parameters are statistically tested with expanded model test method and the decision is made about the significance of the movement models (Pelzer, 1985, 1987; Yalçınkaya, 1994; Ünver, 1996).

Static and kinematic models are sufficient in determining movements due to landslides, but these statistical models neglect climatic (precipitation, groundwater level fluctuations, etc.) effects. Chaotic behavior in the evolution of the landslide system cannot be reflected and, hence, the long-term prediction of landslides cannot be made using these methods. Dynamic models determine movements that are dependent on causative forces, material properties and time. Landslides have a 3D form and a complicated temporal context. They are dynamic systems that are complex in time and space (Varnes and Savage, 1996; Turner and Schuster, 1996). Using dynamic models, the temporal behavior of landslides can be described very closely to reality (Ding et al, 2001; Ren and Ding, 1996; Yalçınkaya and Bayrak, 2001).

To form a dynamic model, it is necessary to know the characteristics of the material investigated. If this is known, mathematical relations can be established between deformations and causative forces over time. As mentioned above, groundwater level changes were recognized as the most important causative factor for Kutlugün landslide. So, changes in groundwater level were regarded as a causative force in the formation of the dynamic model. As a result of the geomorphological investigations, the same soil material was found in the whole study area. So, it was accepted that landslide material was homegeneous for this study. Relying on this assumption, it was adopted that the effect of groundwater level changes on landslide evolution was linear. The dynamic deformation model can be built by adding the causes of movements to the kinematic approach shown in Eq. (3). The dynamic model can be written as follows.

$$x_i = f\,(x_{i-1}, \Delta\, t, \Delta\, s) \tag{4}$$

Where, Δ s is the groundwater level changes at network points at t_i and t_{i-1} times. To determine velocity and acceleration of movement and effect of groundwater level changes on movements, Eq. (4) was reformulated using Taylor series as:

$$x_{(t_i,s_i)} = x_{(t_{i-1},s_{i-1})} + \left.\frac{\partial x}{\partial t}\right|_{(t_{i-1},s_{i-1})} \Delta t + \left.\frac{\partial x}{\partial s}\right|_{(t_{i-1},s_{i-1})} \Delta s + \frac{1}{2}\left.\frac{\partial^2 x}{\partial t^2}\right|_{(t_{i-1},s_{i-1})} \Delta t^2 \tag{5}$$

Velocity and acceleration of movement were determined from first and second derivative of position according to time. Expansion of function with extra parameters can complicate interpretation of movement. Thus, it was decided that determination of velocity and acceleration of movement was adequate and derivation process was terminated at the 2nd degree. First derivative of position according to groundwater level changes was derived to determine the effect of groundwater level changes on position. Because it was assumed that effect of groundwater level changes on landslide evolution was linear, derivation process was terminated at the 1st degree. Eq. (6) was derived by rearranging Eq. (5).

$$x_{(t_i,s_i)} = x_{(t_{i-1},s_{i-1})} + v_{(t_{i-1},s_{i-1})} \Delta t + \frac{1}{2} a_{(t_{i-1},s_{i-1})} \Delta t^2 + b_{(t_{i-1},s_{i-1})} \Delta s \tag{6}$$

Where b is the effect parameter of groundwater to point positions. The dynamic model for three-dimensional networks is formed as shown below.

$$x_j^{(i)} = x_j^{(i-1)} + (t_i - t_{i-1})\,v_{xj} + \tfrac{1}{2}(t_i - t_{i-1})^2 a_{xj} + (s_j^{(i)} - s_j^{(i-1)})b_{xj}$$
$$y_j^{(i)} = y_j^{(i-1)} + (t_i - t_{i-1})\,v_{yj} + \tfrac{1}{2}(t_i - t_{i-1})^2 a_{yj} + (s_j^{(i)} - s_j^{(i-1)})b_{yj} \qquad (7)$$
$$z_j^{(i)} = z_j^{(i-1)} + (t_i - t_{i-1})\,v_{zj} + \tfrac{1}{2}(t_i - t_{i-1})^2 a_{zj} + (s_j^{(i)} - s_j^{(i-1)})b_{zj}$$

Where, $s_j^{(i)}$ and $s_j^{(i-1)}$ are the groundwater levels of j point in the (i) and (i-1) observation period. Also b_{xj}, b_{yj}, b_{zj} are the groundwater coefficients of j point which have x, y, z coordinates in the (i-1) observation period. Coefficients of b_{xj}, b_{yj}, b_{zj} show the effect of changes of groundwater level on x, y, and z coordinates of point j. These coefficients are statistically tested, and it is determined whether the effect of changes of groundwater level is significant or not for the individual points. Eq.(7) is the functional model of the dynamic model. Stochastic models of the dynamic deformation model are taken from the kinematic model solved with Kalman-filter. The functional and stochastic models are solved with the least square adjustment method. The parameters of the position, velocity, acceleration and groundwater are included in this process. It is statistically decided whether expansion of dynamic model with velocity, acceleration and groundwater parameters is significant (Koch, 1999; Wolf, 1997).

Acceleration and groundwater parameter have physical meanings. The sign of acceleration is very significant to be able to interpret deformations. If “acceleration>0”, velocity of deformation increases. This situation shows that landslide is unstable. If “acceleration<0”, velocity of deformation decreases. Physical environment conditions usually determine the sign of acceleration (Pelzer, 1993). The sign of groundwater parameter is also very significant to be able to interpret effect of groundwater level changes onto point movements. If “groundwater parameter > 0”, groundwater level changes increase velocity of deformation. If “groundwater parameter < 0”, effect of groundwater level changes onto point movements decrease. Temporal changes of groundwater level usually determine the sign of groundwater parameter.

3. Application

In order to apply the new dynamic analysis method to landslides, a monitoring system was established to survey slow sliding, monitor deformations and surface movements in Kutlugün village in Çağlayan County in the province of Trabzon on North Eastern part of the Turkish Black Sea coast. The network consists of 14 points, four of them (2, 8, 10, 13) in solid ground. The other points (1, 3, 5, 6, 7, 9, 10, 11, 12, 14) were placed into moving material. All of them were built with pillars. The aim of geodetic monitoring system is to identify accelerations in the movement of the landslide, determine acceleration effect of groundwater level changes on landslide occurrence and call for emergency measures. To be able to monitor temporal changes of deformations, the most appropriate measurement periods have to be determined. Time interval of measurement periods can be determined according to status (active-passive) of causative force. The time interval of measurement periods for this area was determined according to precipitation regime. For this, precipitation data for a ten-year (years of 1990-2000) period was taken from the Trabzon Meteorology Station. Average monthly precipitation was plotted and monthly distribution of precipitation was determined for a year (Fig 2). According to Fig. 2, it was decided that the most appropriate measurements periods were 2nd, 5th, 8th and 11th month of the year. Measurements were made in February 2000, May 2001 and August 2001 according to this assumption. To see if the decisions made for the measurements periods are suitable, average monthly precipitation was plotted for a 1,5 year (months of November 2000-February 2002) period when the measurements were taken. Inspection of the graphic indicated that decisions made were appropriate.

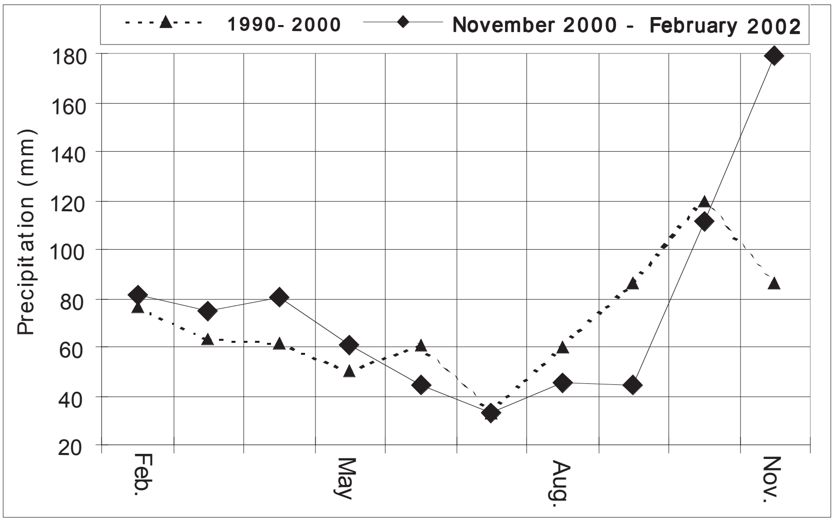

Figure 2. Precipitation regime in the study area

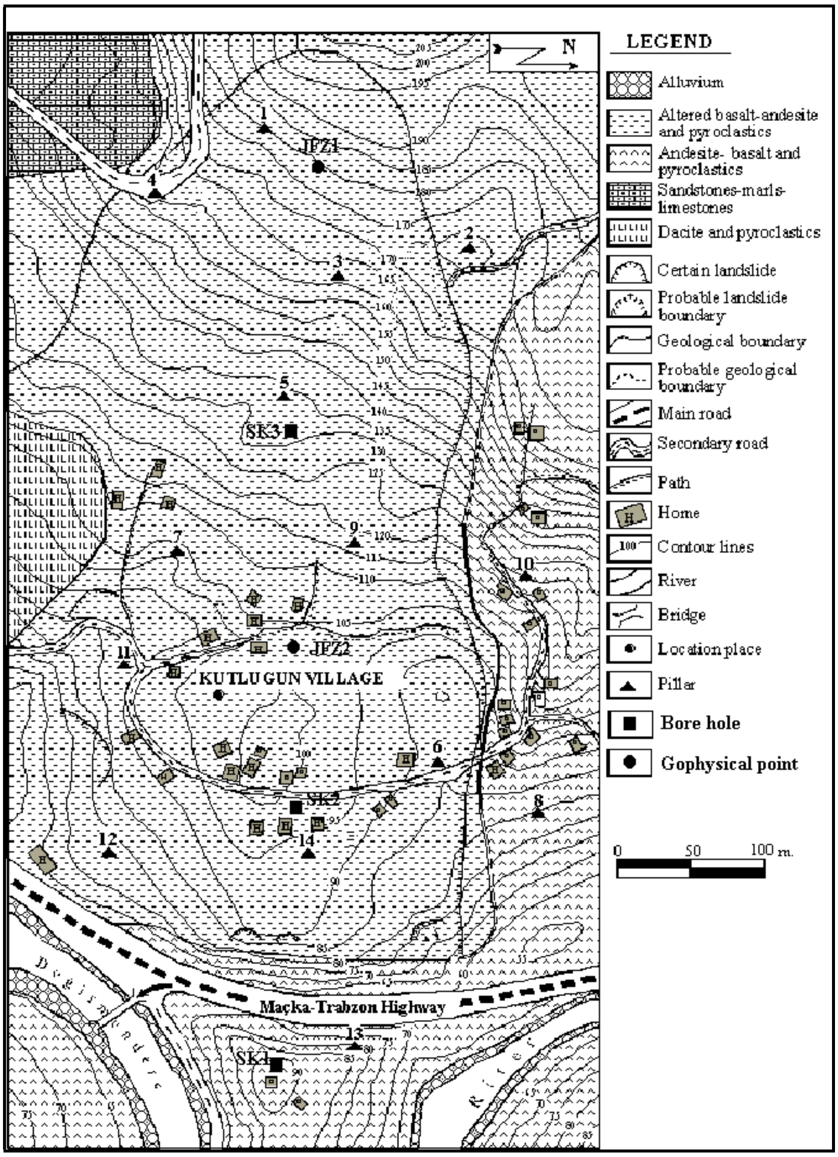

Figure 3. Geology and geomorphology map of the study area

In scope of geological studies, firstly, a geology and geomorphology map of the study area was produced (Fig. 3). Geomorphological structure of the study area was investigated to determine the current border of landslide, and a geomorphology map of the study area was prepared bye scientists of Karadeniz Technical University, Department of Geology and Geophysic. The type of movement according to Varnes (1978) classification of slope movements is slides. The type of material involved in Kutlugün landslides includes soil. Sliding is translational slide. Quantity of movement is several cm/month. Selection of location of network points was made according to this map.

To determine the deformations using the dynamic model, ground water levels at network points have to be determined for each measurement period. To do this, 17 drilling holes drilled by INSITU in 1995 were searched in the study area, but only three of them could be found (SK1, SK2, SK3) (Fig. 3). It was decided that three drilling holes would not be adequate to determine groundwater level changes and that at least two more points were also needed. Drilling a new borehole is expensive and it is difficut to protect it in the course of time due to landslide activity and the other causes. Thus, two points (JFZ1, JFZ2) where groundwater levels were determined by geophysical methods were located (Fig. 3). Vertical Electrical Sound (VES) method, one of the electrical resistivity methods commonly used in Geophysics, was used to determine groundwater levels at these points. VES method is used to determine resistivity distribution of earth in vertical direction. The subsurface is assumed to occur from horizontally stratified layers that are laterally homogeneous and isotrop (Zohdy, 1989; Telford at al, 1992; Loke and Barker, 1995). Measurements were collected with Schlumberger Electrode Array. Geophysical data were evaluated and then groundwater levels determined. As a result, groundwater levels were determined at three geological and two geophysical points. Groundwater level values of moving network points were derived from these five points with interpolation (Fig. 4).

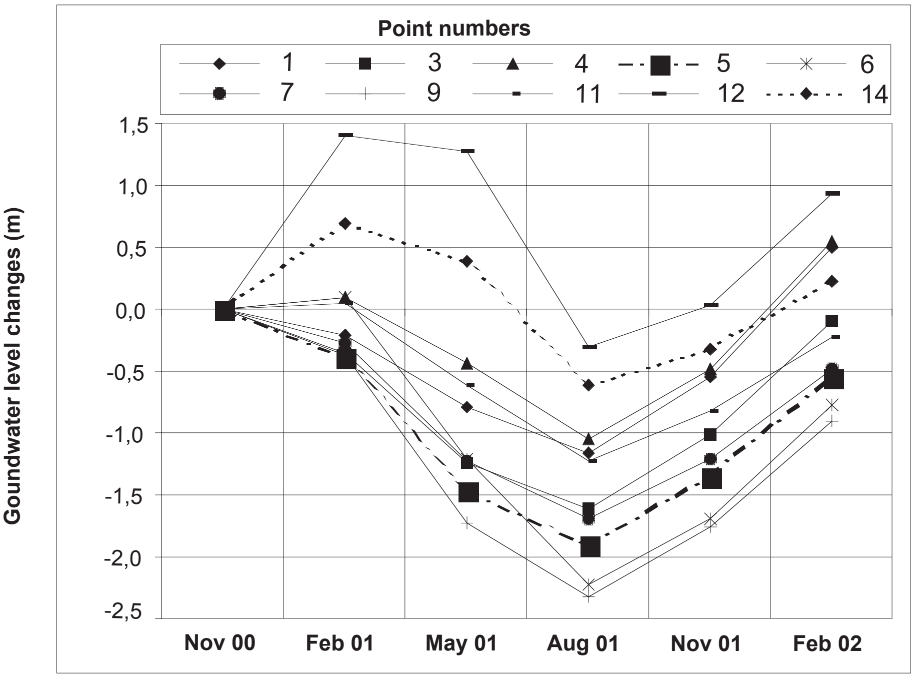

Figure 4. Groundwater levels changes at network points

Periodic deformation measurements with GPS using static mode and groundwater level measurements for six periods in deformation network (October 2000, February 2001, May 2001, August 2001, October 2001, February 2002) were made. Deformation network was adjusted as free in ever periods. In addition to dynamic model, movement were determined with a static (θ^2-criterion) and a kinematic (single point model) model in order to compare dynamic model results. In solving kinematic model, Kalman-filter technique was used. Deformation model results for point 1 were given in Table 2.

Table 2. Deformation model results for Point 1

Point Number: 1	Unit	Parameter	Static	Kinematic	Dynamic
Position	cm	x	-13.8	-16.1	-23.1
		y	16.2	18.4	32.3
		z	-4.8	-6.4	-6.5
Velocity	cm/ay	v_x		-1.3	-0.7
		v_y		2.2	0.3
		v_z		-0.2	-0.8
Acceleration	cm/ay^2	a_x		0.12	0.12
		a_y		0.05	0.04
		a_z		0.14	0.11
Groundwater		b_x			0.037
		b_y			0.016
		b_z			0.043
The most suitable model →			Position	Position + Velocity + Acceleration	Position + Velocity + Acceleration + Groundwater

It can be seen from Table 2, static model can determines only position parameters. Kinematic model can determine position, velocity and acceleration parameters. Static and kinematic models cannot include effect of groundwater level changes. Dynamic model contains calculation of groundwater parameter which shows geometric reflection of physical effect.

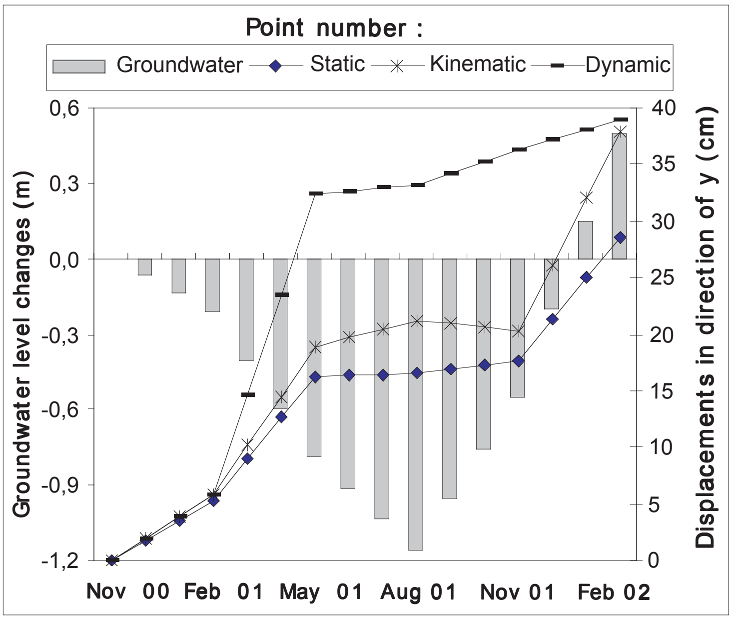

Figure 7. Relationship between static, kinematic, dynamic displacements and groundwater level changes

Figure 7 shows relationship between static, kinematic, dynamic displacements and groundwater level changes. Results of each model are together with harmonious. When examining figure, it can be seen that movements tends to rise when groundwater level changes are large. Movements tend to slowdown when groundwater level changes are small.

Figure 8 shows relationship between groundwater parameter and displacements in direction of y for point 1. Groundwater parameter shows the geometric reflection of groundwater level changes on point movements. When analyzing the sign and magnitude of this parameter, the effect of groundwater changes on point movements can be determined. The sign of groundwater parameter is also very inportant in interpreting the effect of groundwater level changes on point movements. If groundwater parameter is greater than 0, groundwater level changes increase velocity of deformation. If groundwater parameter is less than 0, the effect of groundwater level changes on point movements decrease. Temporal changes of groundwater level usually determine the sign of groundwater parameter. This evaluation enabled a deformation analysis to be made more realistically with respect to physical realities.

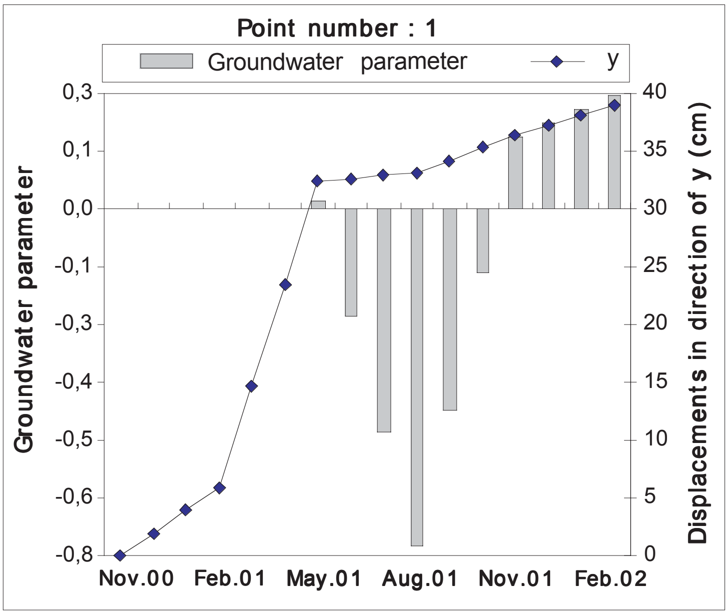

Figure 8. Relationship between acceleration effects of groundwater level changes and displacements

4. Conclusion

This article deals with the relationship between landslides and their causitive factors based on the new dynamic analysis method developed for landslides. The available 1.5 year detailed record of the Kutlugün landside indicates that this slow landslide is active and unstable. The analysis of the groundwater data clearly indicates that large groundwater level changes are an important triggering factor for Kutlugün landslide. Therefore, the effect of groundwater level changes cannot be ignored in the analysis of Kutlugün landslide. Static and kinematic models is sufficient in determining movements, but these statistical models of studying landslide prediction neglect climatic (precipitation, groundwater level changes, etc.) effects. Chaotic behavior in the evolution of the landslide system cannot be reflected and, hence, the long-term prediction of landslides cannot be made using these methods. The dynamic analysis method mentioned above is capable of determining relations between landslide and groundwater fluctuations in addition to displacements, velocities and accelerations of displacements. By means of the dynamic model, the simulation of dynamic behavior of mass having groundwater level changes is possible. Deformations monitoring with the dynamic model, determining relations between movements and groundwater level changes require a cooperation including the assistance of multi-disciplinary fields that span from geo-sciences to engineering. The dynamic model provided more detailed information (direction, greatness, velocity, acceleration of movements) about temporal behavior of landslide. It is possible to formulate more realistic strategies about prevention of landslides using this information.

Acknowledgement

This study was financially supported by KTU Research Fund Project and Chamber of Survey Engineers of Turkey.

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