A New Landslide Inclinometer Using Highly Sensitive Gauges

Cristian Fosalau, Cristian Zet and Daniel Petrisor
Faculty of Electrical Engineering
Technical University of Iasi
Iasi, Romania
cfosalau@ee.tuiasi.ro

Abstract— **The paper presents a device devoted to detect and measure earth displacements produced by landslides. It is part of inclinometer type geotechnical instruments and is based on measuring the deformation produced to a rod vertically mounted into the ground during soil layers sliding. With respect to other commercial devices, our inclinometer is characterized by high sensitivity to very small deformations owing to special strain gauges utilized in its construction, and also by possibility of 3D measuring, it being able to gauge in depth the amplitude and orientation of the soil layers displacement.**

Keywords-landslide, inclinometer, magnetic amorphous microwire, strain gauge, stressimpedance.

I. Introduction

Landslides represent phenomena in which a block of soil, rock or organic materials are moving onto the slopes of the hills or mountains under the influence of gravity. The most important factors that facilitate this phenomenon are the nature of the soil layers into depth, the slope configuration and geometry and the ground-water conditions [1]. Increasing the pore water pressure in soil layers leads to their destabilization and tendency to downslope slide [2]. Some landslides are very slow, of several cm a week, but others catastrophically flow in form of mud or debris with velocities of tens of meters a minute, destroying everything in their way. Usually, a landslide may begin with a very small movement, gradual acceleration and ends with large displacements producing serious damages. That's why monitoring of these incipient movements and using real time data can anticipate and worn about possible further catastrophic hazards.

The known techniques for monitoring landslides activity are divided into the following categories:

i) Satellite and aerial techniques in form of photographic, scanning and processing systems including Global Positioning System, in which sets of images or positions acquired in time over the observed zone are periodically compared [3,4]. In this case, it is necessary the direct sight over the area. The method provides accurate information for large areas of observation, but utilizes very complicated and expensive equipments.

ii) Methods based on geometrical measurements of distances and angles over the earth surface followed by calculus concerning deviations from a fixed position [5]. The precision is very high, here being involved interferometer optical methods, but the measurements are only at surface, and the monitored area is not too large because direct sight is needed between points.

iii) Geotechnical techniques involve utilizing specialized transducers in direct contact with the monitored earth. The main geotechnical sensors used for landslide monitoring include; extensometers, inclinometers, piezometers, strain meters, pressure cells, geophones, tilt meters and crack meters. [6-8]. These sensors are capable to measure directly the soil displacements with good precision, may be connected in sensor networks that can be extended to cover large areas and permit data storing and transmission. The accuracy attainable can be of the order of 2 mm, but the main disadvantage of these type of instruments is that they cannot measure the amplitude and direction of landslide in depth, along the soil layers, which could very useful for geologists for better understanding the mechanism of landslide initiation.

The device described in the paper is a type of inclinometer with enhanced capabilities in terms of sensitivity and flexibility to measure 3D landslide movements as orientation and magnitude in the ground depth. Moreover, the cost of the device is low enough to allow installation of a large number of such devices on a wide area working in a wireless sensor network, even if they might be destroyed during the landslide activity. As a principle, the device measures the deformation of an elastic rod vertically mounted into a borehole in the ground. The deformation is measured using a new type of strain gages based on special materials exhibiting very high sensitivity to strain. The gages are glued onto the rod in a Wheatstone bridge so that both amplitude and direction of the ground displacement may be calculated and monitored.

II. Transducer Construction

The landslide transducer presented in the paper is foreseen to be mounted in a landslide wireless network (LWN) designed to monitor a zone in the Moldavian region of Romania, prone to landslide occurrence. The LWN will be composed of a number of measurement nodes (MN) wirelessly linked in a star configuration and centered to a local server which finally will transmit the acquired information to remote dispatcher by GPRS. In the paper we'll discuss only the MN architecture and realization, along with some experimental features and characteristics.

A. Measurement node

A measurement node is composed of a polypropylene rod (tube) that is vertically mounted into a borehole dig into the earth prone to landslide. The rod comprises several measurement points (MP) distributed along the rod length according to the needs of monitoring sliding of individual soil layers during the landslide. The MP emplacement on the rod is established according to previous geomorphologic studies over the area. All the MPs mounted on the rod, along with additional humidity (HS), temperature and pore water pressure (PWP) specific sensors form the measurement node, as depicted in Fig. 1.

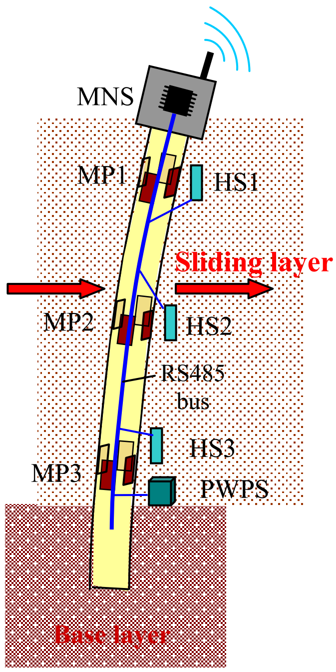


Figure 1. The MN structure: MNS - measurement node server, MP - measurement points, HS – humidity sensor, PWPS – pore water pressure sensor

Each MP consists of a strain gauge bridge whose sensitive devices are disposed along the four cardinal points and paired diametrically opposed. They are able to measure with a high degree of sensitivity the deformation of the rod subject to the soil layers slides and, hence, the amplitude and the orientation of the landslide. One of the main benefits of our transducer with respect to any other commercially available inclinometers is the sensitivity of measurement, which is assured by special strain gauges developed in our laboratory and described in the next section. Every MP is endowed with a minimal primary data conditioning and a microcontroller that acquires the voltages proportional to the deformation, converts them in digital words and send by means of RS485 bus to the measurement node server (MNS) mounted in a waterproof case on the top of the rod. At this level, the voltage values are converted into information about amplitude and orientation and then wirelessly transmitted to the local server of the network (LS). MNS also performs the power management of the MN. This ensemble is supplied with power delivered by a 5 W/12 V solar panel.

B. Sensing element

The landslide transducer sensing element is a full bridge composed of four highly sensitive strain gauges (HSSG) based on magnetic amorphous microwires (MAM), as shown in Fig. 2 [9]. A HSSG consists of two parallel MAMs of 10 mm, bonded on a plastic film which, in turn, is applied on the surface subject to strain.

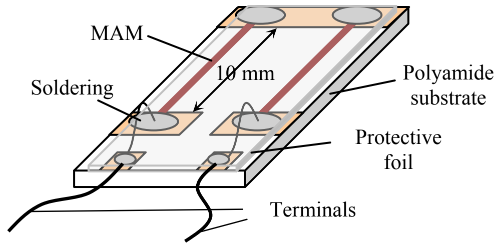


Figure 2. Structure of a highly sensitive strain gauge (HSSG)

A MAM is a magnetic amorphous alloy in wire form, composed of Co, Fe, B and Si in different proportions [10]. It possesses special properties and effects among which is the stressimpedance (SI) effect. According to this, the MAM impedance changes with applied stress, as shown in Fig. 3 [9].

SI effect is a variant of magnetoimpedance (MI) effect, which is a well known effect occurring in such kind of materials, having many practical applications [11]. As deduced from Fig. 3, the gauge factor of such a strain gauge may be as high as more than 2000, 1000 times larger than that of a metallic one with a linear strain span of ± 200 ppm, making it suitable to detect and measure very small strains.

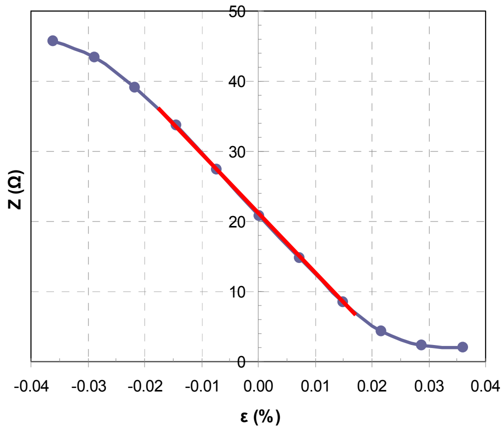


Figure 3. Dependence of HSSG impedance on the applied stress, $\varepsilon = \Delta l/l$

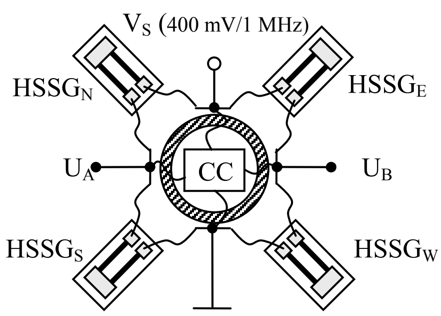


Figure 4. Schematic of a strain bridge: $HSSG_{N, S, E, W}$ – Strain gauges mounted along the N, S, E and W directions, CC – conditioning circuitry

In order to build the landslide transducer, four such strain gauges are bonded 90° circumferentially distanced on a polypropylene cylindrical rod surface so that to form a complete strain bridge (SB), as shown in Fig. 4. The bridge, together with the appropriate conditioning and data processing circuitry, forms a measurement point (MP).

C. *Signal conditioning*

A bloc diagram of the signal conditioning circuitry associated to a MP is presented in Fig.5. The whole ensemble is supplied with a voltage of about 12 V, delivered by a solar panel. Before being applied to the electronic blocks, this voltage is first converted into two differential voltages, ± 5 V and ± 2.5 V in the Power Supply (PS) block. The Strain Bridge (SB) is fed with 400 mV/1 MHz voltage delivered by the Oscillator (OSC) block. This voltage ensures a current of about 10 mA through the MAMs. It has been proved that 10 mA/1 MHz is the optimal current/frequency at which one obtains the maximum sensitivity and linearity for the HSSG [9]. SB is a complete strain bridge that provides as outputs two voltages, U'_A and U'_B, whose amplitudes are dependent on the deformation magnitude and orientation of the rod. U'_A and U'_B, of orders of tens of mV, are then differentially amplified (DA), multiplexed (MUX) and peak detected (PD) so that the outputs $U_{=A} \equiv U_A$ and $U_{=B} \equiv U_B$ are also dependent on the rod deformation. Finally, the dc voltage, U_A and U_B are applied, in turn, to an analogue input of the microcontroller μC that converts them in digital words. From these parameters we may compute the rod displacement magnitude, d, at the MP level along a direction making the angle α with the North direction with the relations [12]:

$$d = \frac{\sqrt{d_N{}^2(U_A,U_B) + d_E{}^2(U_A,U_B)}}{2} \quad (1)$$

$$\alpha = \tan^{-1}\left(-\frac{(k+2)U_A - U_s}{(k+2)U_B - U_s}\right) \quad (2)$$

In the above relations, d_N and d_E are the displacements of the rod along two orthogonal directions on which the strain gauges have been mounted in pairs (e.g. N-S and E-W), and that are dependent on U_A and U_B. Constant k depends on construction parameters of the HSSGs and on their gauge factor. U_s is the amplitude of the supply voltage of the bridge (400 mV).

III. EXPERIMENTAL SETUP

In order to test the transducer, we built an experimental setup designed to simulate as close as possible a landslide. It is a metallic construction allowing the transducer to be bended having two different fulcrums along its length so that one fulcrum is taken as reference simulating the stable soil and the second one is moving according to moving ground layer during landslide. Both fulcrums are able to axially move along the rod. A schematic representation of this setup is presented in Fig. 6.

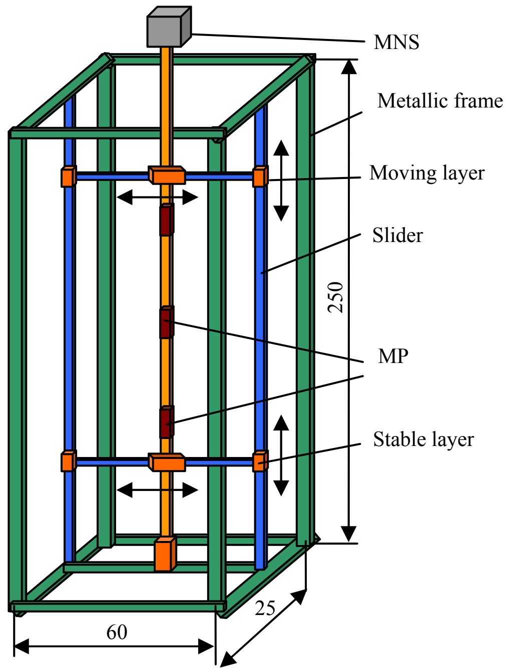


Figure 6. Schematic representation of the experimental setup. Dimensions are in cm.

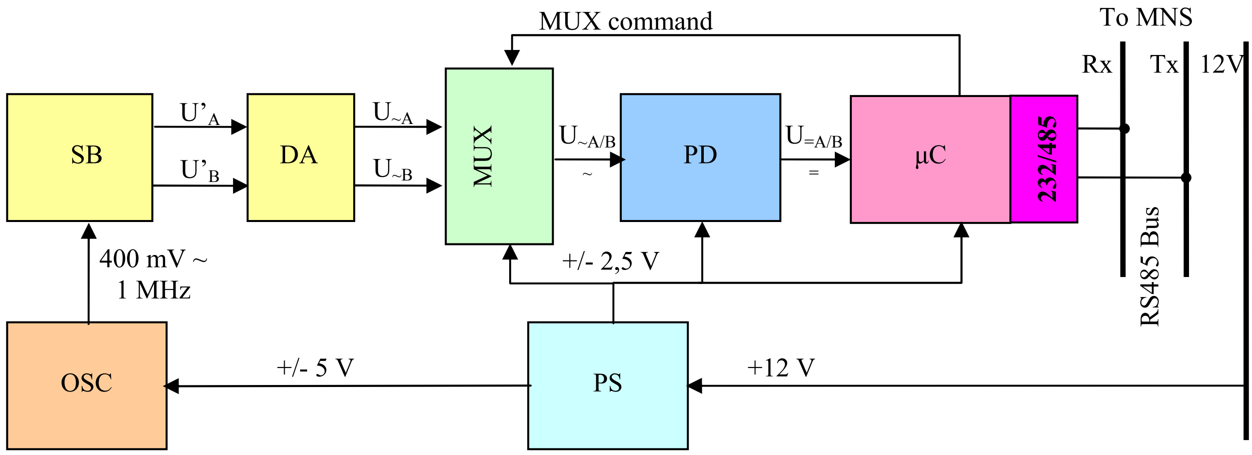


Figure 5. Block diagram of the signal conditioning circuitry for a measurement point: SB - strain bridge, DA – differential amplifier, OSC – sinusoidal oscillator, MUX – analog multiplexer, PD – peak detector, PS – power supply, µC - microcontroller

IV. RESULTS AND DISCUSSIONS

Using the above setup, we tried to assess the performances of the transducer in terms of sensitivity, linearity and accuracy when determining the landslide amplitude and orientation by tracing the dependence of the output voltages delivered by the peak detector, U_A and U_B on the rod deformation along different directions. The tests have been performed taking as variables the displacement of the mobile fulcrum and orientation of deformation with respect to a reference direction, and as parameters the distance of the measurement points to the fixed and mobile fulcrums. We tested the transducer equipped with two measurement points emplaced like in Fig. 7a) and Fig. 8a). Figs. 7 and 8 present the characteristics U_A, $U_B = f(d)$ where d is the displacement amplitude of the mobile fulcrum for two particular directions, NE-SW and NW-SE, that is along the diagonals of the strain bridges, where all HSSGs characteristics should be about the same.

As it may be concluded from the characteristics below, the deformation for MP1, which is closer to the fixed fulcrum, that is closer to the stable landslide substrate is more pronounced than that for MP2, which is closer to the mobile layer surface, fact emphasized by the more sloped characteristics of MP1 than of MP2. However, whereas these characteristics are more sensitive, their linearity dramatically decays as the MP gets closer to the fixed fulcrum. Fortunately, this nonlinearity does not worsen too much the device performance, as we are more interested in sensing the landslide from its very beginning and most important for us is the sensitivity around relaxed state of the traducer.

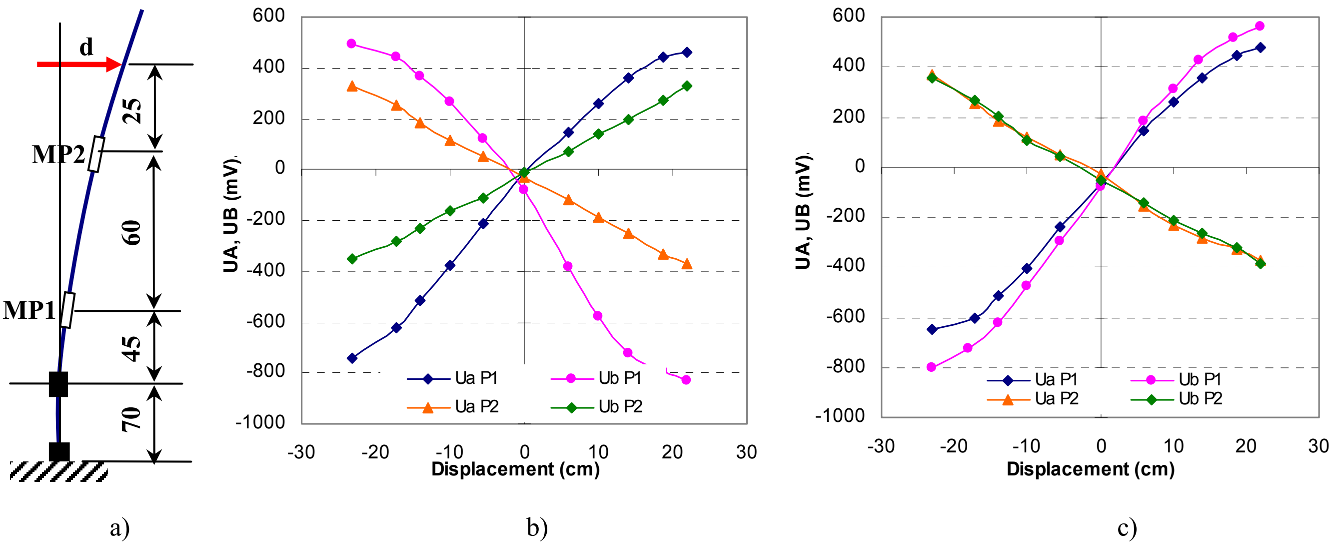


Figure 7. Representation of the voltages delivered by two measurement points vs. displacement d of the mobile fulcrum: a) particular emplacement of MPs with respect to fixed and mobile fulcrums, b) representation $U_{A,B} = f(d)$ for NE-SW orientation of displacement, c) representation $U_{A,B} = f(d)$ for NW-SE orientation of displacement.

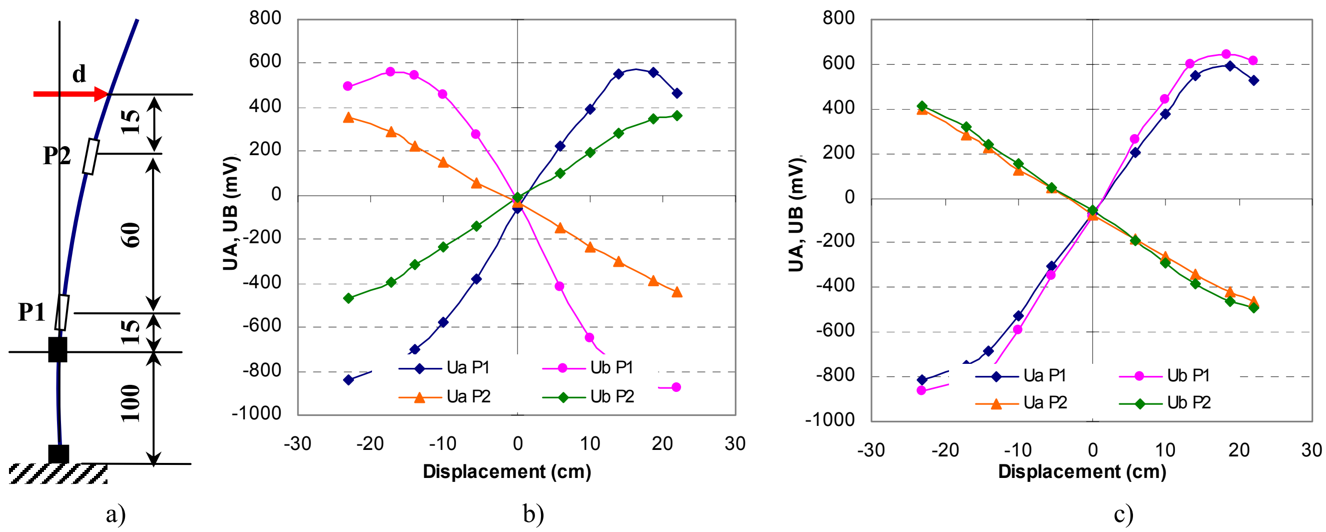
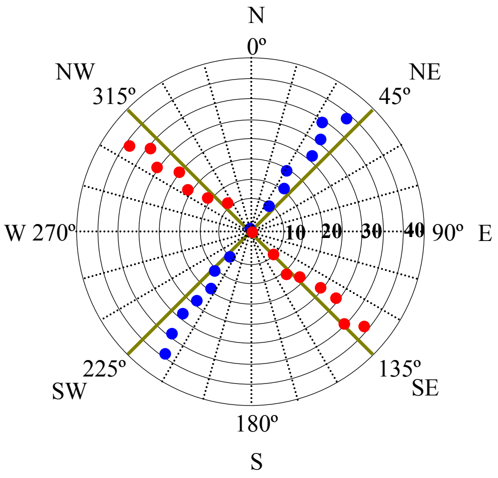
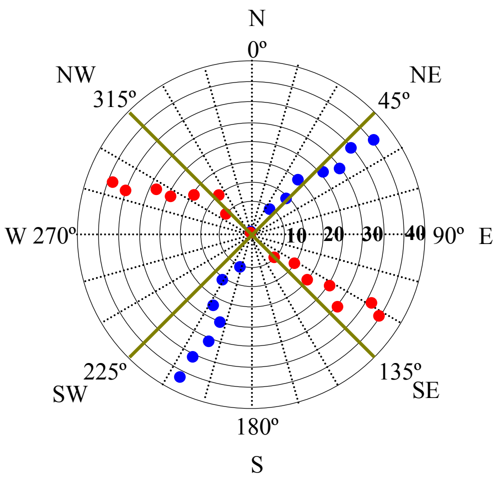


Figure 8. Same representation as in Fig. 7, but for another arrangement of MPs with respect to fulcrums.



a)



b)

Figure 9. Representation in polar coordinates of the displacement amplitude and angle direction calculated with equations (1) and (2) in the two arrangements of Fig. 7 and Fig. 8.

Based on the above sets of data, we calculated and measured the displacement and orientation of every MP using equations (1) and (2). The results are represented in Fig. 9. It may be observed that the values calculated for d and α are affected by quite large errors, mostly in the domain of prominent deformations and small amplitudes of the displacement. These errors do not exceed, however, 12 %, which is considered a satisfactory result for our application. By analyzing the factors that influence the measurement accuracy, we found several sources of errors among which the large dispersion of the new developed strain gauges parameters is maybe the most important, as we have not developed yet the manufacturing technology, but we built them "by hand". We have in view a better technique of gluing the wires onto their support and of controlling the initial tensile stress of the MAM, as this parameter has a great importance on the linearity of the sensor [9]. An error analysis and curves and their dependence on external factors will be provided in the final paper. The preliminary tests performed reveal for the time being a good behavior of this inclinometer in terms of sensitivity, it being able to sense soil displacements as low as 1 mm per measurement point, which is an acceptable result for detecting incipient landslides.

V. Conclusions

In the paper, we presented the construction and characteristics of a new type of inclinometer for detecting and measuring very small displacement of the ground in incipient landslides. The device brings two important benefits, high sensitivity owed to a new type of strain gauges based on magnetic amorphous microwires and possibility of measuring amplitude and direction of the landslide in 3D, thus providing additional information to geologists for a better understanding of this hazard.

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