Development of Landslide Early Warning System Using Macro-bending Loss Based Optical Fibre Sensor

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Abstract. This paper presents the design of a simple and cheap landslide early warning system which mainly consists of a displacement fibre sensor, mechanical displacement converter, and Short Messaging Service (SMS) gateway equipped with a siren. Displacement fibre optic sensors were made by wrapping a polymer optical fibre (POF) around a holey elastic cylinder connected to a mechanical displacement converter that converts a real land displacement in centimetres order of magnitude into millimetres order that fibre optic sensor can detect. From the experimental results we suggest an optical fibre sensor that has ability to monitor land displacement in the range of 40 cm, sensitivity of (5.9 ± 0.2) dB/cm and linearity 99.5% as well as the way of improving sensor performance to meet the real need. A whole system has been tested making use of a slider attached to the mechanical displacement converter. Once a nonzero continuous displacement for 5 seconds or a downward land displacement of 10.0 cm occurs, the system will activate the siren and spread an alert via SMS automatically.

1. Introduction
Geologically, a landslide can be described as downward movement processes of materials forming an inclined ground. Some movements are rapid, take seconds to occur, while others may take years. There are many different causes of landslides, they are usually related to slope instability caused by the failure of earth materials to overcome the force of earth gravity that pulls everything downward. Steep slope and water content are two important factors that can serve as an alert to a potential landslide problem. Ideally, the areas affected by landslide are free from any occupation. Unfortunately, many areas with high landslide potential to occur are versatile and over decades have been densely populated. In many places, evacuating people from their founding fathers’ lands is not easy. Therefore, landslide can cause not only property damages but also injuries and deaths.

Landslide early warning systems are of great benefit since they can reduce loss of life and property. Fibre optic sensor is one of sensors currently used for this purpose. Compared with other types of sensors, fibre optic sensor shows a number of advantages, two of them are due to their high sensitivity and the possibility to measure in hostile environments. There exist a great variety of fibre optic sensors developed for landslide monitoring, such as Fibre Bragg Grating (FBG) [1, 2, 3], Optical Time Domain Reflectometer (OTDR) [4, 5], and Brillouin optical time domain reflectometry (BOTDR) [6]. These sensors are known to have particularly high sensitivity, accuracy and reliability. Despite these outstanding properties, these types of sensors are very expensive and for most region in the developing and under developing countries their price are unaffordable. In this work, a landslide early warning system works based on land movement data collected by an intensity modulated fibre optic sensor was made. The system was designed to provide an early warning via SMS and siren.
simultaneously to the local residents on the impending landslide occurrence nearby. Due to its simplicity and low cost, this sensor can be an ideal landslide monitoring technology for use in developing countries.

2. Experiment

Figure 1 is schematic arrangement model of landslide monitoring system used in this experiment. It mainly consists of three parts: mechanical displacement converter, displacement fibre sensor, and Short Messaging Services (SMS) gateway. Early landslide movement is usually slow; it might be millimetres or centimetres per year. Significant incremental displacement sometimes occurs only in years of higher than normal rainfall. In such a case, continuous displacement of millimetres or even centimetres per day has to be regarded as the initial criteria for early warning. Nevertheless, the magnitude scale of displacement fibre sensor developed in this experiment is in millimetres. In order that landslide movement which is typically measured in centimetres order can be monitored by the sensor, a displacement converter is required. In this experiment, this is done by a pulley system composes of two pairs of identical wheels. Wheel A and C have radius of 10.0 cm, while wheel B and D have radius of 1.0 cm. As shown, wheel A and B are on the same axis and so are the wheel C and D.

As shown, wheel A of radius \( r_A \) and B of radius \( r_B \) are on the same axis and therefore have the same angular speed (\( \omega \)), i.e.:

\[
\omega_A = \omega_B
\]

Taking the angular speed and linear speed (\( v \)) relationship as \( v = \omega r \), we have:

\[
v_B = \frac{r_Bv_A}{r_A}
\]

Similarly, wheel C and D are on the same axis and therefore

\[
v_C = \frac{r_Cv_D}{r_D}
\]

Further from Figure 1, wheel B is coupled by belt E to wheel C and hence \( v_B = v_C \). From equation (1) and (2), therefore we have

\[
\frac{v_D}{v_A} = \frac{r_Dr_B}{r_Cr_A}
\]

Remembering that linear displacement (\( S \)) of any point on the wheel can be expressed as \( S = vt \), we can calculate the relationship between linear displacement of wheel A and D. If X rope is displaced by
landslide movement by $S_A$ then the Y rope that goes to the fibre sensor will be displaced by $S_D$ as expressed by

$$S_D = \frac{r_D r_B}{r_C r_A} S_A = \frac{1}{100} S_A$$

where $r_A$, $r_B$, $r_C$, and $r_D$ are the wheel radius of A, B, C and D, respectively. The multiplication factor as given by equation (3) can be varied by varying the wheels radius or adding more wheels into the pulley system.

Further from Figure 1, light coming out from the light source was coupled into a 50/50 fibre splitter. One arm of the fibre splitter was connected to the modulated fibre and the other one to the reference fibre. Light detected by both light detectors (D1 & D2) were recorded and processed by a computer program to calculate the transmission coefficient ($T$) defined by

$$T = \frac{I_m}{I_r}$$

Light intensity detected from the modulated fibre arm ($I_m$) was designed to be less than that detected from the reference one ($I_r$).

To set the transmission coefficient prior to modulation equals to 1, an attenuator was added to the reference arm. The way in which the fibre coil responds any landslide movements is shown in Figure 2. Fibre coil, which is a hollow mandrel rubber wrapped with polymer optical fibre, was positioned between two walls: fixed and moveable wall. As the suspected land is displaced by $S_A$ (Figure 1), the moveable wall as shown in Figure 2 is pulled by the wire connected to the pulley system by $S_D$ and thereby compressing the coil system and the mandrel circular cross-section changes to an ellipse. As described in the next section, this change will result in decreasing light intensity emerging from the coil ($I_m$). Applying equation (4), the transmission coefficient ($T$) decreases accordingly. To obtain a sensitive fibre sensor, a suitable cylindrical rubber diameter had to be chosen. In this experiment, the most suitable diameter was obtained by comparing the gradient of the optical loss-displacement curve as function of the fibre coil diameter (1.7 cm, 1.4 cm, 1.0 cm) as well as the number of turns of the fibre coil (1, 2, 3, 4 turns). The optimum configuration (coil diameter and number of turns) are then judged by the magnitude of their gradient and the width of their linear part.

In order to examine the sensor system performance, a model of a land movement and an SMS gateway device were made. Figure 3 is an SMS gateway device used in this experiment. This device consists of three main components: micro-controller, TTL to RS232 converter, and modem. Looking back to Figure 1, triggered by a land movement light coming out of the modulated fibre arm ($I_m$) decreases. This intensity change is detected by detector in the form of voltage change. For this
purpose, detector is connected to a port of ADC ATMega8535 microcontroller. This microcontroller is functioned as a control system where voltage data variation taken from detector is processed. To make the system be able to spread a landslide alarm (siren sounds and SMS), the microcontroller is connected to a siren and a Wavecom modem. A computer program containing a defined critical condition at which landslide warning has to be spread out was given to microcontroller. For convenience, the critical condition set in this experiment is the occurrence a nonzero continuous displacement for 5 seconds or a downward land displacement of 10.0 cm.

3. Results and Discussion
Figure 4 presents how bend losses vary as function of the land model displacement measured at different coil mandrel diameters and number of turns of each coil. Since fibre attenuator was added in our experimental setup (Figure 1), the initial transmission coefficient can be managed always equals to 1. It is well known that a bend loss can be expressed in term of a transmission coefficient as

$$\text{Loss}(dB) = 10^{10} \log \left( \frac{1}{T} \right) = 10^{10} \log \left( \frac{I_r}{I_m} \right)$$

Here, the attenuator manages the initial intensity of light passing through fibre reference ($I_r$) such that before displacement was given $I_r/I_m=1$. In other word, the initial loss of all curves can always be set equal to 0. The attenuator added in this setup can thus be functioned as a zero button, which is required for calibration purposes. In general, fibre loss at a given radius is higher for a coil with more turns. The change is more obvious for coils with a diameter of 1.0 cm (Figure 4.c). These typical
results show good agreement with that obtained by other researchers investigating similar sensor designed for microdisplacement [7].

It is clear from Figure 4 that the bend loss increases as the displacement of the land model increases. As the wire in Figure 2 is displaced by $S_D$, the circular shape of the coil changes to the elliptical shape (Figure 5). The vertical axis and horizontal axis of the circular coil become minor and major axis of the ellipse, respectively. From geometric optics point of view, this increase is caused by light radiated out of the fibre at the high curvature point. As shown in Figure 4.b, light is coupled into a multimode fibre within the acceptance angle $\beta$ and incident on the core-cladding interface at the angle of $\theta$. For a given angle $\beta$, there will be a certain number of allowed $\theta \geq \theta_{cr}$ for the light to travel through the fibre. Around the maximum curvature point $X$, many angles $\alpha$’s decrease down to bellow their corresponding critical angles such that total internal reflection cannot occurs. Consequently, part of the light is radiated out of the fibre.

![Figure 5. (a) Coil cross section change due to an applied force. (b) Light leaks out of the bent fibre edge.](image)

There are three groups of coils used in this experiment, i.e., circular coil with the diameter of 1.7 cm, 1.4 cm, and 1.0 cm. For a given displacement, $S_D$, they are transformed into ellipse with different curvature. To understand how this is different, let’s see Figure 4a. As no external force is applied ($F=0$), the coil is in circular shape. This shape turns to an elliptical shape as an external force ($F \neq 0$) is applied. Both shapes therefore have the same perimeter $p$. Taking the ellipse perimeter ($p_{el}$) as

$$p_{el} = 2\pi \left( \frac{a^2 + b^2}{2} \right)^{1/2}$$

(6)

where $a$, $b$ are semi-major and semi-minor of the ellipse, respectively; and noting that the ellipse has the same perimeter as its corresponding circular coil of radius $r$, i.e., $p_{cir} = 2\pi r$, we can write

$$2\pi r = 2\pi \left( \frac{a^2 + b^2}{2} \right)^{1/2}$$

and therefore

$$a = \left(2r^2 + b^2\right)^{1/2}$$

(7)

Looking back to Figure 2, if the moveable wall is displaced by $S_D$, an ellipse is formed (Figure 4). Accordingly, its semi-minor is $b = r - \frac{S_D}{2}$ and from equation (7) its semi-major is

$$a = \left(r^2 + rS_D - \frac{S_D^2}{4}\right)^{1/2}$$

(8)

Knowing that the curvature of an ellipse at any point $(x,y)$ is given by
\[ \kappa = \frac{1}{a^2 b^2} \left( \frac{x^2}{a^2} + \frac{y^2}{b^2} \right)^{-3/2} \]  

(9)

Its maximum curvature, which is the curvature at points \((-a,0)\) and \((a,0)\), can be found as expressed by

\[ \kappa_{\text{max}} = \frac{a}{b^2} = \left( r^2 + S_D - \frac{S_D^2}{4} \right)^{1/2} \left( r^2 - rS_D + \frac{S_D^2}{4} \right)^{-1} \]  

(10)

Figure 5 shows how \(\kappa_{\text{max}}\) of an ellipse formed from a circular coil with diameter \(r\) changes as it is squashed by \(S_D\) by a moveable wall shown in Figure 1. It is clear from Figure 6 that for a given displacement \(S_D\), the maximum curvature of a small ellipse is much higher than the bigger one. As the moveable wall is displaced farther, the curvature of the small size ellipse changes more rapidly than the bigger one. Since the bending loss \((\alpha)\) of a fibre is related to the radius of curvature \((R=\frac{1}{\kappa})\) as given by [8]

\[ \alpha = C_1 \exp(-C_2 R) \]  

(11)

where \(C_1\) and \(C_2\) are constants, then by substituting equation (10) into equation (11) we have

\[ \alpha = C_1 \exp \left(-C_2 \left( r^2 - rS_D + \frac{S_D^2}{4} \right)^{1/2} \left( r^2 + rS_D - \frac{S_D^2}{4} \right)^{-1/2} \right) \]  

(12)

As a consequence, higher loss is achieved by a fibre coiled onto a smaller radius of rubber mandrel than the larger one (Figure 4). The loss change resulted from the successive displacements is more rapid in small size coil than the bigger one. The higher the curvature, the more rapid the loss will be [8]. This effect is much more significant if the number of turns increases.

Figure 6. Maximum curvature variation of ellipses formed from different size of circular coils (diameter of 1.0 cm, 1.4 cm, and 1.7 cm).

Figure 7. Plot showing the linear part of loss Vs displacement curve of a four turns fibre coil formed on mandrel with a diameter of 1.0 cm

Since sensitivity of a sensor is defined as the change in output of the sensor per unit change in the parameter being measured, fibre sensor made by wrapping four polymer optical fibres onto rubber mandrel with the diameter of 1 cm and with the number of turns is 4 is favourable among those presented in this paper. Taking the linear part of the loss-displacement curve belongs to this favourable fibre sensor shown in Figure 4.c; we can modify this curve as shown in Figure 7. Sensor configured in this way has sensitivity of \((5.9 \pm 0.2)\) dB/cm and displacement range 40 cm. The sensitivity and
displacement range of this sensor can still be improved by playing with pulley system and/or number of coil turns. Adding a pair of two coaxial wheels exactly the same as that given in Figure 1, for example, will make a tenfold increase in measurable displacement range, i.e., from displacement range of 40 cm to 4 m.

Fig. 8. (a). A slider used as landslide model. (b). Mechanical displacement converter used to convert land displacement in centimeters order into displacement order within which fibre sensor can detect.

Fig. 9. Land displacement obtained from landslide model

Fig. 10. Example of an SMS alert sent when a landslide is detected by sensor.

A model has been made to test the system performance. A slider (Figure 8.a) attached to a mechanical displacement converter (Figure 8.b) is set to move downward, resulting in displacement of the wall pushing the fibre coil so that its shape turns to ellipse (Figure 2). As the slider displaces continuously downward, the coil curvature will also continuously increase and the fibre loss increases accordingly. Figure. 9 is a typical land displacement history taken from the model made in this research. The actual time required for the land to make a notable displacement varies from site to site [9, 10, 11]. One should note that landslide is an accelerated motion with the initial velocity equals to zero. Alert should therefore be spread from the early stage of motion to provide people to have enough time to evacuate from the danger zone. An early warning system designed in this research is aimed to alert people in a landslide danger zone whenever the sensor detects a continuous nonzero land displacement for few seconds or the magnitude of the land displacement reaches a certain value. People should know that an early step of land movement occurs. Since movement can occur at anytime, alert in the form of SMS is not enough. In order to provide people living in the danger zone with the most effective warning system, a siren has been added to the EWS system developed in this experiment. Alert is sent once sensor detects a nonzero continuous displacement for 5 seconds or the land displaces downward a distance of 10.0 cm. Example of the SMS alert is shown in Figure 10.
4. Conclusions and Future Work

A simple landslide early warning system built based on macro-bending loss in polymer optical fibre has been developed and successfully tested. Fibre optic sensor system presented in this paper allows detection of landslide at the early stage of land movement using only a simple and cheap fibre sensor (polymer optical fibre). The system consists of three main parts: displacement fibre sensor system, pulley system and SMS gateway device equipped with a siren. Typical fibre sensor that measures displacement in micrometers or millimeters scale has been combined with a pulley system to form a new system enabling the scale of measurement which can be scaled up to centimeters. Three groups of fibre coil each has different radius and number of turns have been made and compared. It has been shown that sensor system built by wrapping 4 turns of fibre polymer around a rubber mandrel with diameter of 1.0 cm has better sensor performance than others investigated in this paper. This sensor has ability to monitor land displacement in the range of 40 cm and sensitivity of \((5.9 \pm 0.2)\) dB/cm. The key principle to improve the fibre sensor performance to meet the real need has also been presented, i.e., by managing the pulley system as well as the radius and the number of a used coil. Furthermore, we suggest that alert should be spread whenever sensor detects a nonzero land movement.

Continuing this research, our future work will focus on developing this simple and cheap landslide early warning system such that it is ready for field test and provide an alternative landslide early warning system having performance comparable to that of other already established systems.

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