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Wireless chemiluminescence-based sensor for soil deformation detection

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ABSTRACT

A novel sensing application based on chemiluminescence was designed and tested in the laboratory for deformation monitoring in soil. The device, containing the reactants stored in separate chambers, on activation when deformed under load, result in an almost instantaneous production of light which could be readily detected using low-cost optoelectronics. The attractiveness of this concept for deformation monitoring is that the chemiluminescence sensor is completely passive, requiring no power for it to function. In this paper, the effort was focused on demonstrating the sensing capability of the chemiluminescence-based device for detecting soil deformation or movement in the event of a landslide. Laboratory experiments were conducted to demonstrate the proof-of-concept through a prototype of the device fabricated specifically for this study. Wireless transmission capability was also incorporated into the prototype design in view of the potential deployment in the field.

1. Introduction

Many areas in the world most prone to landslides are also some of the least developed regions. Large scale deforestation, population growth and poorly-engineered structures built along slopes presents high-risk area for landslide particularly during heavy rainfall and for areas located near the epicenter of earthquakes. Even within a developed country like the United States, recent landslide in Charleston, West Virginia in March 2015 and rural Washington in 25 Mar 2014 highlight the fact that this natural catastrophe is not limited to places such as India, Sri Lanka, Myanmar, China, Columbia, Nepal, Philippines where recent landslides have occurred resulted in loss of many lives [1].

The triggers and causes of landslides are diverse and a multidisciplinary approach using a variety of technologies applied to different classes of landslides and in consideration of many other criteria, such as purpose, cost, parameters to monitor, duration, accessibility and others [2]. The availability of a highly-portable, easy-to-install, low-cost sensor alert system placed in the hands of non-technical local communities through non-governmental organizations (i.e. non-profit, voluntary citizens' group) and various social entrepreneurs will greatly improve the chances of survivability of the community in the event of a landslide with early warning provided by the sensor system.

Various approaches in landslide monitoring have been grouped by researchers as remote sensing or satellite techniques, photogrammetric techniques, geodetic or observational techniques, and geotechnical or instrumentation or physical techniques [3]. Based on a more extensive survey of the prior art, there is plentiful of approaches in predicting and providing early warning of landslides ranging from empirical and analytical relations between rainfall and landslide generation [4–6], model-based system [7], satellite technology-based [8–11], monitoring of intensity of rainfall [12–14], model-based [15], Internet-of-Things [16], optical fibre sensors [17] wireless sensor networks [18–25] and many other technologically-advanced methods reported in the literature. However, these systems are either very costly, in need of continuous power supply, requiring long runs of cables or fibre sensors, fragile or too complex to be managed especially by the laymen e.g. communities living in the vicinity of those landslide prone areas. It may be argued that a low-cost, simple to use monitoring system capable of detecting a preset threshold level of a selected parameter (e.g. movement or deformation of soil, this being the 'effect' or 'signature' of early stages in the development of a landslide) which then triggers an immediate alarm through wireless technology will hold the key to an effective early-warning system [26].

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Fig. 1. (a) Photo showing the constituents of the glow-stick: (top most) outer plastic tube and (middle) the inner glass tube containing diphenyl oxalate in red dye. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The proposed technique is novel in that the use of chemiluminescence for landslide monitoring (or structural deformation monitoring) has not been reported in the literature [27,28]. The sensor requires no power to operate; light generation is achieved almost instantaneously on activation in the event where the device is deformed beyond a set-limit. Using low-power wireless transmitter, set to transmit only a very low transmission rate to conserve energy, the system could be a stand-alone monitoring device requiring little or no maintenance. The key benefit of a wireless data acquisition in the field includes the ease of data acquisition from a distributed network of sensors without the need and the associated high cost incurred to lay long lengths of electrical cables. In addition, no signal processing of voluminous data (e.g. in the case of acceleration-type sensing systems) is necessary, further minimizing the power requirement of the wireless system. In view of the low cost of the device, the sensor could be scaled up in quantity readily to achieve sensing redundancy and deployed over a wide area for better coverage.

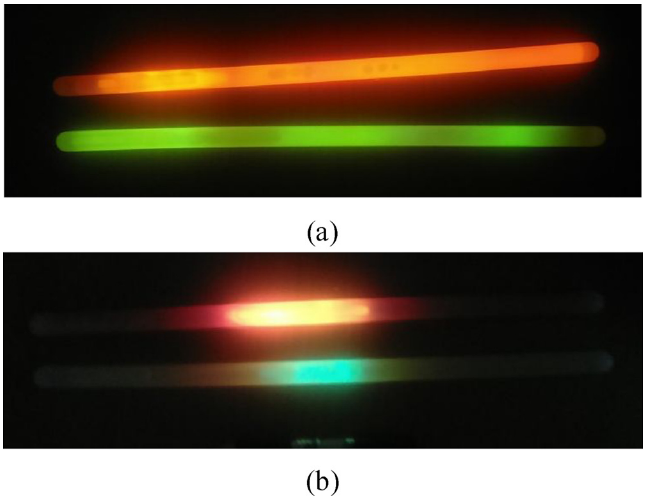
This paper will outline a series of tests carried out to investigate the potential of the chemiluminescence-based sensor for soil deformation or movement monitoring. The working principles of the sensor, design and test results will be presented and discussed.

2. Methodology

2.1. Background

The chemiluminescence-based deformation sensor used in this study consists of a glass ampoule contained within a sealed plastic tube made from low-density poly-ethylene (LDPE). The chemicals within the glass ampoule comprise of a dye and diphenyl oxalate while the chemical inside the plastic tube is hydrogen peroxide. The constituent of the sensor is shown in Fig. 1. By mixing the peroxide with the diphenyl oxalate, a chemical reaction takes place, yielding two molecules of phenol and one molecule of peroxyacid ester (1,2-dioxetanedione). The peroxyacid decomposes spontaneously to carbon dioxide, releasing energy that excites the dye, which then relaxes by releasing a photon. The wavelength of the photon—the color of the emitted light—depends on the dye used. The device, more commonly known as glow-sticks, can be readily purchased from hobby shops, are inexpensive (less than US$1/unit) and available in various lengths, typically in the form of a cylindrical tube. Tubes with dimensions of 400 mm by 15 mm (length x diameter) were used in most of the experiments carried in this study.

The principle of deformation detection is simple and this relies on the activation of chemiluminescence on bending of the tube, where on cracking of the inner glass tube, the two liquid chemicals mixed to produce light without an external energy source. Once the glow-stick is bent or cracked, the stick is then shaken gently to allow complete mixing of the two chemicals thoroughly throughout the tube, illuminating the entire length. In our study, one of the challenges was to detect the presence of the light since the chemiluminescence effect was localized around the vicinity of the crack site as no shaking of the tube was possible when embedded in the soil. Fig. 2 shows the illumination of the glow-stick with and without shaking on activation of the glow stick, highlighting the localized illumination at the central portion of the tube where it was bent.



(a)

(b)

Fig. 2. (a) Illumination of glow stick after shaking the tube to promote mixing throughout length of tube. (b) Illumination of glow stick without shaking on activation.

2.2. Mechanical tests

Prior to assessing the potential of the glow stick for detection soil deformation, a series of glow sticks were initially loaded in a flexure using a three-point-bend set-up. In addition, the individual constituent of the glow stick, namely the low-density polyethylene (LDPE) outer tube and the inner glass tube were also tested separately to obtain the load-displacement response of these parts. A number of glass tube specimens were prepared by first extracting them from the LDPE tubes. In order to access the glass tube, one end of the LDPE tube was cut open using a razor blade. The hydrogen peroxide solution contained within the LDPE tube was disposed safely, while the glass tube was carefully extracted and inserted into a ‘zip-lock’ bag which will prevent spillage during the bending test where the tube will be loaded to failure.

As the glass tube was slightly smaller in diameter than the inner diameter of the LDPE tube, loading of the specimen will first result in the bending of the outer LDPE tube and subsequently the load will be supported by the inner glass tube leading to eventual flexural failure. It was of interest to model the glow stick to identify the crack location as a reference for comparison to the experimental observation. The simulation was carried out in a popular commercial engineering simulation software package known as ANSYS.

2.3. Specimen and experimental rig preparation

The principle of deformation detection is simple and this relies on the activation of chemiluminescence on bending of the tube, where on cracking of the inner glass tube, the two liquid chemicals mixed to produce light without an external energy source. To detect the light emitted from the glow-stick, a low-cost solution was design utilizing an array of light-dependent resistors (LDR) connected to a series voltage divider circuit to detect the light signal emanating from the glow-stick. Since no shaking of the glow-stick (to promote the mixing of the reactants throughout the length of the tube) is possible when embedded in the soil or structure during testing, the light generated will only concentrate around