MONITORING AND ANALYSIS OF INTERNAL DISPLACEMENTS OF A SLOPE AND RELATIONSHIP WITH RAINFALL INFILTRATION

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ABSTRACT

The internal displacement of a slope is a key parameter for assessing the safety of a slope. This paper introduces a sensing technique for measuring internal displacements of a slope. A series of sensing bars embedded with fiber Bragg grating (FBG) sensors was developed and used to monitor the internal deformation. These sensing bars were installed at different depths of two deep boreholes. Monitoring work was carried out and data were collected from 20 June to 25 September 2010. The internal displacements of the slope were analyzed together with the rainfall data which collected by a rainfall gauge. The results show that rainfall has a strong influence on the internal displacements of the slope. But the influence of rainfall reduces dramatically when the depth is beyond 8.0m. In addition, numerical results indicate that the rainfall intensity has a significant effect on the slope stability, especially when the rainfall intensity is larger than 100mm/h.

KEYWORDS

Internal displacement, slope, fibre Bragg grating(FBG), sensing bar, rainfall.

INTRODUCTION

Slope stability is essential to the protection of human life. Factors affecting the slope stability are various and interconnected to each other, such as geologic structure, geometry, soil mechanics characteristics, creep, rainfall, evaporation and earthquake. In recent decades, many researchers have focused on the analysis of the slope stability, including theory analysis (e.g. Morgenstern, 1965; Sarma, 1973; Greco, 1996; Zheng, 2009); numerical analysis, such as finite element method (FEM) (Duncan, 1996; Griffiths, 1999), discontinuous deformation analysis (DDA) (Eberhardt, 2004) and 3-D analytical approaches (Hovland, 1977; Zhang, 1988; Huang and Tsai, 2000; Chang, 2002). Former research showed the primary factors controlling the stability of the slope are rainfall and evaporation (e.g. Collins, 2004; Tohari, 2007; Frattini, 2009; Arezoo, 2010). In addition, Leonardo (2010) indicated that the slow-moving was dominated by the pore water pressure and has a close relationship with seasonal variation. Therefore, it is necessary to study the effect of rainfall on the internal displacement movement and slope stability. For analyzing of this effect, the most direct and efficient way is to monitor and analyze the progressive movement of the slope. In this study, a new technology, named fiber Bragg grating (FBG), has been applied in a selected slope to monitoring the internal displacements. The FBG technology has been widely applied in different areas since Hill *et al* (Hill, 1978) first discovered. The FBG sensors are very sensitive to temperature and strain. Comparing with the traditional sensor technologies, the FBG technology has many advantages, such as high sensibility, small volume and weight, resistance to the corrosion and electromagnetic interference (Yin, 2008; Zhu, 2010). This paper presents a new technology to monitor the internal displacement of a slope so that the deformation was analyzed together with rainfall data. Based on this, the influence of rainfall intensity and duration were examined through a finite element model.

THEORY OF THE FBG SENSING BAR

Since the wavelength of a FBG sensor has a linear relationship with the strain and temperature, the strain can be measured if the temperature effect is separated. The linear relationship is

$$\frac{\Delta\lambda}{\lambda_0} = c_\varepsilon \Delta\varepsilon + c_T \Delta T \tag{1}$$

where λ_0 is the original Bragg wavelength without straining which is typically between 1510 and 1520nm; $\Delta\lambda$ is the variation in the Bragg wavelength due to the applied strain and temperature; c_ε and c_T are the calibration coefficients of strain and temperature. From the laboratory calibration test results, the calibration coefficients of c_ε and c_T are $0.78\times10^{-6}\mu\varepsilon^{-1}$ and $6.67\times10^{-6}℃^{-1}$ respectively. Since there are two FBG sensors on the same position for two opposite sides, the part of temperature effect can be deducted.

Based on this theory, a sensing bar with a diameter of 20mm and 1m length was adopted. The FBG sensors were adhered on the sensing bar, so that the deflection and rotation at the free end can be calculated through the strain measured by the FBG sensors, supposing the other end of the smart bar was fixed. The expression can be written as:

$$d_i = a\varepsilon_{i1} \tag{2}$$

$$\theta_i = b\varepsilon_{i2} \tag{3}$$

where d_i is the deflection of the ith smart bar; θ_i is the rotation of the ith smart bar; a and b are two coefficients; ε_1 and ε_2 are the strains measured by the two different FBG sensors.

Considering a series of smart bar connected together by steel tube, the deflection and rotation can be calculated by the superposition method. The relationship can be derived as follows:

$$d_i = d_{i-1} + L_{i-1}\tan\theta_i + \left(L_{i-1} + l_{i-1}\right)\tan\left(\sum_{i=1}^{i}\theta_i\right) \tag{4}$$

where d_i and d_{i-1} are the deflection of the ith and $(i-1)$th smart bar respectively; L_i and L_{i-1} are the length of the ith and $(i-1)$th steel bar respectively; l_{i-1} is the length of the $(i-1)$th smart sensing bar.

MONITORING RESULTS AND ANALYSIS

Monitoring results

The sensing bars in Boreholes A and B were installed on 20 June 2010 (Figure 1) and the initial wavelengths were taken for further calculation. Base on the equations (1) to (4), the deflections and rotational angles of sensing bars at different depths can be calculated. The monitoring data were collected from 14 July to 25 September. The displacements varied with time at different depths for both Boreholes A and B are shown in Figure 2.

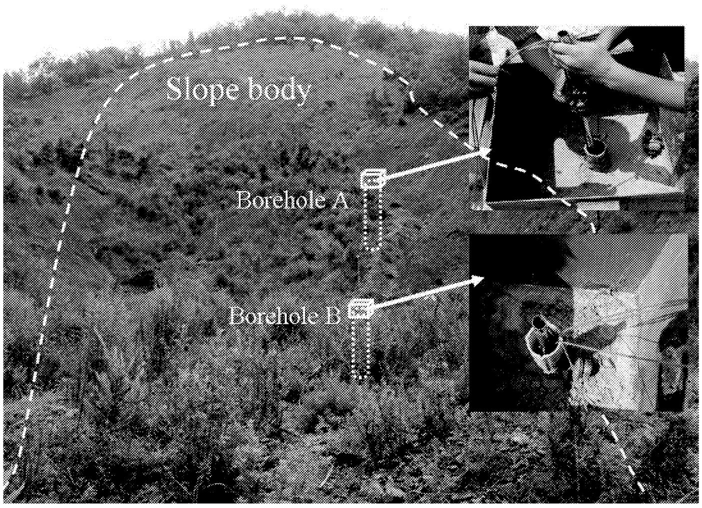
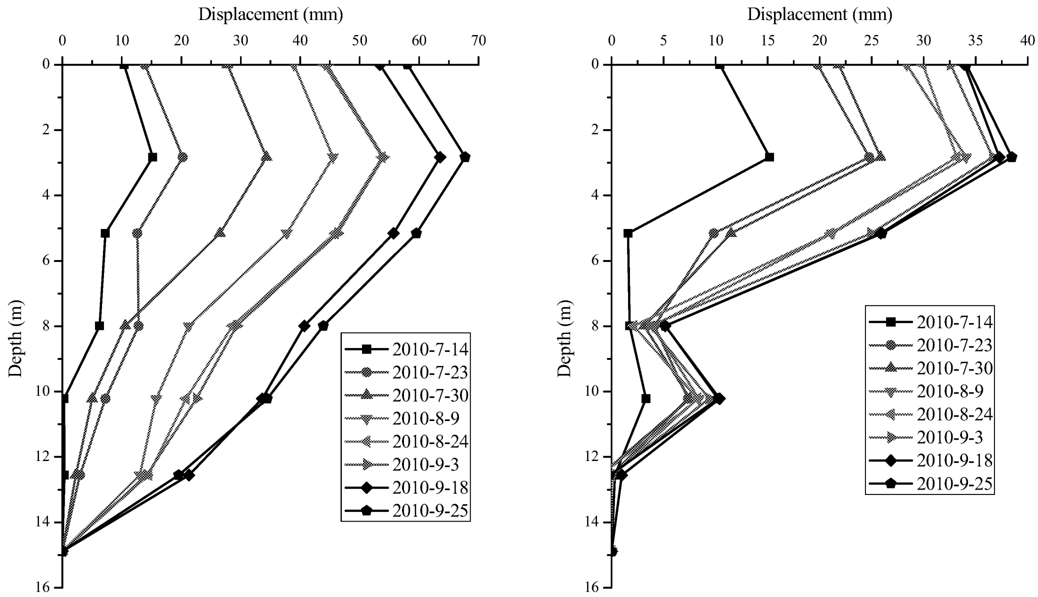


Figure 1 Location and sketch of the boreholes

According to the field monitoring results, the displacement of Borehole A is much larger than that of Borehole B, this is because the elevation of Borehole A is higher than that of Borehole B. Basically, the deformation should increase with time, but we find that this tendency is not all the same. This is because many other factors also have some influence on the displacement, even though the rainfall is the main factor. The surficial displacements are lager then those in the bottom, in other words, the displacement increases with the depth of the slope, except the zero point has some influence by the concrete box. According to Li (Li et al., 2005) and Lee (Lee et al., 2009), for the slope surface, since the soil is unsaturated, rainfall infiltration will result in a reduction of matric suction in soil which in turn reduces the soil shear strength. Meanwhile, the heavy rainfall maybe increase the water table so that it will yield or increase the positive water pressure which will decrease the effective stress of the soil and also reduce the shear strength of the soil. Therefore, it is necessary to analyze the relationship between the rainfall and the displacement in the following study.

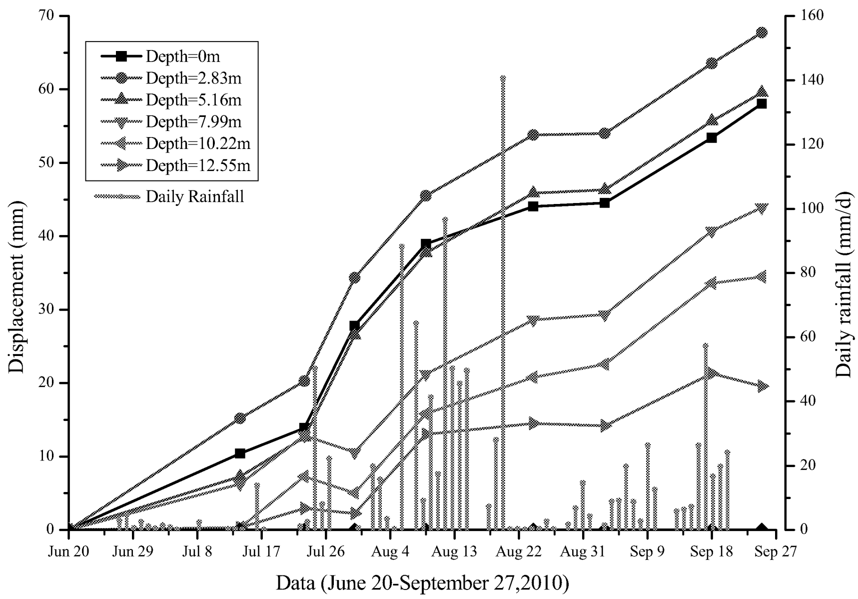


(a) The variation of displacement for Borehole A (b) The variation of displacement for Borehole B

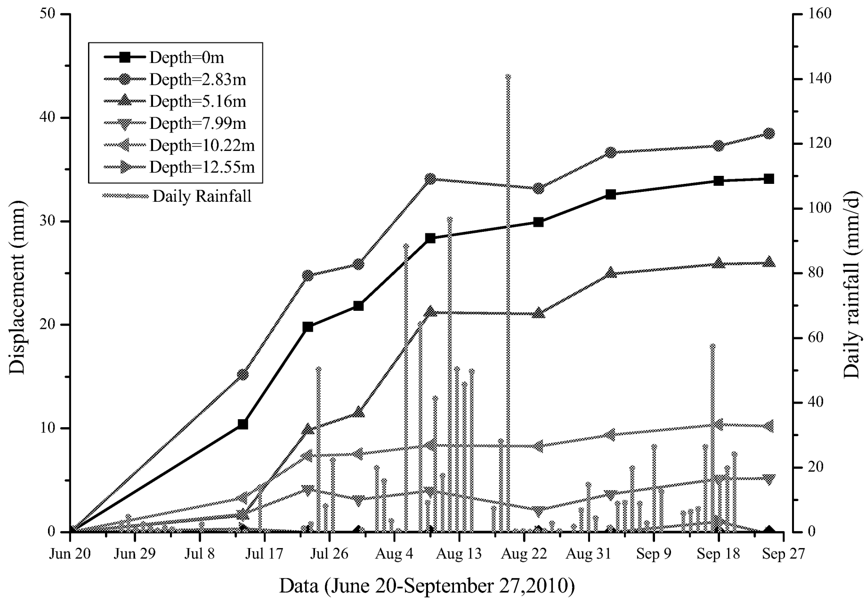
Figure 2 The internal displacement at different depths for the slope

Displacement analysis with rainfall data

In order to analysis the relationship between the displacement and rainfall, the rainfall data were collected from 27 June to 24 September 2010 by a rainfall gauge. The variations of displacement at different depths with the time subjected to the rainfall form 20 June to 25 September 2010 are shown in figure 3 for Boreholes A and B respectively.



(a) Variation of displacement at different depths and the rainfall of Borehole A



(b) Variation of displacement at different depths and the rainfall of Borehole B

Figure 3 Relationship between displacement distribution and rainfall

For Borehole A, figure 3(a) indicates that the increase of displacement is not quick when the rainfall is not very strong before July 14, 2010. After that the displacement has a dramatic increase, especially for the surface of the slope, as the rainy season is coming. We can draw the conclusion that the rainfall has an important role in influence the displacement of the slope. The rainfall also has promote action of the slope internal displacement for Borehole B, as seen in figure 3(b), but the influence decrease a lot compared to Borehole *A* which located in the higher elevated site. For both Boreholes A and B, the influence of rainfall over slope deformation reduces dramatically when the depth beyond 8.0m. The reason for this phenomenon, which has already put forward by some researchers, is that the shallow failures are generated by the short intense rainfall while most deep-seated landslides induced by long-term variation of annual rainfall (Pietro, 2004)

ANALYSIS THE EFFECT OF RAINFALL INTENSITY AND DURATION ON SLOPE SAFETY

In order to understand the effect of rainfall intensity and duration on the stability of the slope, the commercially software SEEP/W and SLOPE/W were used (GeoSlope International Ltd., 2004). Firstly, the SEEP/W was used to conduct seepage analysis and calculate the pore water pressure. Then based on the seepage analysis results, the factor of safety (*FOS*) was calculated by the SLOPE/W.

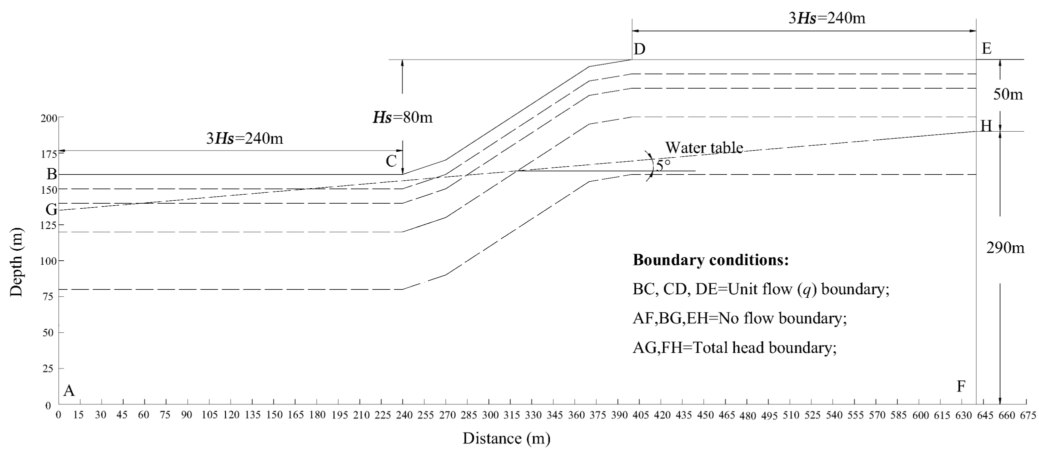
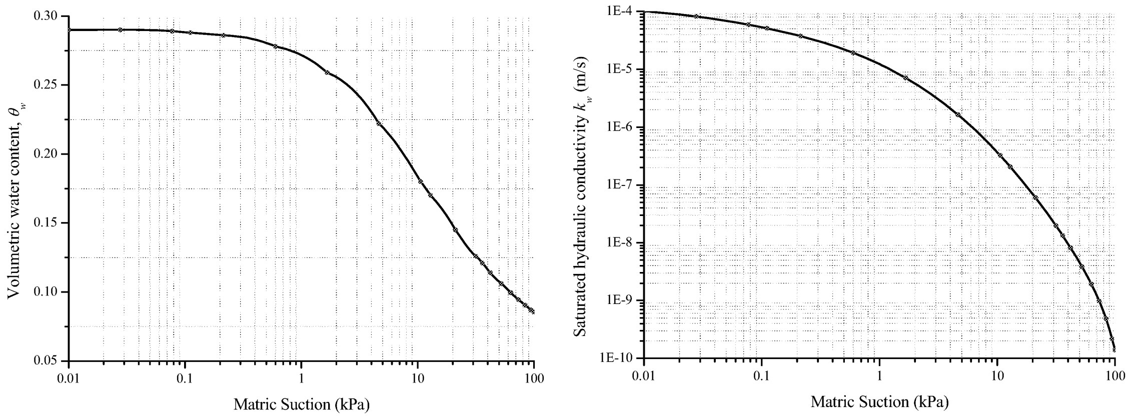


Figure 4 Geometry and boundary conditions of the slope

According to the geography of the slope, an ideal model was established in figure 4 and five different layers were proposed based on the test results of drilling samples. The water table and boundary conditions are shown in this figure. Since this study focuses on the rainfall intensity and duration effect the stability of the slope, the geometry of the slope has less effect on this study as it just effect the initial value. Therefore, the normalized factor of safety F_{sn}, which is the factor of safety at each time step divides by the initial value of *FOS*, was used in comparing and analyzing for the following studies.

The Fredlund and Xing equation was used in this study to develop the volumetric water content function for matric suction between zero and minus 100kPa. In this method, three parameters *a*, *n* and *m* were adopt and represented different means, such as parameter *a* inflects point of the volumetric water content function; *n* controls the slope of the soil-water characteristic curve (SWCC) and *m* controls the residual water content. Figures 5(a) and 5(b) show the SWCC and permeability function curve for a=5kPa, m=1, n=1 and k_s=10^{-4}m/s.



(a) Volumetric water content changes with suction and (b) unsaturated permeability function curve
Figure 5 SWCC and unsaturated permeability function curve

The *FOS* of the slope was examined under different rainfall intensity and duration based on the same parameters of *a*, *m*, *n* and k_s, but the unit flux are different according to the various rainfall intensity. The normalized *FOS* (F_{sn}), the factor of safety at each time step divides by the initial value of *FOS*, was used to compare under different unit flux conditions. The F_{sn} versus rainfall intensity were shown in figure 6. The results indicate that rainfall intensity has strong effect on the slope stability, especially when the rainfall larger than 100mm/h. Before rainfall intensity reaches the saturated permeability k_s, the rainfall intensity 100mm/h is a critical value for this analysis because the *FOS* reduces very quickly after the rainfall intensity exceeds this value.

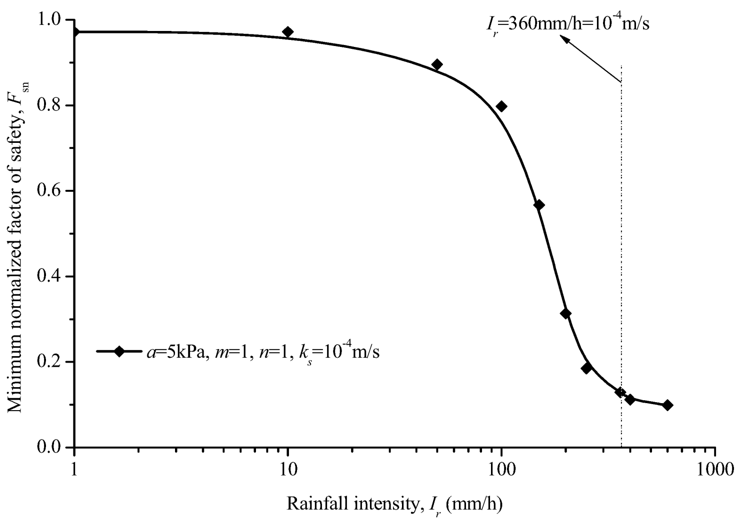


Figure 6 F_{sn} under different rainfall intensity

The effects of rainfall duration are also studied and the results are shown in figure 7. When the rainfall is very small, such as below 0.01mm/h, the rainfall duration has little influence on the slope stability. However, the safety factor of the slope will decrease quickly with increasing rainfall duration when the rainfall intensity greater than 0.1mm/h. It is worth noting that there is a sharp decrease of F_{sn} when rainfall duration is longer than 100h for the rainfall intensity (I_r) at 0.1 and 1.0mm/h. Therefore, critical rainfall duration also exists for this analysis and the slope may collapse when the time beyond the critical value.

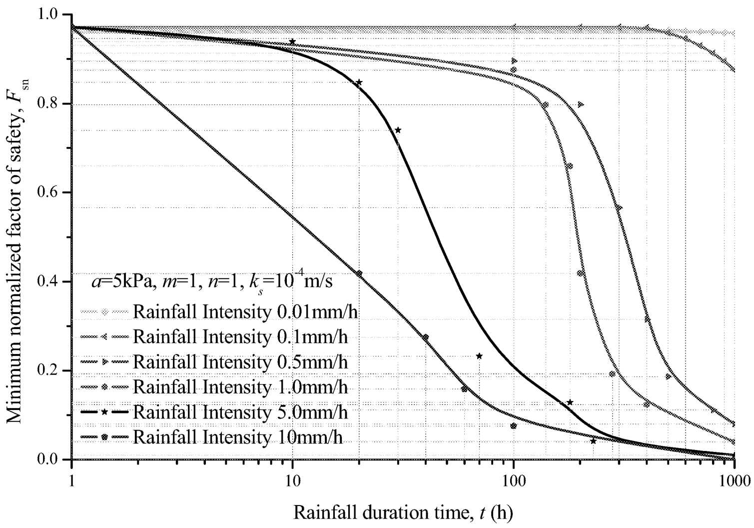


Figure 7 F_{sn} under different rainfall duration

CONCLUSIONS

Based on the field monitoring data of internal displacements and rainfall data, the relationship between the internal displacements and rainfall infiltration were analyzed. In addition, effects of rainfall intensity and duration on the international displacements of the slope were examined based on the finite element analysis. The main conclusions are listed as follows.

(1) The internal displacements increase not quickly when the rainfall is not very strong before July 14, 2010, but once the rainy season is coming, the displacement increases dramatically, especially for the slope surface.
(2) The maximum displacement of Borehole A is much larger than that of Borehole B and the displacements of slope surface are larger than those in the deep depth
(3) The rainfall plays an important role in influence on displacements of the slope. For Borehole B, the influence decreases a lot compared to the Borehole A which was located in the higher elevation of the slope. For both Boreholes A and B, the influence of rainfall on the displacements is getting smaller and smaller when the depth increases beyond 8.0m.
(4) The rainfall intensity has a strong effect on the slope displacements, especially when the rainfall is larger than 100mm/h. Before rainfall intensity reaches the saturated permeability k_s, the rainfall intensity of 100mm/h is a critical value for this analysis, because the *FOS* reduces very quickly after the rainfall intensity exceeds this value.

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