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Application of an Optical Fiber Based Monitoring System to a Mass Movement Area

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ABSTRACT: The purpose of this study is to generate a long-term and continuous monitoring system that is near-real-time for mass movements by utilizing optical fibers. The system is composed of fiber optic cables and a device called BOTDA (Brillouin Optical Time Domain Analyzer), which is responsible for sending laser signals to the fiber optic cable and collecting backscattered light. The system measures the distributed strain along an optical fiber cable when mass movement displaces the cable and causes differences in the cable's initial location. The system was deployed to a mass movement prone field in Kocaeli, Turkey. In this real case application, the influence of triggering factors such as hydrological and hydrogeological conditions along with seismic activity have been studied. A piezometer and an acceleration seismometer were deployed in the application area in the field in order to generate a monitoring system that is capable of evaluating the influence of the hydrological and hydrogeological conditions as well as earthquakes on the deformation characteristics. This paper presents the strain data collected in 2019 by the optical fiber system for a period of 3 months. The data was evaluated together with the ground motion measured by the accelerometer, groundwater level and pore water pressure measured with the piezometer and the precipitation data gathered from the meteorological station. The collected and evaluated results revealed that the deformation is directly related to precipitation, groundwater level, and pore water pressure. Moreover, the seismic activity also influences the deformation as a secondary triggering effect. This study has determined that optical fiber systems are reliable and well-suited for developing monitoring systems of deformation related engineering applications such as mass movements.

1. INTRODUCTION

In the last several decades, population growth caused a need for new settlement areas and for this reason, since the cities tended to expand towards the hazard-prone regions, the number of people adversely affected by natural hazards increased. Mass movements are one of the most frequent and destructive natural hazards in the world. Today, many different instrumentation techniques such as inclinometers, tiltmeters, extensometers, satellite images, air photography, LIDAR systems are present in order to monitor potential and known mass movement areas (Pei et al., 2011). Although all of these techniques have their advantages and may be used to detect deformations, optical fibers are also preferred due to their easy and fast data transfer capability, small diameter, low weight, sensitivity to strain and temperature changes, immunity to environmental and electromagnetic effects, low cost and simultaneous monitoring properties (Gupta, 2012; Wang et al., 2008). In addition, optical fiber monitoring systems are suitable for developing an early warning system because of their continuous and fast data transfer capability. The purpose of this study is to generate a long-term and continuous monitoring system that is near-real-time for mass movements by utilizing optical fibers. The optical fiber system utilized in the study is composed of optical fiber cables and a device called BOTDA (Brillouin Optical Time Domain Analyzer), which is responsible for sending laser signals to the fiber optic cable and collecting backscattered light. The system detects mass movement in terms of distributed relative strain which results from the changes on the cable by measuring the sent and backscattered light. Changes on the cable occur when mass movement displaces the cable and that causes differences in the cable's initial location. In the study, all of the strain measurements were gathered in terms of relative strain which is a measure of change in strain with respect to the previous conditions. However, for the sake of avoiding wordy sentences, relative strain will be referred to as strain in this paper.

The utilized optical fiber system was deployed in a hazard-prone region in Kocaeli, Turkey. In addition to the optical fiber monitoring system, several other types of equipment were also placed in the field in order to determine the effect of the triggering factors. These equipment includes a piezometer for measuring groundwater level and pore water pressure and an acceleration seismometer. Moreover, meteorological data such as precipitation have also been collected. This paper presents the strain measurements gathered by the optical fiber system in between January and March 2019 and discusses the influence of the triggering factors on mass movement.

2. METHODOLOGY

2.1. Optical Fiber System

Optical fiber is a transmission medium that transmits laser from one place to another and is made up of glass (silica) or plastic. Optical fiber cables are thin cables having diameters in the order of µm. The basic structure of the cable is composed of core and cladding. In addition, there is a layer named coating, which is coiled around the core and cladding to protect them. The optical fiber system utilized for this study contains single-mode and single-core optical fiber cables and a device named BOTDA (Brillouin Optical Time Domain Analyzer). The system does not include special sensors at definite locations to measure mass movement. Rather, it uses optical fiber cable as a sensor that is capable of measuring distributed strain along the cable. Hence, the system has the flexibility to be used for different fields of application that may require varying sensor intervals with the same components. This device is called a time-domain analyzer as it uses the time interval between the sent and backscattered light to detect changes that occur on the cable (Ohno et al., 2001). BOTDA working principle is based on Brillouin scattering and it requires two laser beams (launched and backscattered light) having opposite directions in a fiber cable layout. When the frequency difference between these two laser beams equals the Brillouin frequency of the fiber, a peak forms on the measurement graph (Shen et al., 2009; Xiaofei et al., 2011). The location of this peak point shifts by any change on the cables. As a result, strain changes on the cables are detected quantitatively.

2.2. Field Application

The system was implemented in a mass movement region that is located in Kocaeli (Fig. 1). The geological unit in the area is a sandstone-siltstone alternation that belongs to the Incebel formation (Gedik et al., 2005). The sandstone-siltstone alternation was classified as a very poor rock mass (disintegrated/decomposed rock) since the sequence is tectonically deformed. However, detached blocks of varying sizes were observed in several locations within the landslide area. From an engineering geology point of view, the rock mass could be treated as an irregularly jointed, highly foliated and very deformable soil-like lithology. It should be noted that the strength and weathering characteristics of the rock mass is not uniform due to the inclusion of different lithologies that form the sequence. Hence, the engineering geological properties that specify the deformational characteristics are susceptible to relative changes spatially. This study area is a hazard-prone region since the slope has failed in 2010. However, progressive shallow failure continues in the field.

Fig. 1. The mass movement area in Kocaeli, Turkey.

In order to create a monitoring system, a fiber cable network starting from behind the crown of the mass movement was utilized. The cable network was embedded in the moving mass and returned back to a cabin where the starting point was located. For monitoring the deformations that occurred in the landslide, metal poles having a height of 2 m were fixed to the ground in the mass movement region and its close vicinity. The fiber cables were then coiled around these fixing poles (Fig. 2). The locations of the fixing poles were estimated by deformation analyses performed by using the finite element method (FEM) prior to the installation of these poles. For the FEM study, the required shear strength and elastic deformation parameters for the rock mass were determined from the geomechanical characterization of the rock mass (i.e., field study, scan-line survey, etc.), geotechnical boring and laboratory test results along with the back analysis performed in the landslide area. By using the results of the FEM analysis, the portion of the mass movement that is prone to the maximum deformation was determined and the fixing poles were installed into that area (Arslan Kelam et al., 2016).

After the system was set in the field and continuous data measurement and transfer of the optical fiber data was accomplished, studies regarding collecting data for the factors that may trigger the mass movement were started. For this purpose, a piezometer and an acceleration seismometer were placed in the site in order to monitor and understand the effect of the hydrogeological condition as well as the seismic activity. Moreover, meteorological data gathered from the Gölcük station of the Turkish State Meteorological Service (MGM) were evaluated to define the influence of the hydrological conditions on the precipitation results.

Fig. 2. The appearance of the cable fixing poles.

3. MONITORING RESULTS AND DISCUSSION

The strains have been measured by the aid of the utilized optical fiber system in between January and March 2019 were presented in monthly graphs and the change in the strain was evaluated together with the hydrological (i.e., precipitation), hydrogeological (i.e., groundwater level and pore water pressure) and seismic (when the earthquakes occurred within 50 km of the mass movement location, their influence was evaluated by considering the moment magnitude and distance between the study area and epicenter) effects. Since groundwater level and pore water pressure are directly related to each other, only pore water pressure values are presented in the paper and groundwater level changes are not mentioned. In the graphs which are presented for the strain measurements, the y-axis represents the strain created due to dislocation and shape change as a consequence of displacement in the sliding mass, and the x-axis represents the optical fiber cable's length measured from its beginning. Since the part of the optical fiber cable in between 210 m and 280 m was deployed to the sliding mass under question, the graphs show the strain measurements of that interval. It should be noted that each curve in the graph represents a day.

Strains measured in January 2019 are given in Fig. 3. The changes in pore water pressure and cumulative monthly precipitation graphs for January are shown in Fig. 4.

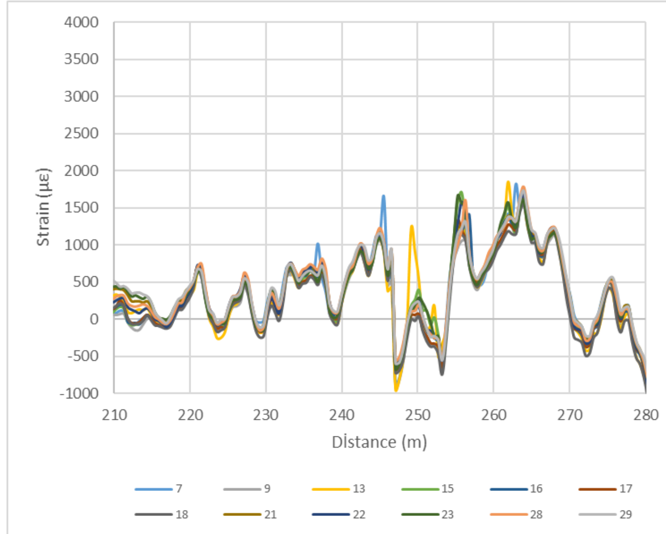

Fig. 3. The relative strain measurements of January 2019.

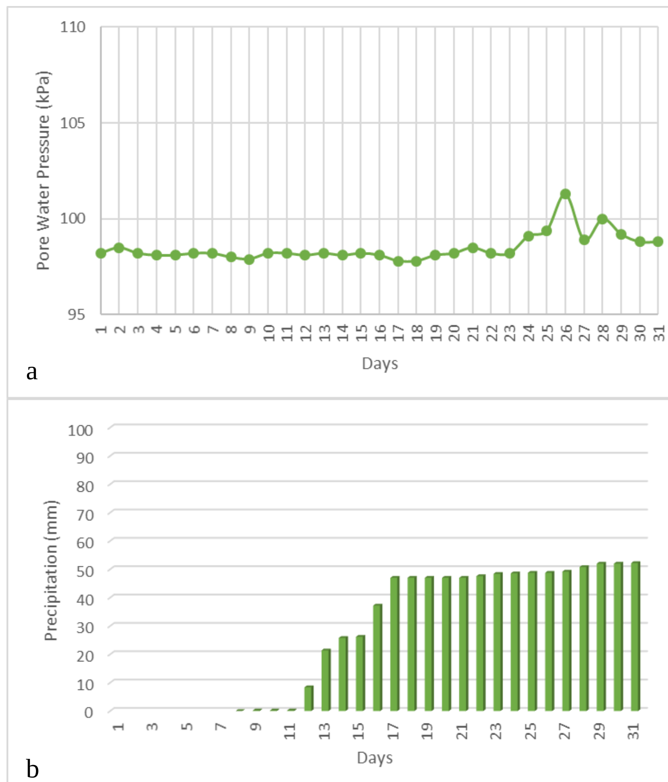

Fig. 4. a) Pore water pressure change and b) cumulative monthly precipitation of January 2019.

In January, cumulative monthly precipitation was 53 mm and mean monthly precipitation was 1.7 mm. The average pore water pressure measured by the piezometer was 98.58 kPa. In January, the strain measurements were available starting from January 7. A significant change in the strain measurements was not detected between 7-13 January. There was an increase in the strain on 13 January due to the effect of precipitation. Although, daily cumulative precipitation was 11 mm, no obvious change in the strain was encountered on 16 January. This behavior may be attributed to the pore water pressure that does not show an increase. Similar strain graphs were obtained until January 21. This characteristic may be explained by pore water pressure, which has not changed significantly. On January 22, an increase in pore water pressure resulted in an increment of strain which was in the order of 200 με on the average. Similarly, the strain change was measured to be 300 με at several points because of the increase of pore water pressure on 28 January.

The measured strains in February 2019 are given in Fig. 5. The changes in pore water pressure and cumulative monthly precipitation graphs for February are shown in Fig. 6.

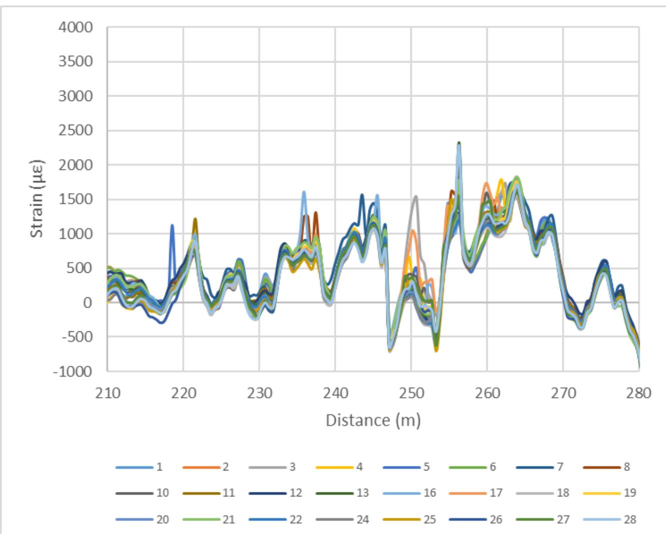

Fig. 5. The relative strain measurements of February 2019.

In February, cumulative monthly precipitation was 96 mm and mean monthly precipitation was 3.4 mm. The average pore water pressure measured by the piezometer was 99.05 kPa. At the beginning of the month, on February 1 and February 2, the strain followed a similar path with the end of January. On February 3, the pore water pressure was measured as 102.7 kPa and this dramatic change caused strain to be 1200 με higher than the previous day. This change may especially be observed at the 250th meter of the optical fiber cable. After that, a significant strain change was not detected until February 7. On February 7, the strain increased to 220 με on the average which is directly proportional to the change in pore water pressure. On February 10, pore water pressure was 104.9 kPa. By the influence of the increment of the pore water pressure, the strain reached 2150 με. On February 13, due to the effect of daily cumulative precipitation of 18 mm, the strain was measured to be 2300 με, which was the maximum value for the month. After 13 February strain increased progressively as precipitation occurred and the pore water pressure increased. An increase in the strain was observed at the 235th and 246th meters of the optical fiber cable on January 15 and in the 250th and 260th meters on January 27.

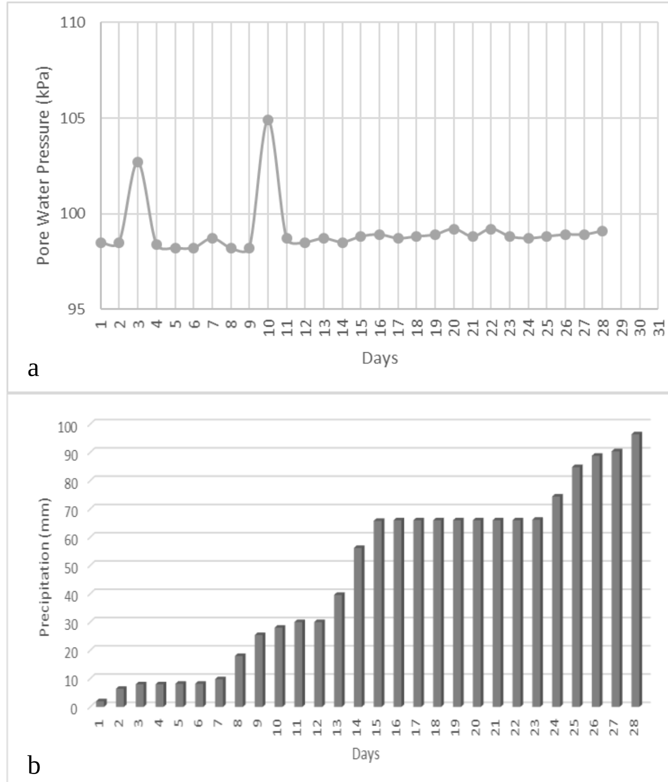

Fig. 6. a) Pore water pressure change and b) cumulative monthly precipitation of February 2019.

The measured strains in March 2019 are given in Fig. 7. The changes in pore water pressure and cumulative monthly precipitation graphs for March are shown in Fig. 8.

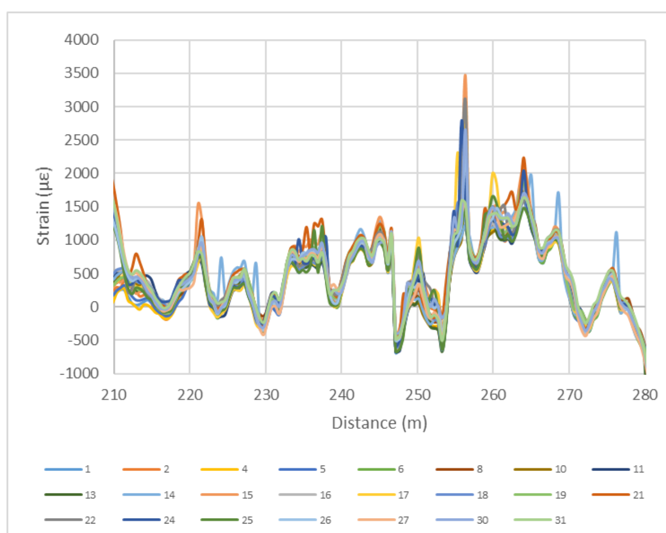

Fig. 7. The relative strain measurements of March 2019.

In March, the cumulative monthly precipitation was 29 mm and the mean monthly precipitation was 0.9 mm. The average pore water pressure measured by the piezometer was 98.74 kPa. It is clear in the pore water pressure graph of March 2019 (Fig. 8.a) that there are no significant peaks in the measurements. Additionally, pore water pressure is more or less the same and high as compared to the other months (excluding the peak values). This can be explained as a rise of the groundwater level and pore water pressure due to the melting of snow by the effect of increasing temperature (changes in between 10 °C and 23 °C according to data gathered from the Turkish State Meteorological Service). At the beginning of the month similar strain values were measured for three days. However, on March 4, the strain measurement showed an increase in the negative direction in general and positive in several locations. This behavior is attributed to the consequence of an earthquake (Mw=4.0) that occurred at the Sea of Marmara on that day. Acceleration measurements obtained from the accelerometer placed in the study area is given in Fig. 9. On March 15, the strain increased and reached to a maximum value of 3500 με with the influence of precipitation on 13, 14 and 15 March. On March 21, an average of 300 με was observed with the influence of a slight increase in the pore water pressure.

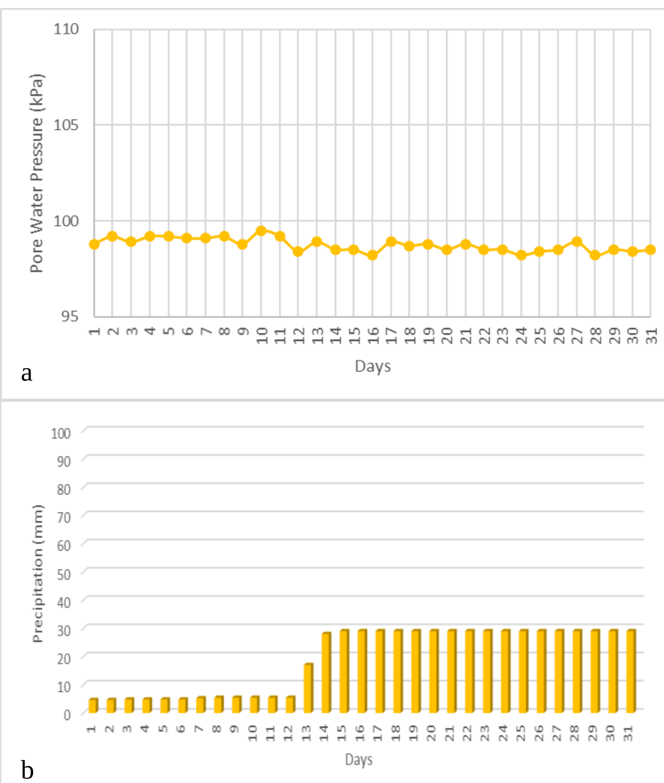

Fig. 8. a) Pore water pressure change and b) cumulative monthly precipitation of March 2019.

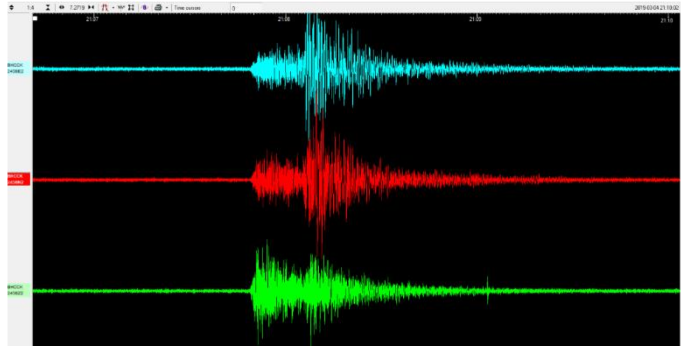

Fig. 9. The acceleration-time history of March 4, 2019 earthquake.

4. CONCLUSIONS

In this study, the relative strain values of the mass movement measured by the optical fiber system have been presented for a period of three months. And later on, the change in strain was evaluated together with the hydrological condition (i.e., precipitation), hydrogeological conditions (i.e., groundwater level and pore water pressure) and the seismic activity in order to understand the influence of the triggering factors on mass movements.

The following discussion can be concluded from the presented data and its evaluation. In January, the average strain measured by the optical fiber monitoring system was 1100 με and the maximum value of strain was 1900 με. These values were gathered as a result of a cumulative monthly precipitation of 53 mm and an average pore water pressure of 98.58 kPa. In February, the cumulative monthly precipitation was 96 mm and an average of pore water pressure was 99.05 kPa. It is obvious that precipitation and water pressure both increased when they are compared to the values of January. The influence of these increases resulted in an overall increment of strain. The average strain was measured as 1350 με and the maximum strain was measured to be 2300 με in February 2019. In March, the cumulative monthly precipitation was 29 mm and the average pore water pressure was 98.74 kPa. It is clear from Fig. 8a that pore water pressure measurement did not show a significant change in March, but the value measured was higher than that of January and February. Although precipitation was lower in March, the strain increased due to the influence of high pore water pressure. The average and maximum strains measured in March were 1520 με and 3500 με' respectively, which were the maximum values measured within the time period considered. The strain along the cable shows relative differences for a measurement. It means that the measured strain is not the same through the landslide. Moreover, change in strain is relatively higher in several locations such as the 250th meter of the cable. This can be explained by non-uniform deformation of rock mass which originates from varying properties of the alternating lithologies.

The results support the fact that the deformation is influenced by precipitation and it is directly related to hydrological conditions along with hydrogeology. However, a detailed study including rainfall duration and intensity to determine the threshold value of precipitation that is capable to create displacement should be conducted. Similarly, a threshold value for pore water pressure should be determined. In addition, the contribution of the seismic activity on mass movement as a function of moment magnitude, epicenter distance, and earthquake depth could be evaluated. This study reveals that optical fiber systems can be utilized for monitoring mass movements and the system gathers sensitive measurements that are enough to observe the influence of the possible triggering factors. Due to their continuous and fast data measurement and transfer capabilities, optical fiber systems are promising not only for monitoring of mass movements but also for the generation of early warning systems. The system developed for this study is expected to be utilized as an early warning system once the sensitivity studies are completed.

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