Monitoring System for Deep-Seated Landslides using Locally-Developed Tilt and Moisture Sensors: System Improvements and Experiences from Real World Deployment

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Abstract —**Landslides pose serious threat in a large number of communities living near steep and unstable slopes in the Philippines. This paper describes the enhancements in the design of an alternative instrumentation for monitoring deep-seated landslides based on tilt and soil moisture sensors. The real time landslide monitoring system is composed of a sensor column buried in a borehole, which can reach up to 40m in depth, in the unstable slope. Each column consists of 0.5-1m segments that contain a tri-axial accelerometer for tilt measurements and a capacitive sensor for soil moisture. In this manner, tilt and soil moisture measurements can be made at a resolution of 0.5 to 1m underground. Sensor measurements from each segment are accessed via Controller Area Network (CAN) protocol and transmitted to a remote host via GSM cellular infrastructure. We also describe the previous deployments in ten different sites in the Philippines as well as share the technical challenges and difficulties faced in deploying the monitoring system in real world setting. The field deployments provided valuable inputs regarding improvements in the sensor design. Furthermore, this paper discusses the experiences in involving the community at risk as part of the synergistic approach in taking progressive steps towards an effective community and technology based early warning system.**

Index Terms– accelerometer tilt sensor, capacitive soil moisture sensor, deep-seated landslide monitoring system, community involvement, real world deployment

I. INTRODUCTION

The geologic, geomorphologic, and climatic setting of the Philippines makes it prone to geohazards. Based on the geohazards map of the Mines and Geosciences Bureau of the Republic of the Philippines shown in Figure 1, more than one third of the land area of the Philippines is highly susceptible to landslides [1]. Unfortunately, these areas at high risk are also densely populated. Despite the availability of the geohazard maps, hazard-based zoning is not strictly enforced due to various social, political, and economical implications. Landslide mitigation through engineering works may not always be feasible due to financial and environmental constraints considering the extent of the high risk unstable slopes [2]. Permanent relocation of communities that are highly vulnerable to landslide risks presents issues on cost of infrastructures and socio-economic factors [3]. Thus, a cost-effective and reliable early warning system is desirable and considered as the only viable risk mitigation option in many cases [4].

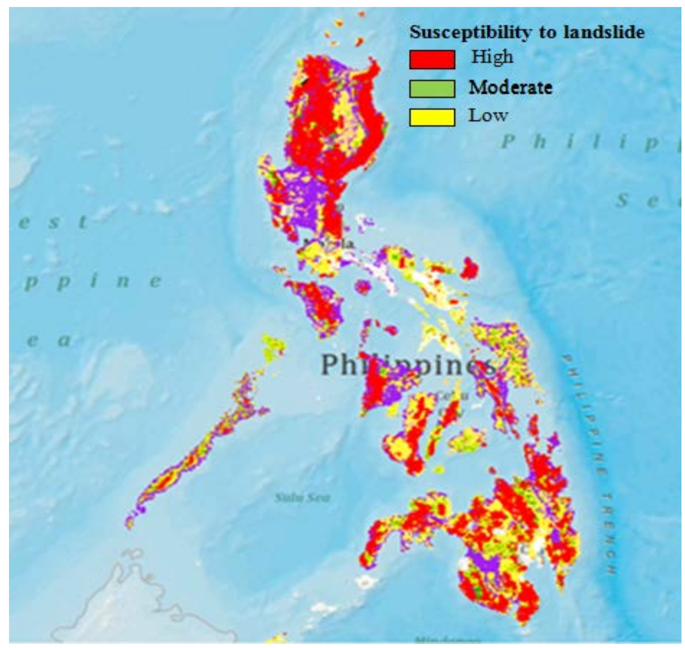

Figure 1. Geohazards map of the Philippines showing susceptibility to landslides [1].

Some of the disastrous landslides happened in the Philippines were often preceded by heavy rainfall [4]. These include the 1999 Cherry hills landslide in Antipolo [5], 2003 Panaon Island-Surigao landslides [6], 2004 Aurora-Quezon landslides [7], 2006 Guinsaugon Landslide [8] and the 2009 Little Kibungan landslide in La Trinidad, Benguet [9]. A commonly used early warning system for landslides is based on rainfall thresholds [10] especially in community-based warning system [11]. However, the available rainfall thresholds for landslides are typically related to shallow type only [12], empirically determined and site specific [4]. But for the more catastrophic deep-seated type of landslides, correlation between rainfall and landslides cannot be established due to the complex hydrology of deep landslides [13]. Furthermore, other factors such as changes in water level, seismic activity, volcanic activity, changes in ground water and combination of these factors [14] can initiate landslides and not solely based on rainfall intensity and volume. Currently available subsurface geotechnical instruments for monitoring landslides and slope failures include piezometers, inclinometers, and time domain reflectometry (TDR) cables [15-16]. Due to the high cost of these instruments and considering the extent of the slope to be instrumented, only few communities can benefit from these technologies.

In 2013, the Philippine government initiated a new nationwide early warning system program for deep-seated landslides and slope failures. This program, the Development and Deployment of Early Warning System for Deep-Seated Catastrophic Landslides and Slope Failures (DEWS-L) is a spin-off of the earlier disaster risk management program introduced in [17] and jointly implemented by the University of the Philippines and the Philippines Institute of Volcanology and Seismology (PHIVOLCS). With funding from the Philippine government, the DEWS-L program aims for further enhancement and testing of the deep-seated landslide monitoring system by deploying it in more landslide prone sites in the country.

The landslide monitoring system is composed of a sensor column consisting of 0.5-1m pipe segments. Each pipe segment has tri-axial accelerometers and capacitive sensor for measuring tilt and soil moisture, respectively. The assembled sensor column is buried underground in a borehole which can reach up to 40m in depth. The sensor readings from each segment are accessed via Controller Area Network (CAN) communications protocol. The collected data from each column are transmitted in a remote host via GSM cellular infrastructure. An illustration of the described landslide monitoring system is shown in Figure 2.

The development of the landslide monitoring system started from creating a small scale prototype that was tested in a series of experiments using a model slope in the laboratory. Based on the results of the experiments, it was concluded that the sensors can estimate the location of landslide slip surface and can provide greater lead time between initial detection and actual collapse of the slope [17-18]. A prototype for real world deployment was then developed and installed in Barangay Puguis, La Trinidad, Benguet where a deadly landslide occurred in 2009. The sensors deployed in this area measured a few centimeters of displacement over a six month period [17].

In the next section, the ensuing deployments of the sensor column in 10 landslide prone sites in the Philippines are discussed. The technical challenges encountered in real world deployments of sensor columns and the experiences gained in engaging the community as part of this disaster mitigation endeavor will be described as well. Samples of data obtained from the sensors deployed in the field will also be presented. In Section III, the enhancements and improvements in the sensor column packaging design, and to the tilt and soil moisture sensors will be explained in detail. Conclusions will be discussed on Section IV to share the efforts made in improving and enhancing the sensor column and in addressing the social related aspects of deploying the landslide monitoring system in real world settings. Section V presents our future work and recommendations by discussing the actions to be undertaken towards the establishment of community and technology based landslide early warning system.

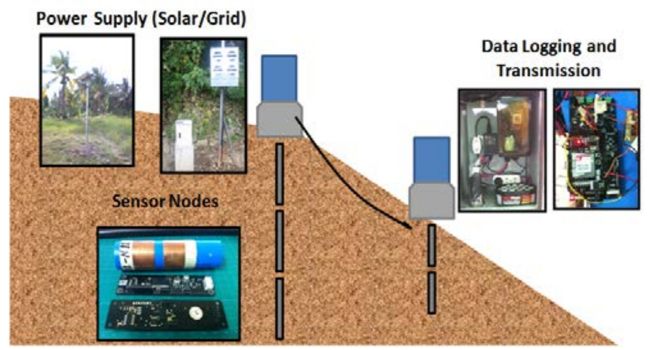

Figure 2. System diagram of the landslide monitoring system consisting of the sensor columns, data logging and transmission unit, and the power source which can be from the grid or solar.

II. Real world deployment: experiences and challenges

With the positive results achieved from the laboratory testing of the sensor column prototype [18], a series of field deployments was implemented to further test and verify the real world performance of the sensors. After the initial field deployment discussed in [17], subsequent reconnaissance for candidate deployment locations was conducted in various regions of the country before the selection of the test sites. The selection of the deployment sites was based on three major components: landslide geological factors (soil material, slope height and gradient, and history of slope activity/movement), community factors (risk exposure and willingness to support), and technical considerations (accessibility, network signal strength and availability of electricity from the grid or feasibility of setting solar power system). The list of the chosen test sites, including the relevant information on the installed sensor columns such as the segment length and the number of nodes per column, is summarized in Table I. A total of 19 sensor columns were installed across 10 sites in the Philippines during a one year period (2012-2013).

The first sensor column installation done at Barangay Puguis, La Trinidad, Benguet was filled with logistical, technical and social challenges [17]. The experiences acquired in this first real world deployment have served as the benchmark for all of the subsequent deployments. In terms of logistics, some problems that were encountered during field deployments were the indefiniteness of the soil drilling and rock coring period. Also, the drilling period takes a longer time than expected during a Standard Penetration Test (SPT). Other common sources of delay in the drilling of the boreholes are the bad weather, rock hardness, slope terrain, and the unavailability of water for wash boring. A well-planned schedule was indeed necessary since there were simultaneous deployments in various locations. Moreover, an efficient method of deployment is of paramount importance, especially during rainy season where the borehole is more prone to cave in. Additional technical difficulties arose during the first few deployments such as the availability of power from the grid for electro-fusing the sensor couplers. Since the sensor nodes are shipped in crates for modular transport, it has to be electro-fused on-site. This compromise in setting up the sensor column for installation becomes even more difficult in remote locations, where there is insufficiency or absence of power from the grid.

TABLE I
DEPLOYMENT SITES OF THE LANDSLIDE MONITORING SYSTEM

Location (*Sitio or Barangay/* Municipality/ Province)		**Date of Sensor Activation**	**Sensor Node length** (meter)	**No. of Sensor Nodes**
Puguis, La Trinidad,Benguet	crest	10/30/2010	1.2	14
	toe	12/7/2010	1.2	10
Sinipsip, Buguias, Benguet	crest	4/27/2012	1.0	29
	toe	6/23/2012	1.0	29
Lipanto, St. Bernard, Southern Leyte	crest	5/29/2012	0.5.	29
	toe	5/29/2012	0.5	30
Bolodbolod, St. Bernard, Southern Leyte	crest only	5/29/2012	0.5	30
Mamuyod, Tublay, Benguet	crest	9/23/2012	1.0	29
	toe	10/17/2012	1.0	24
Oslao, San Francisco, Surigao del Norte	crest	5/23/2013	1.0	23
	toe	5/23/2013	1.0	21
Labey, Bokod, Benguet	toe	3/6/2013	1.0	39
	crest	3/6/2013	1.0	25
Gamut, Tago, Surigao del Sur	toe	5/4/2013	1.0	17
	crest	5/4/2013	1.0	17
Humayhumay, Guihulngan, Negros Oriental	toe	4/9/2013	1.0	22
	crest	4/11/2013	1.0	26
Planas, Guihulngan, Negros Oriental	toe	3/23/2013	0.5	39
	crest	3/23/2013	0.5	40
Boloc, Tubungan, Iloilo	crest	4/6/2013	1.0	19
	toe	4/6/2013	1.0	24

To decrease the set-up time, some adjustments were made such as fusing the couplers by pair before shipping and using a generator set for fusing it on site. Also, a concern during on-site assembly of the sensor column was the difficulty of aligning the sensor segments for tilt measurement in an irregular ground, increasing the man-hours during deployment and resulting to potential error in tilt measurements. Another valuable insight was on the fluctuations of the nominal voltage due to poor regulation in the provincial areas that causing problems on the power supply unit of the sensor columns. The power supply unit of the sensor column that is connected to the distribution grid experiences a nominal voltage greater than its maximum rating at night when most of the appliances of the nearby households are shut down. In some sites where power from the grid is not accessible, a solar energy system was used to power up the sensor columns.

Figure 3 shows the activities involved in the deployment of the landslide monitoring system. The deployment of the sensor column is highlighted by the spirit of *bayanihan* (communal work), a uniquely Filipino trait. The social aspects of this landslide monitoring program posed another set of serious challenges. The security of the sensor columns is one of the concerns after a series of pilferage events occurred during the first few months of the sensor operation. This unfortunate event did not only result to loss of property, but loss of valuable data as well. Another one is the need of prompt sensor maintenance for the resumption of operation during frequent power interruptions and the replacement of faulty modules of the telemetry and power system. Lastly, there was a need for an immediate on-site monitoring and verification of ground movement during detection of potential movement based on the sensor measurements. Thus, the active assistance of the community members was needed not only in securing and maintaining the monitoring system, but also to improve the efficiency of data gathering and analysis.

Figure 3. Transporting the assembled sensor column from the location where it is assembled to the deployment site (*top left*) and installation in the borehole (*bottom left*). The solar panel used to power up the system (*top right*) and the enclosure box that contains the battery and other electronics (*bottom right*).

Addressing these interrelated social concerns, several efforts were formally conducted such as community seminars, skills-based training, and consultations prior to sensor column installation. The primary objective of the seminar is to introduce the nature and goals of the DEWS-L program and the importance of the sensor column as an alternative early-warning system. Increasing the awareness of the community members with regard to the landslide risk in their area is also important.

The objective of the training was to form a Local Landslide Monitoring Committee (LLMC), which is composed of volunteers from the community who will be equipped with basic knowledge and skills that are necessary to accurately monitor, map and survey the visual indicators of ground movement (cracks) in their area, and to maintain the continuous operation of the sensor columns. Lastly, the objective of the consultations is to facilitate an effective communication between the researchers and community members for the entire duration of the research phase, and especially during stormy seasons, and to encourage the support of the Local Government Units (LGUs), electric cooperatives and non-government organizations (NGOs) in equipping disaster-resilient communities.

The seminars have proven to be an effective method of engaging the community and other stakeholders. Since then, there has not been any pilferage event due largely to the fact that the communities have cultivated a sense of ownership of the early-warning system deployed in the area. A continuous and systematic exchange of information between the community and researchers is currently being implemented especially during times of continuous heavy rains and storms. Electric cooperatives have also shown their support by providing free electrification of the sensor columns as part of their corporate social responsibility. On the other hand, the support of the LGUs and NGOs has helped in the seamless integration of our research objectives to the community members especially addressing the language barriers. The activities involved in the seminar and skills-based training are shown in Figure 4. The seminars and trainings are jointly conducted by the geologists, electrical engineers, and members of the LGUs and NGOs. The data from the sensor columns are continuously received and processed in a host computer located in the University of the Philippines. Figure 5 shows the samples of data obtained from the deployed sensors in Benguet and Southern Leyte sites. The plots indicate a sensor column displacement downslope of more than 10cm in Benguet and Southern Leyte sites after a one and two year period, respectively. For the Benguet site, the significant movement recorded over the one year period shows the sensor column tilting in the opposite downslope direction (XZ plane) signifying potential settling of the column inside the borehole. Note that the largest displacement in the sensor column is recorded between March and October 2013. In the case of the Southern Leyte site, potential settling of the sensor column is manifested in the recorded plots between 2012 and 2013. Starting November 2013, the sensor column is tilting towards downslope direction and showing significant displacement between January and March of 2014. Moreover, approximately 15cm displacement was recorded along the XY plane with the sensor column tilting towards left direction facing downslope. The particular significant movements recorded in both the Benguet and Southern Leyte sites may be attributed to the onset of the rainfall season: May to October (Type I climate) for Benguet and November to January (Type II climate) for Southern Leyte. The column displacement and more importantly the rate of change of the column position from the Benguet and Southern Leyte sites as well as the other sites listed in Table I are continuously being monitored for the onset of potential slope failure.

The important lessons learned from the aforementioned social and technical issues served as valuable motivation for the redesign and enhancements of the sensor column, which shall be described in the next section.

III. Design Revisions and System Improvements

A. Sensor column packaging

With the packaging and on-site assembly related problems encountered during the prior deployments, the packaging design was carefully revisited and design revisions were carried out. Modularity and ease of on-site assembly of the sensor column are of paramount importance in redesigning the sensor segment packaging and coupler. A mechanical coupler was designed, fabricated, and tested to replace the previous coupler design that required electro-fusion. The segment coupler was made of high grade stainless steel material due to its resistance to corrosion in soils which is mainly dictated by soil acidity, resistivity, and chloride content [19].Furthermore, the diameter of the sensor segment was also reduced for easier transportation and installation. While there are changes made in the column packaging, the design still ensures waterproofing and structural integrity. The sensor segment packaging including the mechanical coupler was subject to physical (tensile, compressive and flexural tests), chemical (pH), and waterproofing tests to verify its integrity and durability. Manufacturing related concerns for the sensor segment assembly was also addressed and included in redesigning the packaging. A provision for inter-segment alignment, which is crucial for tilt measurements, was also integrated in the design by adding alignment keys in the segment packaging. The new packaging design for the sensor segment and the mechanical coupler is shown in Figure 6(a).

Figure 4. Community consultations and seminars are conducted prior to the deployments. Aside from introducing the program to the community, skills-based training are also conducted like mapping the actual site *(top),* measuring and monitoring cracks *(bottom right)*, and simple maintenance of the sensor column *(bottom left).*

B. Tilt Sensor

The on-board voltage regulation circuit was redesigned to cover smaller PCB space, to improve efficiency, and to ensure voltage stability and noise reduction. Static redundancy at the component level was applied by adding another tri-axial accelerometer in each sensor segment for tilt measurements.

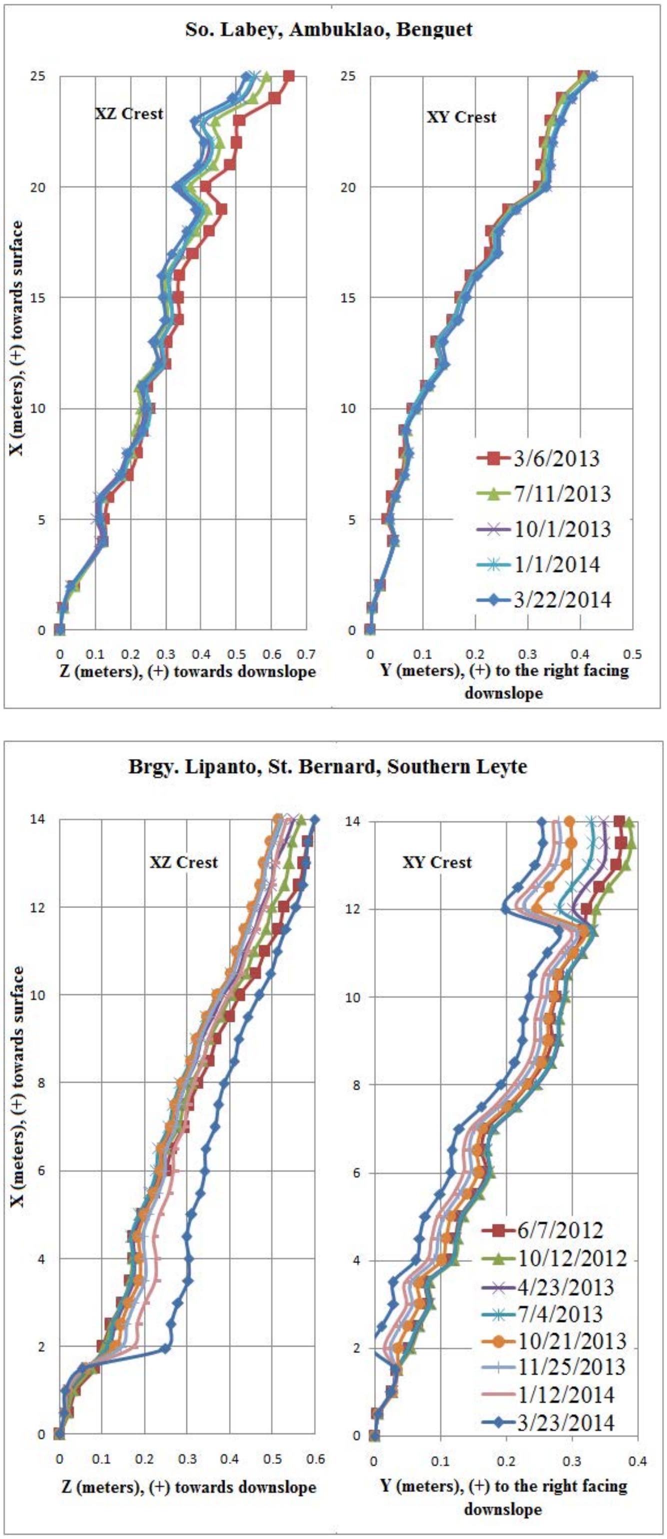

Figure 5. Initial significant tilt data obtained from the sensor column installed in the crest part of the slope in Benguet and Southern Leyte sites.

Although there will be additional costs involved with redundancy, preventing loss of data due to accelerometer faults is more valuable. While the accelerometers are already factory calibrated, recalibration is still needed since the sensors were subjected to thermal stress during the soldering process. With calibration, sensor reading errors can be minimized and tilt measurements between sensor segments can be directly compared. A simple calibration routine with minimal human intervention was devised capable of determining the scale factor and offset of accelerometers.

Only static acceleration was considered in the calibration since tilt measurement is based on the static acceleration due to gravity. To implement this calibration method, a fully automated three degrees-of-freedom (DOF) mechanical gimbal was designed, fabricated and tested. The gimbal can move the sensor boards in different static positions and can handle simultaneous processing of up to five sensor boards with the whole routine takes only five minutes to complete.

However, in this calibration routine a linear and decoupled axes model for accelerometer was assumed for simplicity. Figure 6(b) shows the three degrees-of-freedom gimbal made of acrylic plastic and aluminum materials.

In this calibration method, two points per axis are obtained which corresponds to +1g and -1g static acceleration. Thus, for a tri-axial accelerometer six points will be needed. The two points per axis would be used to compute the scale factor and offset as follows [20]:

$$A_{SF} = A_{+1g} - A_{-1g} \tag{1}$$

$$A_{off} = \frac{A_{+1g} + A_{-1g}}{2} \tag{2}$$

where A_{+1g} and A_{-1g} are the +1g and -1g static acceleration readings.The calibrated accelerometer reading is then computed as [20]:

$$A_{calib} = \frac{A_{raw} - A_{off}}{A_{SF}} \tag{3}$$

The developed calibration method was then applied to three accelerometer samples and repeatedly run to verify consistency of the results. The success of the calibration was confirmed by computing the magnitude (A) of the acceleration reading due to gravity for both calibrated and uncalibrated accelerometer readings in different static positions and comparing with the standard 1g acceleration as shown in Figure 7. Equation (4) is used to compute the static acceleration due to gravity measured by the accelerometer.

$$A\text{ (in g)} = \sqrt{A_X^2 + A_Y^2 + A_Z^2} \tag{4}$$

where A_X, A_Y, and A_Z are the corresponding accelerometer readings in X,Y, and Z axes.

The corresponding root-mean-squared-error or RMSE for both the calibrated and uncalibrated accelerometer measurements are summarized in Table II, where we note a smaller average RMSE of 0.0015 for the calibrated measurement compared to 0.012 for measurements without calibration. The computed RMSE for the calibrated accelerometer measurements of the three accelerometer samples is also consistent to be lower compared to the uncalibrated measurements verifying the success of the simple calibration routine.

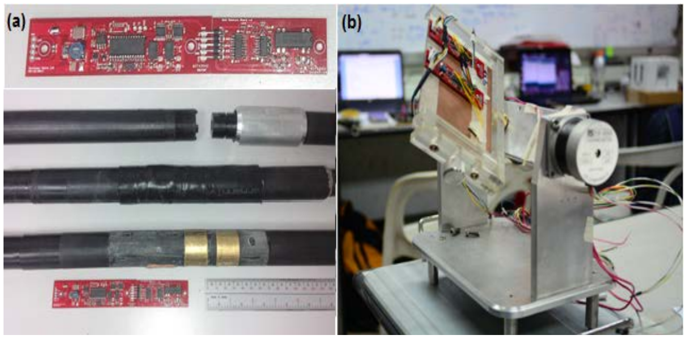

Figure 6. (a) The redesigned sensor board and packaging prototype showing the mechanical segment coupler, segment enclosure with heat shrinkable tube outer layer, the exposed soil moisture capacitor electrodes (brass) and the sensor board with dual accelerometer and soil moisture board. The diameter of the pipe segment was reduced in the new design for easier transporation and insertion in the borehole. (b) The 3 DOF calibration gimbal with sensor boards attached for calibrating accelerometers.

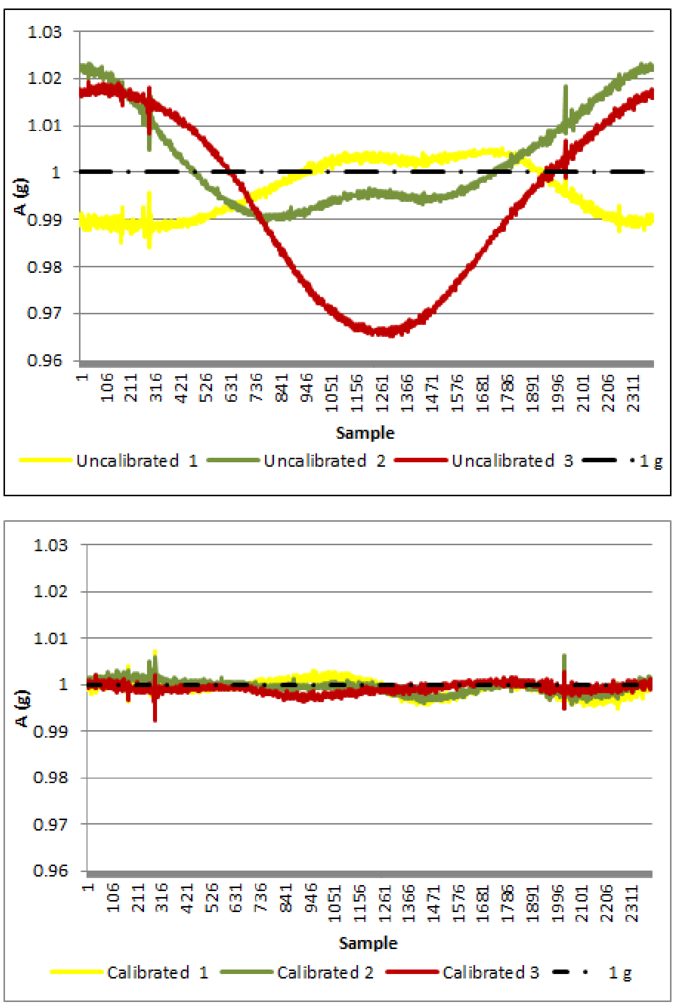

Figure 7. Uncalibrated and calibrated accelerometer 1g measurements for three accelerometer samples moved in several static positions.

TABLE II
RMSE 1G ACCELEROMETER READINGS

Accelerometer	RMSE uncalibrated (in g)	RMSE calibrated (in g)
1	0.0069	0.0017
2	0.011	0.0014
3	0.02	0.0013

C. Soil Moisture Sensor

A major consideration in redesigning the soil moisture sensor is the effect of air gap in the sensitivity and response. For the fringing field type of capacitive sensor on which the current soil moisture sensor design is based, the air gap acts as a capacitance in series with the impedance of the material to be sensed, which may result in inaccurate measurements and poor sensitivity [18, 21]. The occurrence of these air gaps was minimized in the new design.

Furthermore, the presence of air gap between the soil and the sensor column can only be addressed by careful installation of the sensor column into the borehole. Both the soil moisture sensor with and without air gap were characterized in sand and silt by gravimetric sampling and the results are plotted in Figure 9. Significant improvement in the sensitivity and dynamic range of the soil moisture sensor readings after removing the air gap can be observed from the characterization curves in Figure 9. By eliminating air gap in the sensor electrodes, the range became more than twice the range for the sensor with air gap. However, the sensor still needs soil specific calibration due to the differences in soil density of different soil types. Moreover, the sensor readings for the sensor without air gap in 0.1-0.15 kg/kg gravimetric water content tend to be higher compared with the other saturation levels due to compaction errors in silt during the tests. The aforementioned error is not achieved in the sensor readings in sand, brought about by ease in controlling the sand sample.

The aluminum electrodes previously used in [18] were replaced by brass electrodes as shown in Figure 6(a) to minimize the possibility of corrosion. A normalization procedure was also developed to minimize sensor reading errors and sensor-to-sensor variability. Normalization of the soil moisture readings is done by determining the effective range of the sensor measurement that is, the frequency shift (FS) reading when the sensor is exposed in air (lower bound) and in water (upper bound) under identical conditions. Normalized soil moisture sensor reading (NFS) is computed as:

$$NFS = \frac{FS_s - FS_{air}}{FS_{water} - FS_{air}} \quad (5)$$

where FS_s, FS_{air}, and FS_{water} corresponds to the frequency shift output of the soil moisture sensor in soil, air, and water respectively.

All of these features were incorporated in the new sensor columns, which are currently in production. The mass production involves local manufacturers in order to address another objective of the program, which is to enable meaningful collaboration with local industry partners in the area of design for manufacturability (DFM). The new sensor columns are scheduled to be deployed on August 2014.

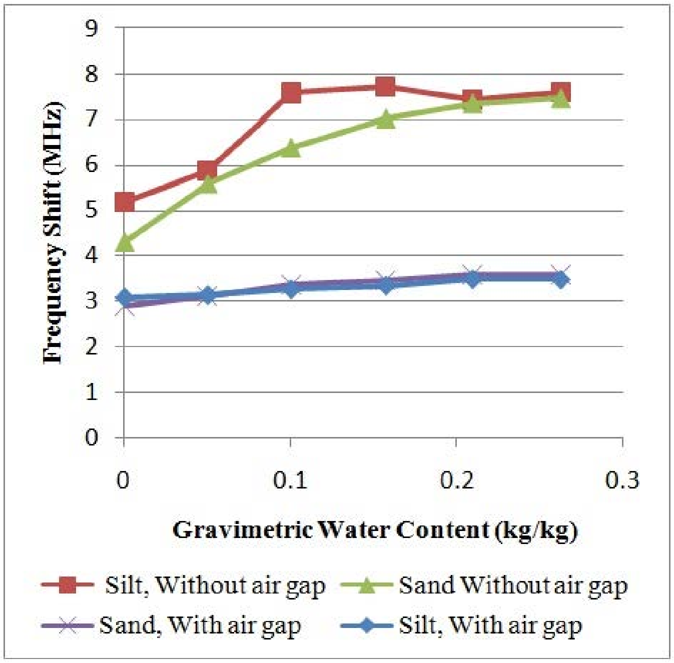

Figure 9. The results of the characterization of the soil moisture sensor with air gap and without air gap in both sand and silt showing improvement in the sensitivity and dynamic range of the soil moisture sensor after removing the air gap.

IV. CONCLUSIONS

This paper presents the current progress of the DEWS-L program of the University of the Philippines and the Philippines Institute of Volcanology and Seismology (PHIVOLCS). The issues related to landslide prevention and mitigation particularly, focusing on the need for developing a cost-effective means of monitoring the more catastrophic deep-seated type of landslide was briefly explained. The experiences and lessons learned from the deployment of the monitoring system in ten different sites across the Philippines were also described in this paper.

An effective monitoring or early warning system requires creating awareness in the community and fostering active community involvement in understanding the risks of landslides. This creates a sense of ownership that addresses security concerns and helps ensure the continuous operation of the deployed monitoring instruments. By empowering the community, the sustainability and the effectiveness of the disaster mitigation program are better assured.

The revisions in the sensor column are intended to enhance the effectiveness, accuracy and reliability of the monitoring system for the deep-seated type of landslide. With the mechanical coupler-based packaging design, modularity is achieved. Thus, on-site assembly and installation requires less resources, man-hours, and effort. Recalibration of the tri-axial accelerometers once mounted in the printed circuit board (PCB) is still required despite factory calibration to further minimize errors and variability in measurements. With the developed simple calibration routine, an average RMSE of 0.0015 is obtained compared with 0.012 without recalibration. By removing the air gaps present in the sensor electrodes, sensitivity and dynamic range of a fringing field type soil moisture sensor can be considerably improved.

V. FUTURE WORK AND RECOMMENDATIONS

With the magnitude of the incoming data from the currently deployed sensor columns in the field and in preparation for the data from the soon to be deployed sensors, the proper structuring of the database is necessary for record keeping and data retrieval for analysis. A web server is currently being developed to aid the geologists and geotechnical engineers in visualizing, analyzing, and interpreting the sensor readings. The processed data shall eventually be made available to the public. Finally, an early warning protocol that incorporates the sensor readings with the visual indicators reported by the LLMC is currently being finalized.

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