President's Cup 2014 - Final Report

"The Implementation of Micro Electro Mechanical Systems (MEMS) sensors for Slope Stability Monitoring"

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Abstract

Numerous kinds of equipment such as geophones, ultrasonic sensors and DGPS (differential ground positioning system) have been used to monitor slope stability in the endeavor to prevent landslides or slope failure. However, these equipment are usually expensive, inflexible and labor-demanding. Whilst, the past decade has given birth to Micro Electro Mechanical Systems (MEMS) technology that allows for batch-wise etching production, thereby reducing manufacturing cost. Today, MEMS accelerometers such as ADXL335 and ADXL445 used in this project are very cheap, costing less than US$10 apiece. Therefore, the ultimate aim of this project is to implement MEMS technology for a smart sensor-based landslide monitoring system that is a promising alternative to conventional systems in terms of cost efficiency, flexibility, easy installation, energy efficiency and reliability.

My role in the project is to interpret the data from these sensors and verify its performance by doing three things: shaking table test, field monitoring and laboratory flume test. The shaking table test is done to check the transfer function of MEMS accelerometers. For this purpose, different frequencies of different amplitudes are generated through a shaking table. The data captured by MEMS accelerometers should be similar to the input.

The field monitoring refers to the regular check on a MEMS sensing package, termed 1st Generation Smart Soil Particle (SSP) that had been set up in Lu Shan, Taiwan for monitoring. During events such as heavy rainfalls and earthquakes, the data captured by SSP are analyzed and compared. MEMS accelerometers installed in the slope successfully captured many features of the slow and episodic landslide behavior.

Lastly, a flume test that simulates a fluidized landslide is done. The data captured by MEMS accelerometers are correlated with physical events that happened during the landslides such as surface tilting and sudden failure. This flume test also will broaden the understanding of the initiation mechanism of fluidized landslide.
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Chapter 1 - Introduction

1.1 Background to Project

Landslide is one of the most widespread and adverse natural hazard on earth. It is reported that 17% of fatalities due to natural hazards are caused by landslides (Brönnimann, 2011) and in addition to that, landslides can also cause great damages to forest growth, farmland, communication systems, engineering constructions, and buildings. Hong Kong is indeed a place susceptible to landslides with about 300 landslides reported every year (Ho and Lau, 2007). One well-known case is the Po Shan Road landslides that happened in 1972. Casualties were high with 67 people killed, 20 injured and 2 buildings totally destroyed (Yang et al., 2008).

One stream that has been adopted to prevent landslides is real-time monitoring systems. Not only the immediate detection of landslide activity can be crucial in making timely decisions about safety, the series of data collected would also provide better understanding of landslide behavior that, in turn, enable scientists and engineers to improve designs to prevent landslides to occur.

However the current available technologies for real-time monitoring systems are expensive and not flexible. For instance, geophones, ultrasonic sensors and DGPS (differential ground positioning system) are instruments commonly used for landslide monitoring purposes. These instruments require exhaustive fabrication and calibration processes which increase their respective prices (Cochran et al. 2009). In response to this, our research team aims to engineer a cost-effective smart sensor-based early warning system for landslide monitoring utilizing Micro Electro Mechanical Systems (henceforth, MEMS) technology. With the hardware done by our research team, the goal of my proposed President’s Cup project is to implement the MEMS sensors for landslide monitoring and the study of landslide mechanism which in turn can lead to even better monitoring and warning system.

1.2 Background to MEMS

In the last decade, the development of MEMS sensors has changed the whole sensor technology. With the advantages of their miniature sizes, low cost and reliability, MEMS have been implemented in consumer electronics devices such as game controllers, cell phones, digital
cameras and even in computers. Nonetheless, MEMS technology is not popular in geotechnical engineering related applications. Hence, one objective of this proposed study is to apply the MEMS sensors and their accompanying techniques developed in other fields to geotechnical engineering, especially in landslide monitoring.

In this study, two accelerometers are going to be used, ADXL335 and ADXL345, three-axis MEMS accelerometers produced by Analog Devices. Both have a dimension of 4 x 4 x 1.45 mm (Length x Width x Thickness) and both cost less than US$10 apiece, which is a lot cheaper than other traditional sensors used for field monitoring. Their features, i.e. small sizes and low-cost, allow MEMS accelerometers to be buried inside soil specimen to capture soil movements during landslide.

Figure 1.1 Wired ADXL 335 used in this project (after Ooi, 2013)

Calibration, then, is essential. Finding out bias offset and sensitivity values for each sensor are the aims for calibration since quality of sensors varies during manufacturing process. The three equations below describe the relationship between the signals the accelerometer sends to the real acceleration,

\[ a_x = \frac{(V - V_{x,off})}{S_x} g \]  \hspace{1cm} (1.1)

\[ a_y = \frac{(V - V_{y,off})}{S_y} g \]  \hspace{1cm} (1.2)

\[ a_z = \frac{(V - V_{z,off})}{S_z} g \]  \hspace{1cm} (1.3)
where $a_x$ is the acceleration along x-axis, $a_y$ is the acceleration along y-axis, $a_z$ is the acceleration along z-axis, $V$ is the measured voltage, $V_{x,off}$ is the measured voltage along x-axis, $V_{y,off}$ is the measured voltage along y-axis, $V_{z,off}$ is the measured voltage along z-axis, $S_x$ is the sensitivity along x-axis, $S_y$ is the sensitivity along y-axis, $S_z$ is the sensitivity along z-axis, $g$ is the gravity acceleration. The resultant acceleration is governed by the equation below

$$a_{resultant} = \sqrt{a_x^2 + a_y^2 + a_z^2}$$  \hspace{1cm} (1.4)

and at static condition, the resultant is obtained as follow

$$a_{resultant} = \sqrt{a_x^2 + a_y^2 + a_z^2} = 1 \, g$$  \hspace{1cm} (1.5)

If each bias offset value and sensitivity are known, acceleration of each axis can be calculated. The above equations would be written as algorithm to convert the voltage values to acceleration in g using computer. Using the static acceleration, which is supposedly to be 1 g, calibration on the parameters in Equations (1.1), (1.2), and (1.3) can be back-calculated. The details of this calibration will be omitted in this report. Also keep in mind that because the sensors are sampled at 5000 Hz in the experiment, a lot of noise, usually high frequency, would be included in the signal. Ooi (2012) mentioned that butterworth lowpass filter consisting of a passband ripple of 3 dB and a stopband ripple of 60 dB can be used to filter the frequencies from 500 Hz onwards.

1.3 Structure of the Report

This chapter outlines brief literature review that explains the motivation of the project to apply MEMS technology to geotechnical problems. Chapter 2 outlines the laboratory shaking table tests done to find the transfer function of the MEMS accelerometers. A commercial uniaxial accelerometer, EpiSensor, is used as a benchmark. Chapter 3 explains the field monitoring data sent from MEMS sensors from Lu Shan, Taiwan. Chapter 4 unveils the results of laboratory flume tests carried out. This includes the presentation of data obtained, interpretation, discussion on slope stability. Lastly, concluding remarks and further works are presented in the last chapter, Chapter 5. A complete picture of this project can be seen from Figure 1.1.
Chapter 2 - Laboratory Shaking Table Test

2.1 Introduction

Our research team has engineered a sensor module utilizing MEMS technology. The module is called 1<sup>st</sup> Generation Field Smart Soil Particle (henceforth, SSP). Each SSP mounts ADXL345 whose performance is tested in this project. The sampling rate of SSP is 800 Hz.
One way of checking the performance of the accelerometers is to find its transfer function, viz. checking on the output generated by the SSP as compared to the given input at different frequencies. Transfer function of the sensor is obtained by the following equation

\[ H = \frac{O}{I} \]  

where \( H \) is the transfer function, \( O \) is the output amplitude at certain frequency and \( I \) is the input amplitude at the same frequency.

Sine waves of different frequencies can be generated by shaking tables. The shaking table used in this project is the *Quanser XY Shaking Table* (henceforth, Quanser). The Quanser shaking table is a high power table that can deliver high acceleration and velocity to a load up to 100 kg. It is powered using linear motor technology and thus has a minimum number of moving parts and is very quiet during operation.

![Figure 2.2 Shaking table test set-up](image)

![Figure 2.3 Close-up of the SSP on Quanser Shaking Table](image)
To get the transfer function, one approach that has been done in this project is to generate a sweep-sine wave and correlate the data with the signal sent by SSP. The performance of the SSP at different frequencies can instantly be known by doing Fourier Transform (in this project, Fast Fourier Transform is used) and some filtering to reduce the noise. However, this method proves to be weak for lower frequencies. For example, a sine-sweep increases linearly from 0 Hz to 400 Hz in 40 seconds. This means that a sine wave of one frequency will be generated for around 0.1 seconds before the next frequency is generated. However, a 5 Hz sine wave requires 0.2 seconds for a full period to finish. This shows that 0.1 seconds is insufficient for a 5 Hz sine wave to be complete its period. According to Santamarina (1998), this incomplete cycle of wave has truncation problems. He explained that the Fourier Transform of the signal will be subjected to a lot of disturbance.

The second approach is to generate sine waves at different frequencies. For this test frequencies of powers of 2 (1 Hz, 2 Hz, 4 Hz, 8 Hz and 16 Hz) are used. Studies have shown that natural earth movements such as earthquakes and landslides have frequencies less than 15 Hz (USGS, 2012). This method is tedious but effective and therefore adopted in this project. As a benchmark the performance of SSP will be compared to the performance of Kinematics EpiSensor ES-U1 uniaxial accelerometer (henceforth, EpiSensor, see Figure 2.2). The recorded signal from SSP is then calibrated by comparing it to the recorded signal from EpiSensor.

2.2 Results and Discussions

After doing the shaking table tests to measure the performance of the SSP, the transfer function plots can be seen in Figure 2.4, for all the axes. The data from the SSP are compared to the data captured by EpiSensor. All three plots share similar trends: increasing trend before 2 Hz followed by a decreasing trend after 2 Hz up until 16 Hz. Particular attention is to be shown to z-axis. Comparing this to the other two directions, the results for z-axis is rather lower. One reason for this phenomenon is that the fixing in z-axis is less rigid than the fixing for both x-axis and y-axis (Figure 2.3). Although the transfer function $H$ of the accelerometer is not 1, this will be very useful results for future reference and future development of SSP. Every sensor is not perfect but MEMS sensors are good enough to capture the movements and in this project, it would be used to capture slope movements which will be presented in Chapter 3 and Chapter 4.
Chapter 3 - Field Monitoring

3.1 Introduction

In the summer of 2013, 3 units of SSP were installed in Lu Shan, Taiwan and currently up and available for real-time monitoring (Figure 3.1). That particular location was chosen because of two reasons: the unique topography and geomorphology of Taiwan have made it easily subjected to frequent tropical cyclones and earthquake events and the location where 3G mobile data service is available. The data obtained by the SSP then can be transferred from Taiwan to the database in Hong Kong through the mobile data service.

Mass movements of soil usually happen under external events. Heavy rainfalls, earthquakes and typhoons are major causes of mass movements that would potentially lead to landslides. With this in mind, the most interesting readings of the SSP would be under those circumstances. Since the flume test would emphasize more on the role of water, the set of data chosen to be presented in this chapter is the SSP readings under earthquakes.
Figure 3.1 The set up of three SSPs: (a) The general overview of the field, (b) SSP 001 (powered by solar panel); (b) SSP 003 (powered by solar panel); (c) SSP 004 (powered by wire) (photos accredited to Loong Cheng Ning)

3.2 Results and Discussions

Several earthquake events happened in Taiwan during in summer 2013. Seismic activities subject slopes to horizontal and vertical accelerations that result in cyclic fluctuations in stresses within the slope. This increases the load from static values to larger dynamic values for brief periods (typically fractions of a second). These extra loads, which in turn contribute to extra driving force of the slope can potentially cause landslides to occur.

Seismic records from official Taiwan’s Central Weather Bureau (CWB) is used as reference. An example to compare the time and magnitude of the seismic event between the official result and the measured data is presented. An earthquake happened on 16 July 2013 at 18:11 local time. The data presented are from CWB and from the SSP. It can be seen that there is a slight difference between these two figures (Figure 3.2). Note that both of the graphs are not
plotted in the same coordinate system. The government’s accelerometer was placed with the z-direction pointing upwards while the other two directions chosen were in respect of NS and EW. On the other hand, the placement of SSP was in different coordinate system. Therefore, both of the plots are not one-to-one comparison. However, the most important point of this result is that SPP captured the short-lived earthquakes. Therefore, this study has shown how MEMS sensors can indeed be used to monitor a slope real-time and ultimately contribute to timely decisions about safety of the landslides.

![Figure 3.2 Comparison of the earthquakes data from Taiwan government (left) and SSP (right)](image)

**Chapter 4 - Laboratory Flume Test**

**4.1 Introduction**

Another approach, perhaps the most important approach in this project, of evaluating the performance of MEMS sensors are through laboratory flume test. In this experiment, a mini landslide of loose soil specimen (89% river sand + 11% Toyoura sand) is simulated. The data captured by MEMS sensors can then be compared to physical events that happened during the test. The soil specimen will be placed layer by layer in a container named soil prism, with dimension of 100 x 45.2 x 30 cm (L x W x H). The soil prism is encased with two transparent acrylic boards on both sides and porous stone on the bottom that allows for drainage. At each 7 cm layer, MEMS sensors (ADXL335 labeled M1 to M10) are embedded within the soil. The arrangement of the MEMS sensors can be seen in Figure 4.2. The flume is going to be inclined at
$30^\circ$ and groundwater will be supplied from the bottom of the flume to imitate the increase in pore-water pressure due to the rise in water table.

Then, other than these sensors, there are other cameras that have to be set up. The picture illustrating the arrangements of the equipment for the experiment can be seen in Figure 4.1. Firstly, one JVC Everio camcorder was placed above the flume (henceforth labeled, JVC Top) to capture the aerial view of the flume. This was accompanied by the JVC Everio camcorder that was placed by the side (henceforth labeled, JVC Side). The other details of sensors arrangement such as pore-pressure transducers, flowmeters and Kinect will not be discussed in this report.

![Figure 4.1 Set-up of the flume laboratory test](image1)

![Figure 4.2 Set-up of the MEMS sensors in the flume](image2)
4.2 Results

The summary of all the events can be seen in Table 4.1. The stopwatch (using a cell-phone), JVC cameras, and MEMS data logger were all synchronized. Time difference would all be taken into consideration for the plots later. Note that MEMS time will be used for reference in this report.

Table 4.1 Summary of the events with the respective time for reference

<table>
<thead>
<tr>
<th>Events</th>
<th>Time</th>
<th>MEMS Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JVC Top On</td>
<td>0:00:00</td>
<td></td>
</tr>
<tr>
<td>SONY Side On</td>
<td>0:01:29</td>
<td></td>
</tr>
<tr>
<td>MEMS On</td>
<td>0:04:06</td>
<td>0</td>
</tr>
<tr>
<td>Small Pump On</td>
<td>0:05:06</td>
<td>60</td>
</tr>
<tr>
<td>Small Pump Off</td>
<td>0:17:58</td>
<td>832</td>
</tr>
<tr>
<td>Front Pump On</td>
<td>0:26:13</td>
<td>1327</td>
</tr>
<tr>
<td>Back Pump On</td>
<td>0:28:00</td>
<td>1434</td>
</tr>
<tr>
<td>First Movement</td>
<td>0:29:03</td>
<td>1497</td>
</tr>
<tr>
<td>Slow Failure (Progressing)</td>
<td>0:29:15</td>
<td>1509</td>
</tr>
<tr>
<td>Slow Failure Steady State</td>
<td>0:37:36</td>
<td>2010</td>
</tr>
</tbody>
</table>

At 60 seconds MEMS time, the small pump is turned on, allowing the soil specimen to saturate. This process took around 13 minutes to complete, ending at 832 seconds MEMS time. During this time, images from both cameras record slow consolidation of the soil specimen. Also, a triangular wedge space at the rear was formed as the soil detached itself away from the saturation box. The largest deformation occurred on the surface, measuring about 2 cm from the saturation box but no observable deformation was noted at the bottom porous stone and there the soil was still in touch with the saturation box. More importantly, MEMS sensors recorded this movement. The consolidation is reflected by the decreasing trend that can be seen especially in y-axis and z-axis of M5 (Figure 4.3). This shows how MEMS sensors can detect even slightest movement of a slope.
After this, both front and back pumps were turned on to allow small flow rate to simulate effects of groundwater. Each of the 1 L/m flow was subsequently divided into 2 channels in which then, each would be divided furthers into 3 channels. Thus, altogether, there are 12 inflow points going into the flume. Failure occurred suddenly at 170 seconds (or at 1497 seconds MEMS time) after the front pump was turned on. The mode of failure was circular and a slip surface could be observed at around 7 cm above the porous stone (Figure 4.4). After this first failure occurred, there was a halt for around 220 seconds before another sudden movement was detected. This second sudden movement triggered subsequent movements which were observed to progress slowly. At this period, the landslide could be classified as debris flow because the water-laden masses of soil rush down the slope. The flow eroded the soil and slowly leading more and more volume to be washed down. Lastly, when there was no sign of movement of the soil anymore, though water was still flowing, both pumps were turned off. This marked the end of the experiment.
Figure 4.4 Pictures of the flume (top: JVC Top, bottom: JVC Side) at 1327 s (left), 1497 s (middle) and 2010 s (right) MEMS time and M2 data for discussion
4.3 Discussions

All MEMS sensors showed different responses as they were placed at different segments of the flume. One particular MEMS sensor, M2, will be discussed. Figure 4.4 illustrate progression of the failure in time. Right after consolidation stage, at around 1327 seconds onwards (Part 1 in Figure 4.4), the slope is more or less in static equilibrium. Correspondingly, the M2 the resultant plot is almost 1 g.

Then, sudden failure occurred at 1497 seconds. The data of all three axes showed sudden jumps in the reading, corresponding to the sudden mass movement. Again, the MEMS data reflected the physical phenomena happening during the experiment.

After which, the slope started to move very slowly as shown in Part 2. This corresponds to the decreasing trend in acceleration of x-axis and z-axis. Slightly after 1727 seconds MEMS time, the slope failed yet once again. This time, the failure is classified as debris flow as mentioned before. Note that M2 is buried relatively deep in the soil (Figure 4.2). Though affected by the previous sudden movements, it was not until 1803 seconds MEMS time that M2 started to be washed away by the debris flow. The top pictures from Figure 4.4 indicate different locations of M2 over time. The data recorded during this time (Part 3) shows more dynamic movements through the fluctuations. This clearly reflects the physical phenomena of the washing of M2 by the debris flow. As M2 was deposited at its final destination, the resultant data was close to 1 g, indicating once again static equilibrium. This marked the end of the experiment.

The laboratory flume test has shown how reliable the data from MEMS are. In addition to that, it also unveils more understanding of debris flow. As pore-water pressure increased due to the groundwater inflow, the soil increased in weight due to saturation. This induces more overturning moment about the slip surface and resulted in sudden failure, which was rather shallow. The failure left a lot of soil still below the slip surface. Then, due to the continuous water inflow, the next phase of failure occurred slowly. The increasing pore-water pressure fluidized the soil, forming flow landslide usually called debris flow. Debris flow gradually eroded the soil and in this case, also brought sensor M2 with it. All these observations are valuable and could then be used to improve current understanding of flow landslide and the mitigation that could be done to prevent future landslides to occur.
Chapter 5 - Conclusion

5.1 Conclusion
In conclusion, from all three sectors of the project: the shaking table test, the field monitoring and the laboratory flume test, the potential of MEMS sensors is manifested. The shaking table test shows how the MEMS accelerometers are comparable to established commercial accelerometers, though not perfect. The field monitoring has shown that real movement, even for a split of a second, such as earthquake movements that potentially destabilize the slope, can be captured by MEMS accelerometers. Lastly, the series of flume tests show how each phenomenon that happened physically can be captured. Moreover, deeper understanding on landslide initiation mechanism can also be obtained from analyzing of the data captured by MEMS sensors. Therefore, MEMS accelerometers are capable and reliable of capturing physical movements that happen in a landslide.

5.2 Impacts
The ultimate aim of this project is to implement MEMS technology for a smart sensor-based landslide monitoring system that is a promising alternative to conventional systems in terms of cost efficiency, flexibility, easy installation, and reliability. With this monitoring system, coupled with early warning system that is going to be developed in the future, human lives in landslide-prone areas can be better protected against landslide hazards.

Lastly, due to its flexibility and versatility, we will see this technology being applied to: (1) other natural disaster prevention like tsunami and volcanic activities monitoring, (2) structural health monitoring system, and (3) field monitoring of geotechnical construction work such as deep excavation and tunneling.
Reference


1 The SSP also mounts another motion tracking sensor, viz. MPU6050. The details of this tracking sensor are omitted in this report.