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Prediction of Time to Failure in Creep Type Large-Scale Landslide

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ABSTRACT

Aims Time prediction of the main failure is of great assistance in managing the risk involved in landslide occurrence. The complexity of subsurface structure, lack of sufficient information about the slip surface, and complexity of seasonal factors make the prediction more difficult. Most of the solutions proposed for modeling the prediction of the main failure are not efficient and are associated with considerable errors due to the oversimplification. It makes the simultaneous incorporation of all effective factors nearly impossible. In this study, a reliable method was proposed for selecting the appropriate time to analyze the landslide movement and providing the speed threshold leading to the main landslide occurrence in a large-scale rockslide in the Anguran Open-Pit Mine.

Materials & Methods In this study, the data set of two years movement of a reliable creep type landslide in Anguran Mine (Zanjan, Iran) were implemented to modify the prediction method suggested by the previous study. The method of this study was a careful comparison of accelerator factors and landslide motion.

Findings The independence of the movement speed from the effective factors such as precipitation could be a reliable situation that can be used to predict the critical condition of landslide motion toward final and rapid failure. In this rockslide, 1.5 million m^3 block of stone slid into the open pit.

Conclusion The employed method presented in this study allows predicting the occurrence of a final rockslide within a reasonable interval of time and preventing the damage occurred through the timely evacuation of workers and equipment.

Keywords Landslide; Creep; Prediction; Early Warning

CITATION LINKS

[1] Environmental hazards: Assessing risk and reducing disasters [2] Special lecture: Some practical lessons in the investigation and field monitoring of landslides [3] Landslide susceptibility mapping and risk assessment on the Bamenda Mountain (Cameroon Volcanic Line) [4] The modelling of landslide hazards using Gis [5] A method for prediction of volcanic eruptions [6] A relation to describe rate-dependent material failure [7] How to obtain alert velocity thresholds for large rockslides [8] Failure forecast for large rock slides by surface displacement measurements [9] A methodology for physically based rockfall hazard assessment [10] Mechanism of landslides [11] Creep problems in soils, snow, and ice [12] Simulation of slope creep [13] Creep processes in landslides [14] A materials failure relation of accelerating creep as empirical description of damage accumulation [15] Forecasting the time of occurrence of a slope failure [16] A method to predict the time of slope failure caused by rainfall using the inverse number of velocity of surface displacement (in Japanese) [17] Accelerating creep of the slopes of a coal mine [18] A simple definition of a landslide [19] Failure of soil due to creep [20] Forecasting time of slope failure by tertiary creep [21] An application of Voight empirical model for the prediction of soil and rock instabilities [22] A materials failure relation of accelerating creep as empirical description of damage accumulation [23] Structural constraints on deep-seated slope deformation kinematics [24] Predicting time-to-failure in rock extrapolated from secondary creep [25] Recovery of lead-zinc from Angouran mine Iran [26] Hypogene Zn carbonate ores in the Angouran deposit, NW Iran [27] Marble-hosted sulfide ores in the Angouran Zn-(Pb-Ag) deposit NW Iran: Interaction of sedimentary brines with a metamorphic core complex [28] Seimareh landslide, the largest complex slide in the world [29] Mechanism of the giant Seimareh landslide, Iran, and the longevity of its landslide dams [30] Long-term stability of clayey slopes [31] Landslides, disaster risk reduction

Introduction

Landslide control programs and remedial works are almost impossible in large-scale landslides. In this regard, one of the important solutions in risk management is the time prediction of the main failure for evacuating the population and protecting the assets against landslide, mass movement, and debris flow. The activity of landslides is affected by various factors, which make it difficult to find a reliable model for predicting the time of ultimate catastrophic failure [1]. Factors such as the heterogeneity of the sliding mass, the complexity of subsurface structures, and the multiplicity of seasonal factors affecting the activity of landslides, make the time prediction of the landslide failure more difficult and less precise. This inaccuracy and difficulty are directly related to the scale of the landslide; the larger the landslide and the extent of the area involved in the instability, the more complicated the predictive process, and the less accurate the predicted failure time. Considering the complexity of the analysis of several variables affecting the slope displacement in predicting the time of main failure and since all factors affecting the slope activity are manifested in its displacement behavior, the use of time relations and displacement changes in time prediction of the main failure has received the attention of engineering geologists and landslide scholars. Regarding the lack of access to all information needed to provide a precise model; the proposed solutions are inefficient and involve significant errors due to the simplification of models and the impossibility of applying all effective factors simultaneously. The most important factors to be considered in modeling are the complexity of the slip structure, the nonlinear relations of time and displacement, and seasonal effects on sliding behavior [2]. Despite the complexity of this issue, the importance of achieving a reliable method for predicting the time of the main failure of the large-scale landslide and its role in risk management has led to numerous efforts.

In addition, given the high cost of remedial works to control the large-scale landslides and, in many cases, technological shortcomings for assessing the large-scale landslides, urban planners and managers seek rigorously to predict the future behavior of landslide accurately and to predict the main failure time for the early warning. Having sufficient and relatively reliable information about the landslides occurrence probability in areas such as open-pit mines, slopes in uplands of towns, villages and economic areas, steep slopes adjacent to highways, railways, and other lifelines such as electric lines and gas and oil pipelines can be very effective in evacuating people, interrupting traffic and electricity, and controlling the flow of oil and gas to reduce damages. In this connection, for a reliable prediction and management of the large-scale landslide crisis, analysis of the relationship between slope activity and changes in triggering factors is of high necessity. As a result, monitoring the displacement behavior of landslides and the factors effective on landslide motion is of paramount importance in predicting the future behavior of the landslide and the probable time of the main failure for developing a reliable model. The relevant literature in this regard focuses on collecting the monitoring information as a network for obtaining the yield levels of factors (for example, displacement, motion rate, rainfall, underground fluctuation, etc.) and presenting a model for predicting the occurrence of the main failure of the landslide. One of the most important challenges in landslide studies is the lack of reliable predictions of the main failure made by different models using displacement-effective factors curve. The main reason for these uncertainties seems to be the lack of a clear indication of selecting the proper point on these curves as the threshold speed resulting in a final disastrous landslide.

In this paper, it is tried to use reliable data on a critical slope in an open mine using the model presented by Voight [3-6] and Crosta and Agliardi [7] to find out how to analyze the information and choose the best method for selecting the proper point of time displacement curve to achieve a successful model for the failure time estimation. The case study is located in a relatively large-scale slope in one of the largest and oldest Iranian lead and zinc mine in Zanjan province, Iran. The mine is located in the northwest of Iran, which has an extraction history of about 70 years. The first evidence of instability indicators in the northern outcrop of the mine was reported in the winter of 2004. Considering the very high risk of landslide occurrence in this mine, which could have resulted in financial losses and possibly fatalities, it was attempted to more accurately identify the unstable area and predict the areas with large-scale sliding probability in the plan of the mine managing team. Using the Voight [5, 6] and the modified Crosta models [8, 9] and with the help of an empirical analysis on 94 sets of weekly data in the Anguran Mine, a reliable method is presented for the analysis of information and predict the time of occurrence of the main landslide.

Slope Stability Theory: Given that in a finite slope, the assumption of mass homogeneity is acceptable, the use of the limit equilibrium equations, which are based on two stable and unstable states on a slope, is usually well responsive. However, due to the structural complexity of large-scale slides, it is not generally possible to assume homogeneity. Accordingly, the use of limit equilibrium equations is usually not recommended, as they do not have the ability to assess the long-term instability in a rockslide or rock block glide.

In large landslides, due to the large size of the unstable block and its massive mass, mass changes in the displacement route are negligible. Here, the conditions are characterized by the presence of a continuous and permanent (constant) stress and a gradual downward sliding. This sliding behavior was named by Terzaghi [10] and later by Haefeli [11] as creep landslide. Creep is technically defined as the deformation or flow of soil, rock, or ice by its own weight or the continuous external force that lasts on a slope over a relatively long time [12]. Several factors can lead to the formation of creep landslide. One of the main reasons for these features might be the change in the geometric shape of the slope due to the progress of the process, such as water erosion and consequently increases in the shear driving force comparing to the shear resistant forces. Another reason for the activation of a creep landslide can be the progression of weathering processes and the change in the geotechnical properties of slope masses. The onset of a creep landslide usually begins with a slow motion followed by a progressive movement with a gradual displacement, which ultimately results in an abrupt high-velocity landslide [5, 13-16]. Various models have been presented for monitoring and predicting the time of ultimate failure in creep type landslide. Regarding the accepted principles of creep landslide [17, 18], the models work based on linear equations, an exponential function, or power function [15, 19, 20]. For example, in, the theory of nonlinear landslide behavior was presented and an equation was proposed for predicting the deformation rate with time as follows:

$$log(t_f) = c - m \, log \, \dot{\Omega} \qquad (1)$$

Where, tf is the time of occurrence of the landslide, $\dot{\Omega}$ is the displacement rate or deformation; c and m are the experimental coefficients.

The model presented by Saito [15] has a weak correlation with the behavior of creep type landslides. In the method proposed by Fukuzono [16] and Voight [5, 6], some important and fundamental changes in the theory of creep were presented. Fukuzono proposed an empirical relation for creep, which later was analyzed and validated by Voight [5] assuming a constant and non-variable load with the power law method as follows:

$$\ddot{\Omega} = \mathrm{A} \, \dot{\Omega}^{a} \qquad (2)$$

Where, $\ddot{\Omega}$ is the acceleration of the displacement, $\dot{\Omega}$ is speed, and A and a are numerical constants.

The Voight equation for $\alpha > 1$ can be represented as an exponential function (Power Law) as follows:

$$\dot{\Omega} = \left[A(a\text{-}1)(tf\text{-}t) + \dot{\Omega}_f^{1\text{-}a}\right]^{1/_{1\text{-}a}} \qquad (3)$$

Where, tf is the time of landslide occurrence (if threshold speed $\dot{\Omega}_f$ happened), α is a dimensionless parameter varying between 1.7 and 2.2, which expresses the sensitivity of the slip acceleration variations (Diagram 1), and A is a positive constant that controls the shape of the curve.

This method was performed by examining the time series of displacement and external factor such as precipitation. As can be seen, the model proposed by Voight is more similar to the physical and empirical-based models. An example of such a model was developed by Saito [19, 20] that nearly was able to predict the time of main failure [6, 21, 14]. One major drawback to these models is that they are only used in situations where the landslide has a continuous acceleration rate under the influence of an external or internal constant factor. This model will not succeed, for example, if one of the factors is not constant over time and is affected by seasonal changes such as rainfall and temperature. In the model suggested by Crosta and Agliardi [7], an effective time-dependent method was suggested using the semi-experimental method of Voight [5, 6] for predicting large slides. This method involves the calibration of the Voight model to discover the curve characteristics and the nonlinear relationship of rock mass behavior toward the complete landslide, which is based on the time series data of land kinematics and climatic conditions. The Voight model is an empirical physical model previously proposed by Saito [19]. The model was able to provide satisfactory predictions [6, 14, 23, 24].

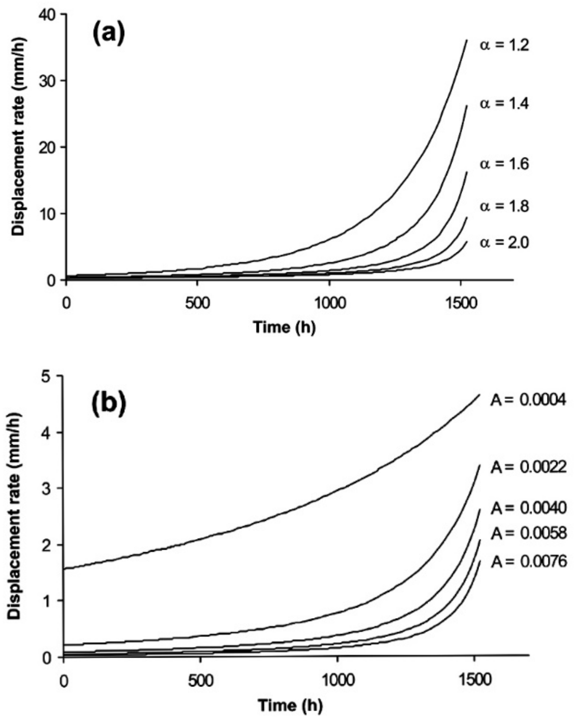

Diagram 1) Sensitivity analysis of the Voight model using Eq. 3 for parameters α (left) and A (right) [2]

In a practical example, the stability and reliability of threshold speeds were evaluated for the large-scale Vajont rockslide [5], for which, the movement rates of 10, 20, and 60mm d^{-1} were obtained for 30, 15, and 7 days before the final failure (October 9, 1963), respectively. The parameter A was calculated for different displacement thresholds velocity of 20, 40, and 75mm d^{-1} is well suited to the threshold intended to Vajont rockslide (Diagram 2).

It is observed that this method has good advantages because of the experience of Voight and other predictive models provided. The model can be easily implemented in land planning and disaster management and does not have problems with the application of other predictive models. It is inferred from the Voight model, which is highly nonlinear, the controlling factors such as velocity and displacement can perfectly interpret the process of changing a creep landslide to a rapid failure of the landslide. In addition, the delay in predicting failure times due to the weather effects occurring at the end of each season changes the curve adaptation of the Voight method to the curve obtained using the collected data. For instance, in the time-displacement diagram of the Vajont rockslide, two states could be recommended to predict a final failure (thick and thin curves, Diagram 2), while the main failure occurred in the second increasing part of the curve (thin curve). This issue is one of the most important ambiguities in using this method. Generally, as long as there is a seasonal behavior, the method proposed by Crosta and Agliardi [8] is reliable for a special condition. Thus, when the season is an active period of slope movement (rainy seasons), the data analysis must be continuously updated and new threshold rate of landslide should be used for more precise prediction. The main problem in this regard is choosing intervals from the curve, for example the movement rate of the transition to the threshold range, which is a very difficult task due to the alterations of rainy and dry seasons (active and semi-active slope movements).

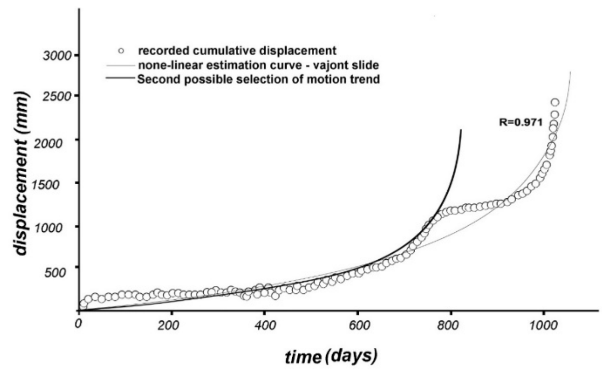

Diagram 2) Verification of the reliability of the Voight model to achieve threshold velocities for the large-scale Vajont Rockslide [5]

Overall, it has to be admitted that the studies were carried out by Terzaghi [10] and after that by Haefeli [11], and valuable studies were conducted by Saito [15], Fukuzono [16], and

Voight [5] can be utilized for the appropriate modeling of continuous monitoring of a creep landslide. These researchers broadly discuss the time prediction of the occurrence of a final disastrous failure in creep type landslides. One of the latest researches is the study of Crosta and Agliardi [8] who modified the model proposed by Voight [6], which was able to provide acceptable prediction accuracy. As mentioned earlier, in most of these models, there is a fundamental problem that can only be used for continuous acceleration information under the influence of a constant external factor. As long as the external conditions are not constant and are sensitive to seasonal variations such as rainfall and temperature, the model will not provide a good prediction. The main drawback of this uncertainty is the repetition of similar nonlinear behaviors since each period of rate increase can be considered as the entry of the creep curve into the final creep (Tertiary creep), while it is a seasonal nonlinear increase.

In the present study, a reliable method was proposed for selecting the appropriate time to analyze the landslide movement and providing the speed threshold leading to the main landslide occurrence using 665-day (95-week) observation in a large-scale rockslide in the Anguran Open-Pit Mine.

Materials and Methods

In this research work, the reliable data set of movement, as well as basic information and maps of Anguran Mine, were employed to develop a new approach for prediction of time to failure in creep type landslide in this mine.

Anguran Open-Pit Mine: The Anguran Mine is an open-pit mine of Zinc and Copper that is located in the northwest of Iran and in the boundary of the three western provinces of Iran including East Azerbaijan, Zanjan, and Kurdistan (Figure 1). The average elevation of the area is 3100 meters (a.s.l.).

The study area has mild summers and cold and long winters. The temperature in the coldest period in winter reaches -30°C. The average annual rainfall in the region reaches a maximum of 300 to 400mm. The average long-term rainfall in the mining area reaches 280mm y^{-1}, with the heaviest rainfall in the spring and fall and heaviest snowfall in the winter. Review of mine history and documents shows that the mine operations were planned for an open-pit mining without predicting any possibility for instabilities in the surrounding flanks. Anguran Mine extraction have been started since 1945 using an underground operation system, but the development of open-pit mine activities has begun since 1973. Anguran Ore is one of the most valuable and rare deposits in the region, with the Zinc content of 32% and Lead content of 3% [24, 25]. The storage volume was estimated to be about 17.6 million m^3 of ore. The composition of deposits is Sphalerite, Galena, Smithsonite, and Cerussite [26]. According to the extraction plans, the average exploitation in 1973 was about 17,000 tons per year and the open-pit mine operations would last up to 2024 and will be continued as an underground mine operation [26]. The first report of instability in the northern outcrop of mines dates back to the winter of 2004 (Figure 1). During this event, evidence of cracks in surface soils and exposed hard rocks in the northern side of outcrop at the northeast of pit mine was observed. Based on a preliminary morphological analysis of the region, the probability of a massive rockslide into the mine pit became stronger. The intensive and detailed investigations including continuous monitoring of slope movement, engineering geology, geotechnics, and hydrogeology were planned to recognize the scale of instability and to achieve a model for early warning. Soon after the formation of the study team, monitoring of land movement was started using field survey equipment (Total Station) since the spring of 2005.

Anguran Mine Creep Rockslide: Considering the initiation of the creeping movement observed in northwest flank of the open pit of the Anguran Mine since winter 2004 and due to the high risk of such potential rockslide, a comprehensive study was put on the agenda to determine the expansion of the unstable region and develop a model for early warning system and risk assessment. At the beginning of the study, benchmarks (BM) were set and the movement of the unstable area was monitored using the total stations (Figure 2). The weekly data of BMs were collected for several months. This monitoring work was continued for detecting any unexpected motion that can be used for securing the study team as an early warning system. The geologic formation in the unstable region is a portion of the geological of Central Iran Zone, which is located in Takhte-Soleiman geological map (Geological survey of

Iran, 1:250,000 series of the map, Takhte-Soleiman quadrangle map, 47°00' to 47°30'E and 36°30' to 37°00′N). This region geologically has a specific complexity, ranging from the Cambrian to the present (Figure 3); however, the formation and stratigraphic features in the landslide area is simple.

In general, the geology of the region consists of complexes of intrusive and extrusive igneous rocks, as well as sedimentary and metamorphic rock complexes. The area has been exposed to relatively large intrusive masses leading to its massive metamorphism. The reasons for the severely low shear strength of the rocks in this area are their high weathering susceptibility of metamorphic masses especially schist to clay minerals that have resulted in many slope instabilities in the region. One of the relatively large-scale landslides in the region was the reactivated landslide in the northwest flank of open-pit Anguran Mine, which was selected for present study (Figure 3). The extensive development of faults and fractures in the region and the secondary activities of post-magmatic, such as hydrothermal liquid penetration into these opening, have led to the formation of a vast amount of mineral deposits in the region. In addition to the inherent geological factors, the effect of relatively heavy rainfall in the region and the transfer of groundwater through limestone formations from adjacent basins can also be one of the major causes of the occurrence of landslides in this area. Also, the role of the humans in creating steep slopes through road construction, open-pit mining, and other development activities should be taken into account as the factors that stimulate slope instabilities. To clarify the detailed subsurface geological structure, a borehole drilling was planned. By employing the data obtained from surface surveying studies, geomorphology, engineering geology, surface topography, and a geological log of the borehole, the profile of the unstable block along the main axis of the unstable block was prepared (Diagram 3). As the occurrence of instability in this open-pit was not predicted in its operation plans, no historical background was found in mine documentation. As can be seen, the calcareous block of landslide with an altitude of about 120m (from the bottom of the mine pit) slid down over a layer of schist.

The result of the preliminary studies confirmed that the presence of numerous joints and cracks system in the overlaid limestone and rapid penetration of rainwater into the depth and to the contact of limestone and schist caused the deep weathering of this discontinuity. This process leads to the decomposition of the minerals of schist layered and the formation of clay minerals, thus creating a surface with a low shear strength and landslide occurrence. In general, the hard rock unit involved in the unstable block includes a series of weathered limestone with dissolving joints over the crystalline schist layers. The limestone of the region is highly fractured and has dissolution features along the fractures. Even in some parts of this dissolution, the formation of small caves is seen. Schistose inherently weak rock that affected by alteration and weathering. In most discontinuities such as contact of the layer, the main and secondary faults that were influenced by water and hydrothermal fluid are filled by highly loose and weak cement. Because of the structural conditions and high permeability of overlaid layers, the progressive secondary weathering in the region has been remarkable. Accordingly, even in some of the opening and surfaces, clay minerals have formed, which has led to a sharp decrease in shear strength of material along these discontinuities. This condition has made the area susceptible to different types of landslides. In short, the abundance of weak layer such as schist, the presence of altered limestone layers, the high dissolution of lime, the high permeability of overlaid formation, susceptibility of underlay formations to weather, the development of various fault systems, and finally the hydrothermal activity, are among the factors contributing to the development of landslide activities in the region.

Anguran Mine Rock Slide Monitoring: For detail studies, various instruments such as field survey instrument (Total Station), surface invar line extensometer, Dual Frequency GPS (DGPS), and in-borehole extensometer were considered. Due to the unstable wall of the drilled borehole, it was not possible to install a suitable casing for depth reading by the borehole inclinometer. Thus, the plan of drilling more boreholes was canceled. Considering the importance of the landslide risk in Anguran Mine, weekly monitoring was implemented using Total Station from the spring of 2005 before the installation of any fixed tools. This network includes 40 benchmarks over the unstable block (Figure 2). In the second phase, after completion of geological studies, all active joints and discontinuities were examined and the approximate border of the unstable block was determined. Cracks at the initiation stage of instability (April 2005) and their development (August 2005) are shown in Figure 2. Two invar line extensometers were set across the most active cracks at the upper limit of the unstable block (Figure 2). The DGPS tool was used for measurement of displacement at 14 benchmarks installed on the study area, which include 11 benchmarks on the unstable region, 2 benchmarks at the stable upstream region, and 1 benchmark as reference point in the distant areas (1km away from the open-pit; Figure 2).

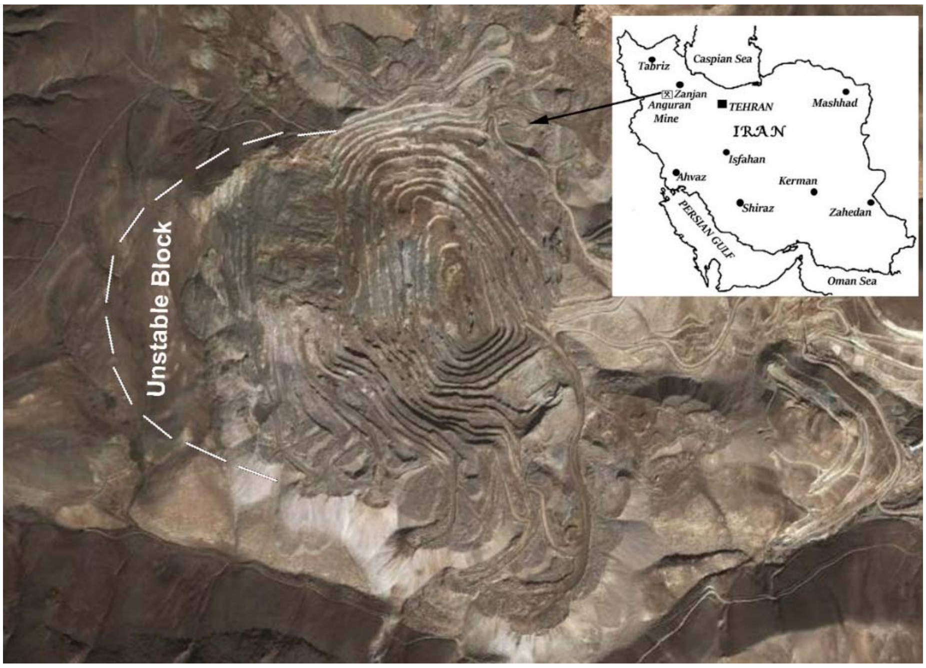

Figure 1) Location of the studied landslide

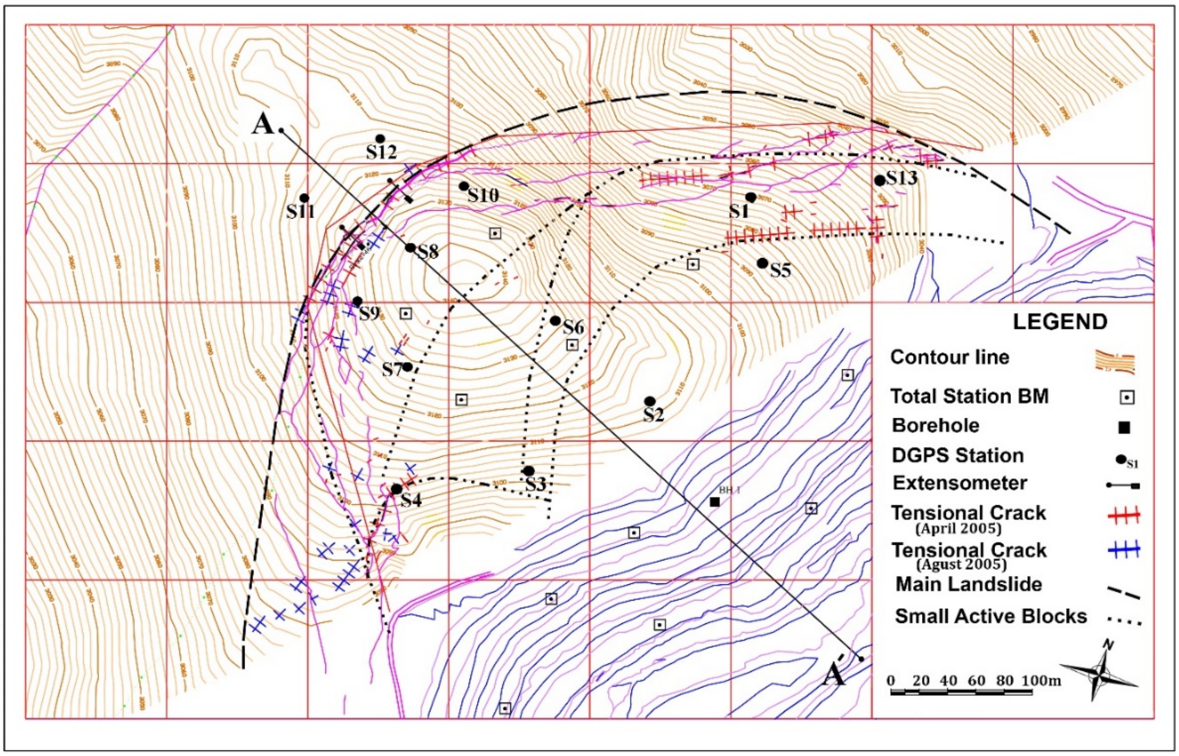

Figure 2) Simplified engineering geology map and monitoring system (line AA′ refer to the direction of the prepared profile shown in Figure 3)

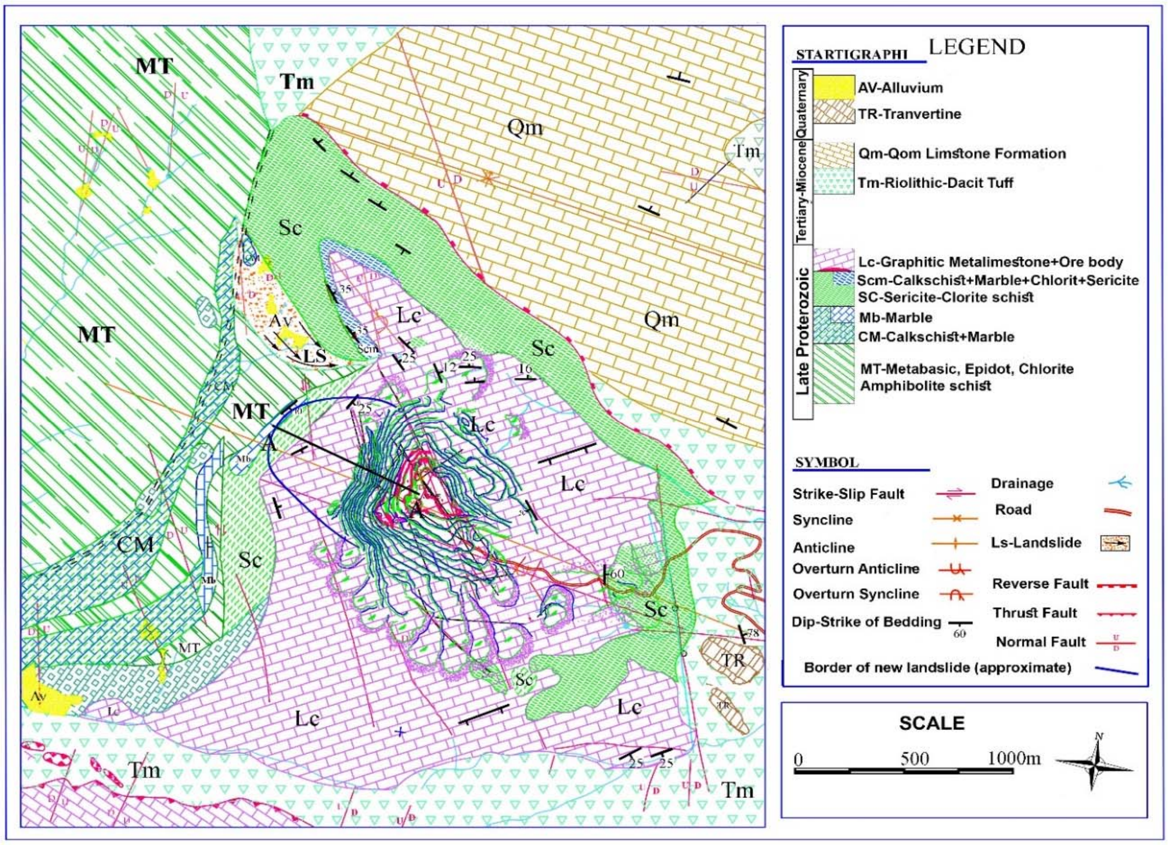

Figure 3) General geology and structural geology map of the Anguran Mine, its adjacent area, and the landslide location

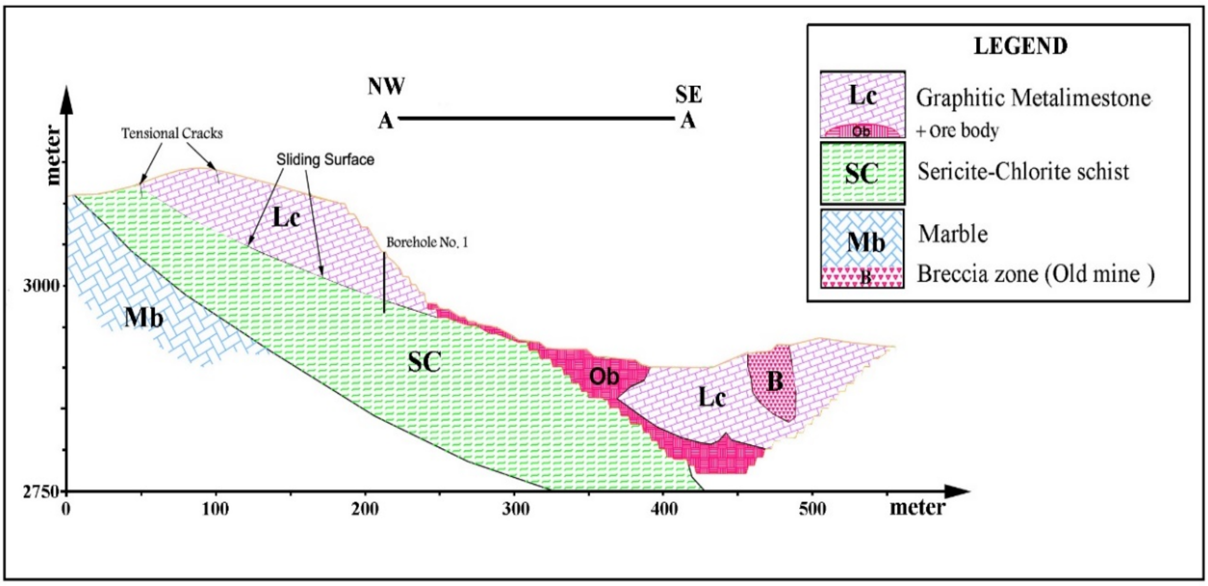

Diagram 3) A geological cross-section of the unstable block shown in Figure 3

Findings

Monitoring Results: As mentioned earlier, monitoring began in spring 2005 using field survey equipment (Total Station) on a weekly basis, which provided proper time series data of landslide movement. Due to disturbance of the surface of the unstable block and destruction of some selected sites, the data collected from fall

of 2005 were not reliable and then were discarded. The weekly data obtained from the landslide displacement measurements by the Total Station from the spring to the end of summer of 2005 (March to September 2005) were added to the data recorded by the extensometer (since fall 2005), which were used in this work.

Monitoring by DGPS: The monitoring of slope movement by DGPS was started from fall 2005 (October 2005) to summer 2006 (August 2006). In each step of reading, the coordinates of 14 platforms (11 platforms on the unstable zone and 2 platforms out of the unstable area and 1 platform as a reference point) were measured in X, Y, and Z directions. Then, by subtracting the current measurement from the previous step, the rate of displacement of the ground was obtained in the three original X, Y, and Z directions for intervals of two readings. In the next step, the resultant vector on the X-Y plane was drawn on the position of the sliding surface as the real displacement. Since the information obtained in DGPS monitoring was periodic and discontinuous, their direct use in the analysis of the motion behavior of creeps was not desirable. Nevertheless, it can provide an effective map for understanding the incremental or decreasing the rate of movement and their distribution of motion in the unstable area. The surface monitoring of landslide movement using DGPS was performed almost every 45 days; *i.e.*, two readings per season. Each step of measurement took place in less than a week. In order to reduce the error caused by the frequent installation of the antenna on the benchmarks, each station has an appropriate bolt for direct mounting of antennas on benchmarks. In order to increase the accuracy of readings, the DGPS reading network was programmed in such a way that each station has at least three readings from three surrounding stations in each step. The reading time was chosen in such a way that the region would have the most coverage of 12 reliable satellites. Among the different methods of reading by DGPS, the static method with the highest accuracy was selected. The appropriate time for picking and recording data for each station was decided based on the device software offer. Accordingly, the time for recording data at each station took up to 45-90 minutes for each step. The displacement at the reference point (S14) benchmark, which was located few hundred meters far from the unstable area and in the office area of the mine, was almost zero at all steps of reading, indicating the proper selection of this point as Reference. The displacement rate at stations S11 and S12 was also within the error limit of the device and was considered as relatively stable points outside of the unstable area. The results of the 6 steps are shown in Figure 4. It is concluded from this map that the displacement rate of the stations located on the landslide area was ascending with an average displacement of 35 to 50mm in the first three readings in a 45-day period. The trend from 4 to 6 reading was particularly significant, with the last reading of the shift in 11 stations located on the unstable region between 110 and 150mm in the interval between the readings. Unfortunately, due to the increased displacement and dislocation of benchmarks on the unstable block, the 7th step of measurement was not possible and the main rockslide occurred on October 7, 2006.

Monitoring by Invar Wire Extensometer: To develop a model based on changes in the velocity and displacement rate of a landslide, continuous time series data are required. As the displacement measurement by DGPS was done every 45 days, this information was not fully satisfying the need of this research. However, it was very useful for controlling the trend of increasing or decreasing rate of movement. Therefore, to complete the required data, two invar wire extensometers were used for recording continues changes of movement. The installation location of the extensometers is shown in Figure 2 Because of the necessity of full information coverage and the need to complete the time series data, the weekly data recorded by the Total Station from the spring of 2005 were added to the information obtained by the extensometer starting in fall 2005. For uniformity of the obtained information, the extensometer-recorded data were also converted to weekly measurements. In this way, the information on the slope behavior of the Anguran Mine used for creep analysis was completed with the appropriate coverage from spring 2005 to fall 2006.

Based on the field survey conducted in spring (March, April, and May) 2005, the observed small cracks confirmed the initiation of rock block slide on the northwest flank of the open-pit of Anguran Mine. The recorded movement of the early spring (March) of 2005 was very small and reached some 0.1mm in few weeks of time intervals. In the last month of the spring (May 2005), the total displacement in the stations near the main slope was 2mm per week. With the onset of the summer season (June 2005), the growth has been slowed down and limited to less than 1mm. With the start of the fall season and the beginning of season rainfall (October 2005), the rate of movement increased and surface evidence of slope movements became more evident, by the appearance of growing of tensional cracks in the surface soils, and the weekly movement reached about 2.8 to 0.4mm acceleration in different station. Growth in the slope movement at the final month of fall (December 2005) increased and reached about 2.40 to 3.60mm per week. The decrease in the displacement amount in the summer and then increase the in fall of 2005, which coincided with the increase in the rainfall in the region, is strong evidence that the displacement of this slope is affected by seasonal changes. Landslide activity was clearly reduced at the beginning of the winter (January 2006), so the landslide displacement rate of early winter was about 3.1mm per week. Despite the high precipitation in winter, the decrease in the rate of movement could be due to precipitation in the form of snow and the absence of runoff due to extreme cold. This low activity of slope lasted until the end of the winter (early March 2006). With the onset of the spring season (late March 2006) and the onset of spring rainfall, together with the melting of accumulated snow, the moving rate increased dramatically and reached 6.2mm per week on first of spring (early March 2006). This growth has also been evident in DGPS readings. In the second month of spring (April 2006), the rate of movement has been around three times the first month; *i.e.*, 11.4 to 18.4mm in different stations. The abundance of runoff in spring is the main cause of acceleration of landslide motion rate. In the last month of the spring (late June 2006) the trend of movement continued to increase such that the rate of movement with a growth rate lower than the second month varies from 11.66 to 20mm per week. Within the first month of summer (late June), weekly shift in the displacement rate was observed. The decreasing rate was from 6.7 to 17.2mm per week in different stations. According to the experience of the last summer and winter, with a decrease in runoff and water penetration in the masses, the displacement rate was reduced. Moreover, despite observing an apparent and expected decrease in the first month of summer, from the beginning of the second month of summer (July 2006), the rate of displacement increased and reached about 42-49mm per week. Although there was no significant rainfall in the area, in the third month of summer (August 2006), up to September 15, the trend continued to increase and reached about 70-84mm per week. In the late September (20-25), 2006, the rate of displacement increased dramatically, reaching about 140mm per week in the last week of September and around 280-420mm in the first week of October 2006 in different stations. From 6, October 2006, the information was not recorded due to the invar line breakage. The main failure and destructive landslide started on October 6, 2006, at around 18:30 and continued until 5:00 AM. of the following day. The recorded data by extensometer and total station for 84 weeks from spring 2005 to fall 2006 is presented in Diagram 4.

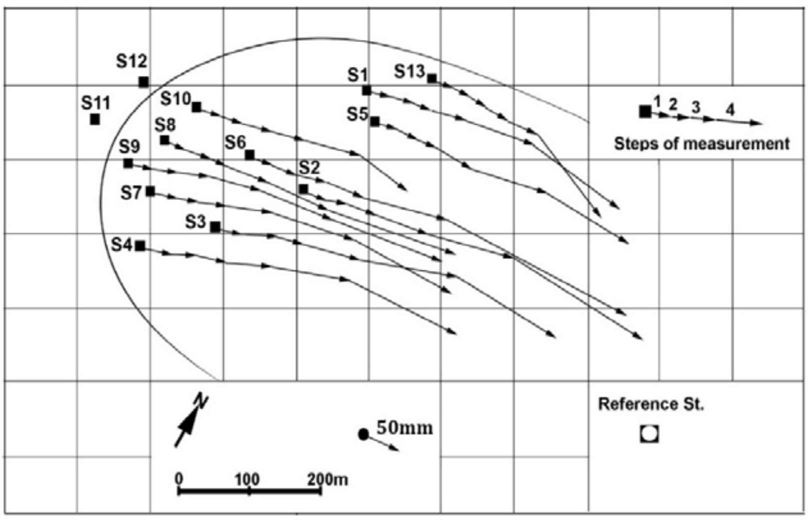

Figure 4) The map of displacement vectors for 6 reading steps measured by DGPS for 13 stations in a northwest block of Anguran open pit Mine and one reference station

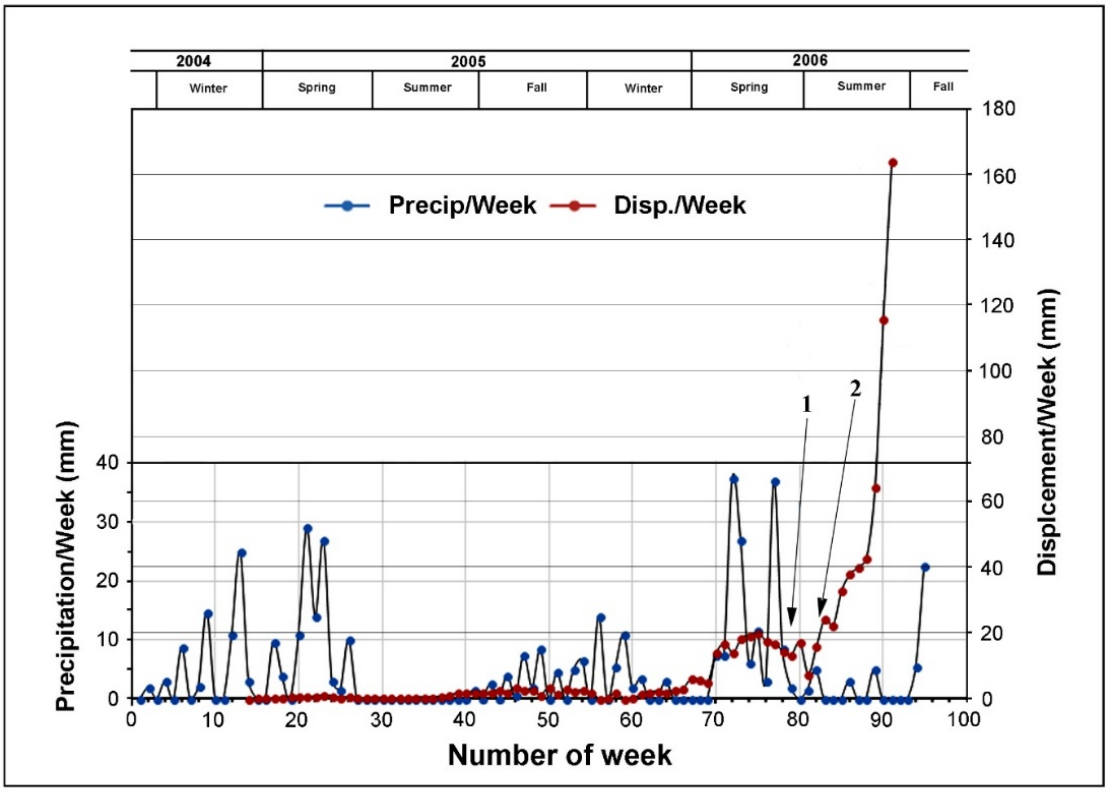

Diagram 4) The graph of precipitation and movement for 94 weeks (winter 2004 to fall 2006)

Discussion

Several studies have been carried out on the use of creep behavior to predict the time of the main failure of landslides. Terzaghi [10] is likely the one who put forward the first idea in this regard. The idea was completed later by Haefeli [11]. Further valuable research works were discussed and developed by Voight [6], Saito [15], and Fukuzono [16]. These investigations have been able to largely utilize appropriate models based on continuous monitoring of a creep type landslide. The latest research on this subject was conducted by Crosta and Agliardi [7], which provides an almost accurate model through modification of the model provided by Voight [6].

In most models, there are fundamental problems that limit their application in an accelerating motion under the influence of a constant external factor. To be more specific, since the external conditions are not constant and vary according to seasonal changes, such as rainfall, groundwater fluctuation, and temperature, the model will not provide a reasonable prediction.

Another uncertainty is to select the most fitted part of the curve of time-effective factors variations, which leads to the main failure. To our knowledge, the behavior of a given landslide is a function of the geological structure, type and geotechnical properties of the sliding surface materials, and the intensity and the rate of changes in effective factors. The landslide movement behavior acts irregularly at the initiation of its creep, due to the lack of continuous sliding surface. However, as the sliding progresses, the complete slip surface forms and the creeping landslide behavior begins. The continuous recording of the factors affecting slope activity, such as. The rate of slope movement, makes it possible to develop a more precise model predicting the time of the main failure in a creep-type active landslide. This time prediction will be a key factor for risk management and estimating the probable damages [27, 28]. Having accurate information on the shape and position of the sliding surface and even the information on its constituent material and the analysis of the geotechnical behavior of the mass and sliding surface can provide a better prediction of the type of motion and the travel distance of masses, resulting inaccurate prediction of the consequent damages [29, 30].

In reviewing the history of the Anguran Mine landslide, it seems that the movement of a hard limestone block on a soft layer has initiated several years ago. As in the winter of 2004, tensional cracks emerged at the upper hand of the block. The creep behavior of landslide began by increasing the rate of slope movement. By the spring of 2005, more tensional cracks on the surface were observed. Since summer 2005, the surface evidence was observed with the continuation of mild movement and the formation of the sliding surface (Diagram 4). Evaluation of the movement rate in different seasons from 2005 to 2006 revealed that the landslide in Anguran Open-Pit Mine has a high sensitivity to rainfall events. This sensitivity can be attributed to an increase in the weight of sliding mass or the effect on the fluctuation of the groundwater table. The data from a borehole on the mine area over the unstable blocks showed that due to the presence of many fractures and joints in the overlaid limestone and the underlying schist layer, formation of the continuous water table in the sliding block is not expected. Thus, monitoring of changes in the groundwater table is not possible. In a slope instability standpoint, it is likely that the causes of slope movement should be due to an increase in the block weight and an increase in driving force caused by mass water absorption.

As noted by Voight [6], the essential condition for a reliable prediction is the existence of a non-variable external factor that practically does not occur in many creep landslides. The main problem in this regard is to choose the best point of the creep cumulative curve for making an early warning alarm for evacuation. The model proposed in this study is based on the theory provided by Voight [6]. Based on the findings; it is possible to choose the correct portion of the creep curve that leads to final and disastrous failure with the highest precision. The monitoring results of extensometer and total station for 84 weeks from spring 2005 to fall 2006 present a series of steps of increase and decrease in the displacement rate (Diagram 4). Each sharply increasing portion of the curve in the time-displacement graph could be considered as the time for final failure occurrence, which is in fact uncertainty in the decision of the appropriate time selection. In Anguran region, spring, fall, and winter are relatively rainy seasons while no substantial rain is expected in summer. Based on the Voight's model, each increasing portion could be considered as the critical condition that does not result in the accurate prediction. For a better understanding, the cumulative curve of precipitation and displacement for the entire period is shown in Diagram 5.

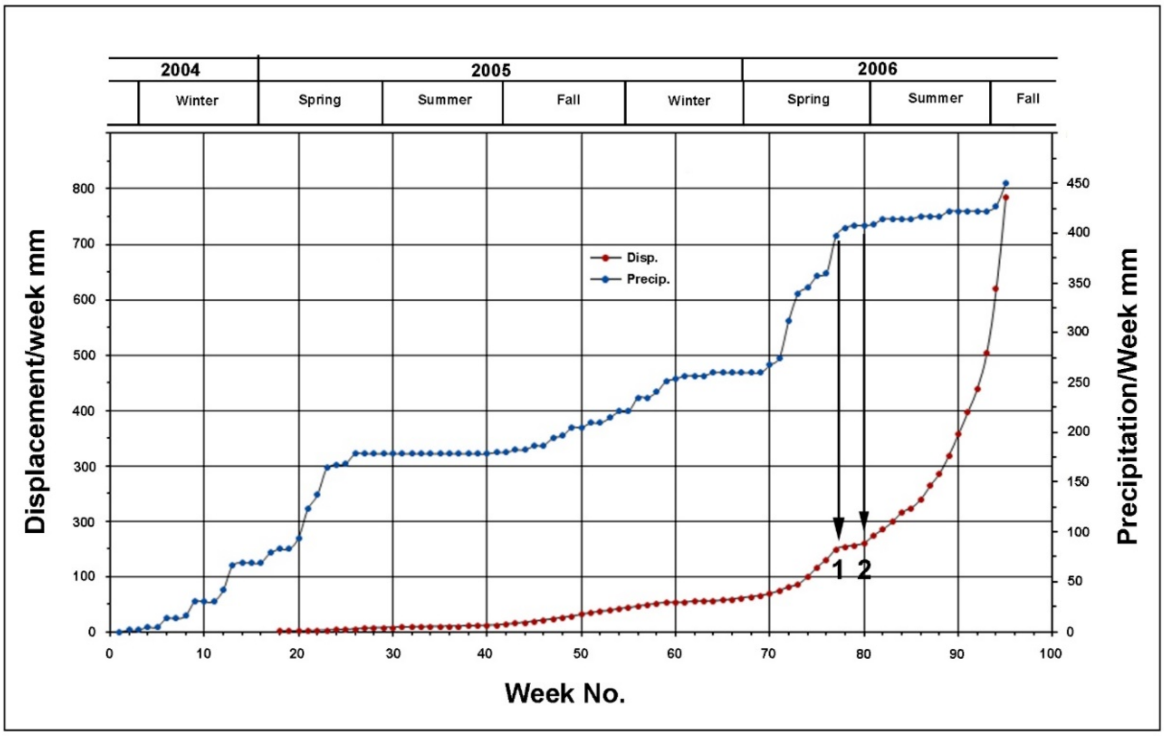

Diagram 5) The cumulative curve of precipitation and displacement for the whole study duration (fall 2004 to fall 2006)

In the first 16 weeks (fall and winter of 2004), when some evidence of instability was reported, the surface indicators were very weak and invisible. From week 16 (onset of spring 2005), the land movement evidence has become more visible with a displacement rate of 0.1mm per week. The displacement rate was not changed much in the summer and was consistent with rainfall declination. Since the beginning of fall 2005 (week 18) and the seasonal rainfall, the cumulative movement has also been increasing. Despite a relatively high precipitation in winter, the decrease in the rate of movement could be due to snowfall and the absence of infiltration due to extreme cold. This low activity of slope lasted until the end of the winter. The logical relationship between rainfall and the amount of displacement is well evident and the similarity of the process of displacement and precipitation proves that creeping of the landslide is a function of precipitation (points 1 and 2 in Diagrams 4 and 5).

Thus, the choice of rainfall variables and their comparison with the rate of displacement seems to be reasonable in this region. With the onset of the spring and rising runoff and water infiltration from rain and melting snow, the slope activity increased sharply and continued until the end of spring.

Conclusion

In Anguran landslide, the increase and decrease in the weekly displacements were proportional to seasonal precipitation from spring 2005 to spring 2006. In the late May of 2005, the rate of movement starts to decline with a drop in the spring precipitation until the week85. However, in week86, despite the lack of remarkable rainfall, there was a marked increase in the displacement. This increase demonstrates a clear divergence between the precipitation and displacement (point 2 in Diagram 5) that was considered as the warning point indicating the occurrence of a final failure. From the results obtained in this work, it could be concluded that in creep landslides, the rate of slope movement changes with seasonal variations of an external effective factor. This periodic process will have continued until the critical state. At critical state, the displacement rate dependency on the effective factor is significantly divergent. Such a divergence can be considered as a precautionary warning time of the final and destructive landslide. In other words, in the proposed method, the beginning of motion fluctuation independent of the variation of effective factors (for example precipitation and groundwater threshold level) could be considered as the early warning time to manage the risk.

By implementing this method in the Anguran Mine, an early warning alert was initiated two weeks before the main disastrous landslide failure. Based on this warning, all workers, equipment, and machinery were evacuated from the danger zone. The main motion started from October 6, 2006, at around 18:30 and continued until 5:00 AM. Of the following day. The displacement rate at stations S2, S3, S4, S6, and S8 was calculated using the data of Total Station; *i.e.*, the total movement of rock blocks that is 90 to 120m. Considering the event duration of around 12 hours, the landslide velocity at the final rupture (tertiary creep stage) was calculated to be between 180 and 240m d^{-1} or 7.5 to 10m h^{-1}. The DEM map of the unstable area in Anguran open-pit mine before and after the failure is shown in Figure 5.

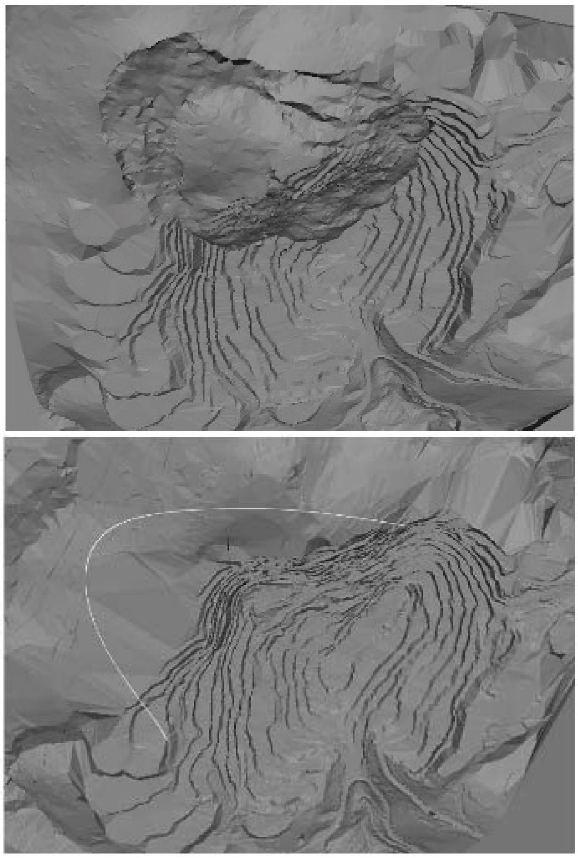

Figure 5) Digital Elevation Model (DEM) of the unstable area in Anguran open pit mine before the failure (right) and after the failure (left)

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References

1- Smith K, Petley DN. Environmental hazards: Assessing risk and reducing disasters. 5th Edition. Abingdon: Routledge; 2009.

2- Bhandari RK. Special lecture: Some practical lessons in the investigation and field monitoring of landslides. The 5th International Symposium on Landslides, 1988 July 10-15, Lausanne, Switzerland. Roterdam: Bulkema; 1988.

3- Guedjeo CS, Kagou Dongmo A, Wotchoko P, Nkouathio DG, Chenyi ML, Wilson Buma G, et al. Landslide susceptibility mapping and risk assessment on the Bamenda Mountain (Cameroon Volcanic Line). J Geosci Geomat. 2017;5(4):173-85.

4- Van Westen CJ. The modelling of landslide hazards using Gis. Surv Geophys. 2000;21(2-3):241-55.

5- Voight B. A method for prediction of volcanic eruptions. Nature. 1988;332(6160):125-30.

6- Voight B. A relation to describe rate-dependent material failure. Science. 1989;243(4888):200-3.

7- Crosta GB, Agliardi F. How to obtain alert velocity thresholds for large rockslides. Phys Chem Earth Parts A B C. 2002;27(36):1557-65.

8- Crosta GB, Agliardi F. Failure forecast for large rock slides by surface displacement measurements. Can Geotech J. 2003;40(1):176-91.

9- Crosta GB, Agliardi F. A methodology for physically based rockfall hazard assessment. Nat Hazards Earth Syst Sci. 2003;3:407-22.

10- Terzaghi K. Mechanism of landslides. In: Paige S, editor. Application of geology to engineering practice (Berkey Volume). Boulder: Geological Society of America; 1950. pp. 83-123.

11- Haefeli R. Creep problems in soils, snow, and ice. The 3rd International Conference on Soil Mechanics and Foundation Engineering, 1953 August 16-27, Zürich, Switzerland. Unknown Publisher; 1953. pp. 238-51.

12- Emery JJ. Simulation of slope creep. In: Voight B, editor. Rockslides and avalanches developments in geotechnical engineering. 14th Volume. Amsterdam: Elsevier; 1979. pp. 669-91.

13- Van Asch TWJ. Creep processes in landslides. Earth Surf Process Landf. 1984;9(6):573-83.

14- Cornelius RR, Scott PA. A materials failure relation of accelerating creep as empirical description of damage accumulation. Rock Mech Rock Eng. 1993;26(3):233-52.

15- Saito M. Forecasting the time of occurrence of a slope failure. The 6th International Conference on Soil Mechanics and Foundation Engineering, 1965 September 8-15, Montreal, Canada. Toronto: University of Toronto Press; 1965. pp. 537-41.

16- Fukuzono T. A method to predict the time of slope failure caused by rainfall using the inverse number of velocity of surface displacement (in Japanese). J Japan Landslide Soc. 1985;22(2):8-14. [Japanese]

17- Cruden DM, Masoumzadeh S. Accelerating creep of the slopes of a coal mine. Rock Mech Rock Eng. 1987;20(2):123-35.

18- Cruden DM. A simple definition of a landslide. Bull Int Assoc Eng Geol. 1991;43(1):27-9.

19- Saito M, Uezawa H. Failure of soil due to creep. The 5th International Conference on Soil Mechanics and Foundation Engineering, 1961 July 17-22, Paris. Paris: Dunod; 1961. pp. 315-8.

20- Saito M. Forecasting time of slope failure by tertiary creep. The 7th International Conference on Soil Mechanics and Foundation Engineering, 1969, Mexico City, Mexico. Mexico: Sociedad Mexicana de Mecanica de Suelos, A.C.; 1969. pp. 677-83.

21- Borsetto M, Frassoni A, La Barbera G, Fanelli M, Giuseppetti G, Mazza G. An application of Voight empirical model for the prediction of soil and rock instabilities. The 5th International Symposium on Landslides, 1988 July 10-15, Lausanne, Christchurch. Rotterdam: Balkema; 1991. pp. 335-41.

22- Agliardi F, Crosta G, Zanchi A. Structural constraints on deep-seated slope deformation kinematics. Eng Geol. 2001;59(1-2):83-102.

23- Hao SW, Zhang BJ, Tian JF, Elsworth D. Predicting time-to-failure in rock extrapolated from secondary creep. J Geophys Res: Solid Earth. 2014;119(3):1942-53.

24- Pazouki A, Yeganeh BY. Recovery of lead-zinc from Angouran mine Iran. J Metall Mater Sci. 2000;42(4):221-6.

25- Boni M, Gilg H, Balassone G, Schneider J, Allen CR, Moore F. Hypogene Zn carbonate ores in the Angouran deposit, NW Iran. Mineralium Deposita. 2007;42(8):799-820.

26- Gilg HA, Boni M, Balassone G, Allen CR, Banks D, Moore F. Marble-hosted sulfide ores in the Angouran Zn-(Pb-Ag) deposit NW Iran: Interaction of sedimentary brines with a metamorphic core complex. Mineralium Deposita. 2006;41:1.

27- Shoaei Z, Ghayoumian J. Seimareh landslide, the largest complex slide in the world. The 8th International Congress, International Association for Engineering Geology and the Environment, 1998 September 21-25, Vancouver, Canada. Rotterdam: Balkema; 1998. pp. 1337-42.

28- Shoaei Z. Mechanism of the giant Seimareh landslide, Iran, and the longevity of its landslide dams. Environ Earth Sci. 2014;72(7):2411-22.

29- Skempton AW. Long-term stability of clayey slopes. Geotechnique. 1964;14(2):77-102.

30- Sassa K, Canuti P. Landslides, disaster risk reduction. Berlin: Springer; 2009. p. 649.