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Monitoring seismic-induced soil movements using magnetic tracking system

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ABSTRACT: To study ground deformations induced by earthquake, this paper aims to present an efficient sensing technique for capturing both translation and rotation of soil mass. The proposed magnetic tracking system uses permanent magnets as trackers and magnetometers as receivers. When permanent magnets, deployed within the soil to serve as excitation sources, move with the soil body during an earthquake, they generate static magnetic fields whose flux densities are related to the positions and orientations of the magnets. Magnetometers are used to detect the generated magnetic fields, which can be further used in calculating the magnets' locations and orientations based on appropriate algorithms. For verification purpose, shaking table tests are performed and comparison between the sensing results with those obtained from a linear variable differential transducer (LVDT) shows excellent accuracy. Errors in the detection and frequency limit for capturing motion are analyzed. Finally, further applications of the proposed system are discussed.

1 INTRODUCTION

Economic cost and human loss from earthquake-induced geohazards, such as liquefaction and landslides, lead to the requirements for mitigation methods in order to reduce the risks of such hazards. Identification of possible failure mechanisms and assessment of potential damage associated with earthquake hazards are important ingredients in mitigating their impacts to the built environment (Orense 2003). No matter what complex mechanisms are behind them, these geohazards, such as landslides and soil liquefaction, manifest themselves in the form of soil movements or the potential of soil movements.

A lot of researches have already emphasized the need for slope movement analysis during earthquakes. Starting with Newmark (1965), a sliding block model was used to estimate the movements under earthquake excitation. Further refinements of the Newmark model were validated in a shaking table experiment by Wartman et al. (2003). Also, Makdisi and Seed (1978) predicted permanent movements of slopes by using average accelerations combined with the sliding block model. Moreover, liquefaction-induced ground movements were given special attentions to by geotechnical engineering communities, since further evaluations of damage due to liquefaction rely on the ability to accurately prognosticate ground deformations, such as cyclic ground movements and permanent lateral movements. Although delicately designed laboratory tests and high-quality field investigations have already been conducted by researchers to study the cause of and the mechanism of seismically-induced ground surface deformation, sub-surface deformations and particle movements within a soil body are beyond recognitions due to the opaqueness of the soil grains.

On the other hand, there is also a need to assess the temporal development of failure, especially for mountainous regions that have high potential risk of landslides triggered by earthquakes. Monitoring and early warning systems are believed to be one of the most effective and straightforward techniques to achieve this (Lin et al. 2015). For example, Dai et al. (2002) proposed to establish a sensor system based on pseudo-static analysis of slope stability under cyclic loadings. Accordingly, real-time monitoring of landslides typically includes deformations of both slope surface and subsurface, as well as the rate of deformation and direction of deformation. As a result, considering the needs of both mechanism study and early warning system, other methods of monitoring subsurface deformation that can withstand underground condition (e.g. presence of soil cover, saturated soil environment, etc.) need to be developed.

In general, movement sensing can be categorized into two groups: positioning sensing and displacement sensing (Nyce 2004). In positioning sensing, the distance between a reference point and the present location of the target is measured. For example, in landslide monitoring, extensometers are widely used by utilizing long wires and fixed poles. Conversely, displacement sensing calculates the distance between the current location and the previously recorded location given some information, such as velocity and acceleration. For example, an inertial navigation system (INS) is a relative measurement which does not rely on external fixed point. Akeila et al. (2007; 2010) used smart pebbles embedded with a strap-down INS system to monitor riverbed sediment transport. Motions of a target in three-dimensional space can be then calculated mathematically by integrating the accelerations and rotations about the three axes. Since the integration process creates errors that grow with time, a Global Positioning System (GPS)-aided INS can be applied in the smart pebble to increase the level of accuracy and reliability as well as the information update rate. However, as the targets of interest are usually buried if used in geotechnical environments, which means the signals of smart pebble underground need to penetrate the depth of soil without being blocked, the strength of the signal may not be strong enough to guarantee the accuracy.

In order to overcome the shortcomings described above, a novel way of being able to monitor subsurface ground deformations under cyclic loading is examined. Firstly, the mathematical background of the magnetic tracking system is discussed. Secondly, a verification test comparing tracking results of cyclic motions between the magnetic tracking system and linear variable differential transducer (LVDT) is performed. Finally, errors are analyzed and future applications of the proposed system on mitigating the effect of earthquake-induced ground deformations are discussed.

2 MAGNETIC TRACKING SYSTEM

2.1 *Background*

The proposed magnetic tracking system belongs to the category of positioning sensing technique with a permanent magnet as a tracker and magnetometers as receivers. When a permanent magnet is deployed inside the subsoil, it will generate a static magnetic field which can be detected by magnetometers outside the soil body. Usually the magnetic flux density ($\vec{B}$ with the unit of Tesla) detected by multiple magnetometers can provide enough information to pinpoint the position as well as the direction of the permanent magnet. Displacement of the permanent magnet at any time interval can then be measured from the change of the positions. Since the proposed system is in essence a positioning sensing technique, while the tracker (permanent magnet) is under cyclic motions inside the soil, a magnetometer array is fixed outside the moving soil mass. Because soil has magnetic permeability very similar to that of non-ferromagnetic materials, such as air and water, its influence on the static magnetic field generated by the magnets is negligible. Therefore, it is possible to locate a magnetic tracker buried in soil with high accuracy. The magnetic tracking technique has already been used outside geotechnical engineering. For example, Schlageter et al. (2001) developed a system capable of tracking a permanent magnet with a 2D-array of 16 cylindrical Hall sensors. Hu et al. (2006) investigated the use of magnet-based localization in wireless capsule endoscopic technique.

There are some advantages of the proposed magnetic tracking system compared to other existing techniques when being used to monitor earthquake-induced soil movements: (1) there are few ways to completely block a magnetic field, so the tracking system has the potential to be well-applied underground; (2) subsoil displacements can be measured directly, therefore better understanding of earthquake-induced liquefaction and landslide can be expected by applying the proposed system in their investigation; (3) a permanent magnet as tracker is easy to set up without the need for energy supplier or auxiliary circuits to transmit data, therefore tracker of size down to millimeter scale can be expected given sensitive-enough magnetometers and small sensing range; consequently, the system can be appropriate especially for small-scale experiments, such as centrifuge tests, after careful designs and proper improvements; and (4) an upgraded early warning system for earthquake induced landslide can make use of the magnetic tracking system combined with the well-developed pseudo-static model given the subsurface deformations being accessible.

2.2 *Mathematic model*

By using a permanent magnet as tracker, a convenient approximation is to consider the magnet as a point dipole whose largest dimension is much smaller than the distance from the receiver (magnetometer array). As shown in Figure 1, the relationship between the magnetic flux density at a spatial point and the location of that point is illustrated by Equations (1) and (2):

$$\vec{\boldsymbol{B}} = \frac{\mu_0 m}{4\pi r^3}\left(2cos\theta\widehat{r} + sin\theta\widehat{\theta}\right) \tag{1}$$

$$\vec{\boldsymbol{B}} = \vec{\boldsymbol{B}}_{\boldsymbol{x}} + \vec{\boldsymbol{B}}_{\boldsymbol{y}} = 3\frac{\mu_0 m}{4\pi r^3} sin\theta cos\theta \cdot \widehat{x} + \frac{\mu_0 m}{4\pi r^3}(3\cos^2\theta - 1)\cdot\widehat{\boldsymbol{y}} \tag{2}$$

where m is the magnetic moment of the dipole whose unit is $A \cdot m^2$ (where A is ampere and m is meter); μ_0 is the permeability of a vacuum whose unit is $T \cdot m/A$ (where T is Tesla), and $\vec{\boldsymbol{B}}$ is measured in Tesla. The values of r and θ provide the information of the location of the magnetic tracker in polar coordinates. $\widehat{\boldsymbol{r}}$ and $\widehat{\boldsymbol{\theta}}$ are unit vectors as shown in Figure 1.

Magnetic positioning in this paper is actually a 5-D positioning because, in addition to 3 unknowns related with the location, there are 2 more unknowns required to indicate the orientation. In the algorithm presented in this paper, (a, b, c) denotes the 3 unknown locations on the three orthogonal axes of the 3D Cartesian coordinate system, and (m, n, p) denote the orientations with the relationship $m^2 + n^2 + p^2 = 1$ holds. Substituting r and θ into Equations (1) and (2) by (a, b, c) and (m, n, p), the following equations can be derived:

$$\vec{\boldsymbol{B}}_{\boldsymbol{l}} = B_T\left(\frac{3\left(\vec{\boldsymbol{M}}_{\boldsymbol{0}}\cdot\vec{\boldsymbol{R}}_{\boldsymbol{l}}\right)\cdot\vec{\boldsymbol{R}}_{\boldsymbol{l}}}{R_i^5} - \frac{\vec{\boldsymbol{M}}_{\boldsymbol{0}}}{R_i^3}\right) \tag{3}$$

$$R_i = \sqrt{(x_i - a)^2 + (y_i - b)^2 + (z_i - c)^2} \tag{4}$$

$$\vec{\boldsymbol{R}}_{\boldsymbol{l}} = (x_i - a, y_i - b, z_i - c) \tag{5}$$

$$\vec{\boldsymbol{M}}_{\boldsymbol{0}} = (m, n, p) \tag{6}$$

where B_T is a constant parameter related to the magnet being used; $\vec{\boldsymbol{B}}_{\boldsymbol{l}}$ is the magnetic flux density detected by magnetometer i, where the location of the magnetometer i is indicated by (x_i, y_i, z_i); is a unit vector which indicates the direction of the magnetic dipole, as shown in

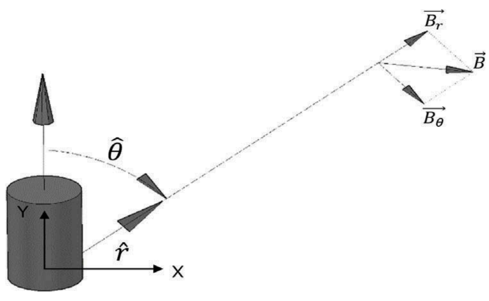

Figure 1. Schematic of the magnetic flux density generated by a magnetic dipole.

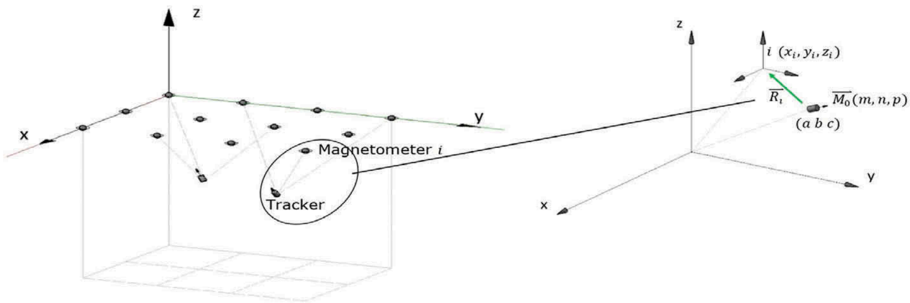

Figure 2. Schematic of the magnetic sensor system in the 3D Cartesian coordinate system.

Figure 2. Further discussions of the algorithm developed and validation using finite element method magnetics are presented by Chen and Orense (2017).

2.3 *Hardware calibration*

The magnetic flux density used in calculating the location and orientation of tracker should not include the earth magnetic field; therefore, the signal produced by the earth magnetic field should be filtered. In laboratory study of earthquake-induced soil movement, signal from the earth magnetic field can be recorded at the very beginning and then be subtracted from the system considering the stability of earth magnetic field during the duration of an experiment. For an early warning system installed in the field, real-time fluctuations of earth magnetic field can be measured by another 3-axis magnetic sensor placed outside the sensing range.

Besides, as mentioned above, the constant parameter B_T, related to the permanent magnet being used, should be figured out. Although B_T can be obtained through the manufacturer specifications for the permanent magnet, it is more straightforward to regard it as the sensitivity (or gain) of the magnetometer. For example, in the x-axis readings of magnetometer i, the relationship of the sampled data and the location information, as well as the orientation information, can be represented by Equation 7:

$$B_{xi} = K_x\left(\frac{3[m(x_i - a) + n(y_i - b) + p(z_i - c)] \cdot (x_i - a)}{R_i^5} - \frac{m}{R_i^3}\right) \tag{7}$$

where B_{xi} is the sampled data in the x axis from magnetometer i, while K_x is the sensitivity of that axis. Other parameters are the same as those in Equations (3) to (6). In order to acquire the sensitivity of the x axis of magnetometer i, a permanent magnet is moved along the magnetometer x axis on the line where the y and z components are 0, such that $x_i = y_i = z_i = b = c = 0$ and $n = p = 0$, $m = 1$. During the calibration, the sampled data B_{xi} and displacements between magnet and magnetometer (a) are recorded. Therefore, the sensitivity K_x is derived as:

$$K_x = \frac{B_{xi} \cdot (-a)^3}{2} \tag{8}$$

Same calibrations should be done on all 3 axes of all the magnetometers, after which the 5 unknowns related with the location and orientation information of the tracker can be calculated by solving a group of high-order nonlinear equations derived from Equation (3). Due to space limitation, the algorithm for solving the group of equations are not presented here.

3 VERIFICATION TESTS

This section presents verifications of the proposed magnetic tracking system based on a research of earthquake-induced soil movements with two separate parts. Firstly, tests were performed for evaluating the influence of the presence of soil (both dry and wet) on tracking accuracy considering its future applications under geotechnical environments. Secondly, a cyclic test was conducted by mounting the tracker on a small shaker which can generate cyclic motions up to 6 Hz. A comparison between the results from the magnetic tracking system and a LVDT is then presented. In both verifications, the tracker covered by plastic foam, as shown in Figure 3(a), was used; the wooden platform for the magnetometer array (with 12 magnetometers) is shown in Figure 3(b).

Neodymium is considered to be the strongest available magnet material, which is therefore used in the tracking system. The size of the magnet used was 15 mm in diameter and 20 mm in height with a residual magnetism (B_r) of 1.32-1.37 Tesla. The magnetometer used in the proposed tracking system was a 3-axis Freescale magnetic sensor, MAG3110, which has a full-scale range of ±1000 µT and a sensitivity of 0.10 µT.

3.1 *Influence of the presence of soil*

The effectiveness of a magnetic tracking system relies on an accurate detection of the magnetic field generated by the tracker. As a result, the accuracy depends on: 1) the sensitivity of the magnetometer used; 2) the strength of the permanent magnet as tracker; and 3) the extent to which the flux density is deteriorated due to: i) increasing sensing range; and ii) environmental interference, e.g. medium. Even though soil, as a main medium in geotechnical-orientated system, is believed to have little impact on tracking accuracy, some proofs are still considered necessary.

The control group was tested in which the tracker was exposed to air. For convenience, the tracker was set up to move in a rigid tube under a known path, which was fixed on the soil box, as shown in Figure 4(a). The coordinates of the start point on the tube were x=0.5 m, y=-0.20 m and z=-0.25 m. The result derived from the magnetic tracking system is shown in Figure 4(b), with the y- and z-coordinates staying roughly constant at y=-0.207 m and z=-0.258 m, respectively.

For the test group, a soil box was filled with dry sand, which buried the tube completely. Another soil box filled with wet soil was placed right on top of the first box, as shown in Figure 5. Results indicate that the trace of the tracker's movement was not changed that much, with y=-0.209 m and z=-0.259 m, respectively. Thus, it can be observed that movements from both the control group and the test group have similar values on z- as well as y-axis. Comparison of movements between the test group and control group projected on the X-Z surface is plotted in Figure 6, where no significant difference is observed. Because the tube was always fixed at the same location on the soil box, it can be concluded that the presence of soil (wet and dry) did not influence the general accuracy as expected.

3.2 *Verification using cyclic motion*

The same platform of magnetometer array was used in this verification. The permanent magnet was mounted at one end of a long plastic tube which was then anchored on a small shaker, as shown in Figure 7. Since the small shaker provides shaking by using magnetic force, a safe distance was kept between the magnet and the shaker to avoid significant impact

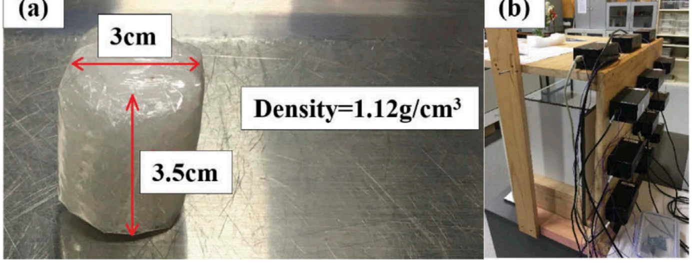

Figure 3. (a) Permanent magnet covered by plastic foam; (b) wooden platform with 12 magnetometers

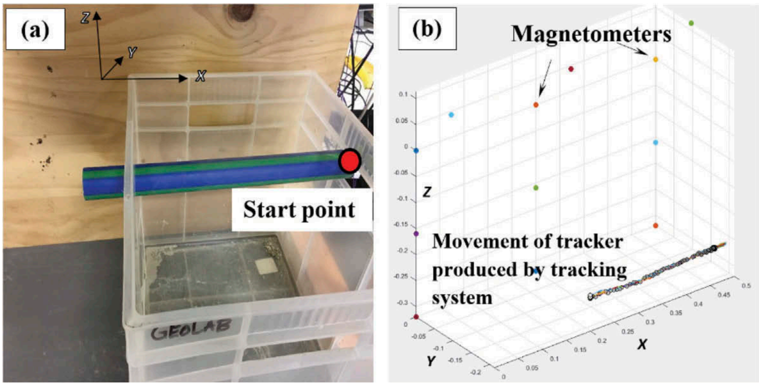

Figure 4. (a) Tracker moving in a fixed tube as reference; (b) tracking results from magnetometer array.

Figure 5. Tube buried in soil for the test group.

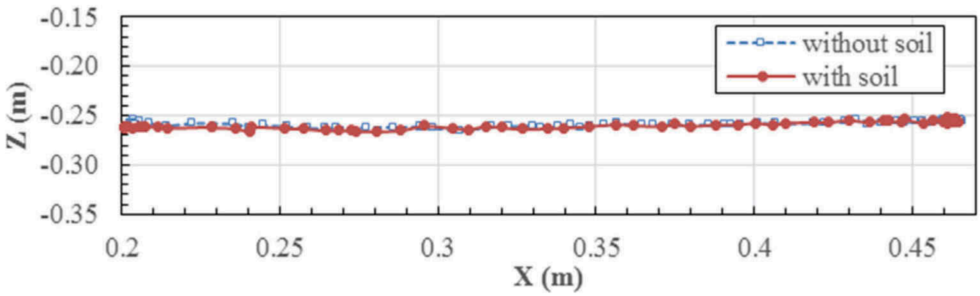

Figure 6. Projections of movements on *X-Z* surface of test group (without soil) and control group (with soil).

on the readings from the surrounding magnetic field. For comparison, a LVDT was attached to the permanent magnet to record displacements.

Tests results are shown in Figure 8, including comparisons under different frequencies. It can be seen from the results that the magnetic tracking system is able to detect the position of the magnet under cyclic motions quite accurately. Errors were calculated by averaging the discrepancies between the data from LVDT and magnetic tracking system at the times the sampling are taken. For the shaking having frequency of 3 Hz and maximum amplitude of 15 mm, the calculated error was ±1.5 mm; for frequency of 5 Hz and maximum amplitude of 7 mm, the calculated error was ±0.9 mm; and for frequency of 6 Hz and maximum amplitude of 5mm, the calculated error was ±0.8 mm.

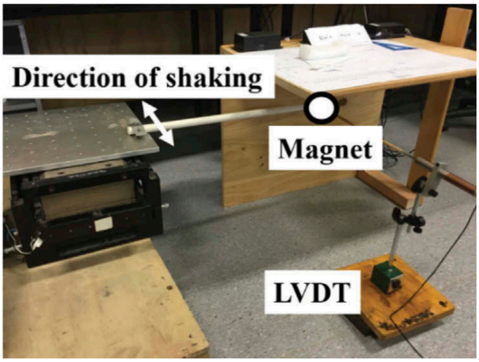

Figure 7. Test set up for cyclic verification.

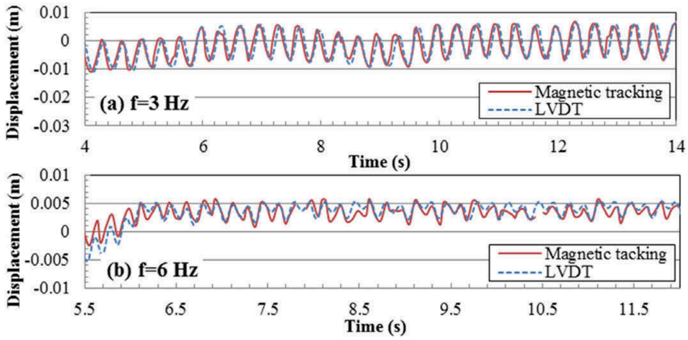

Figure 8. Comparison of results between magnetic tracking system and LVDT, with shaking frequency of: (a) 3 Hz; and (b) 6 Hz.

Although a bit of shift can be observed at the beginning of motion under 6 Hz, as shown in Figure 8 (bottom), which is partly due to the disconnection between the tracker and LVDT, the average error is acceptable, considering the size of the tracker as well as the distance between the tracker and magnetometer array (0.26 m).

4 CONCLUDING REMARKS

This paper presents a magnetic tracking system having the potential to use permanent magnet as a tracker to detect subsoil displacements under cyclic motions, which is considered being able to provide better understanding of earthquake-induced landslide and liquefaction-induced deformations and amount to the core part of an early warning system. Results of verifications are provided under cyclic motions simulating the seismic environment for further applications. The total cost of the proposed tracking system for the presented laboratory investigation is around US$500.

Note that a wireless sensor technology has been used in smart infrastructure monitoring system by Kaya et al. (2014) to confirm the seismic capacity of structures and provide real-time damage assessment during earthquake. An obvious advantage of wireless sensors is that they can be perfectly embedded in construction materials, such as concrete. Through working along with construction materials, wireless sensors can get real-time information about the overall conditions about structures of interests. Similarly, soil, as the most common material related with geotechnical engineering, can also take advantage of this property of wireless sensor. Currently in structure engineering, researchers are developing adaptive systems being able to adjust themselves to environmental changes using sensor technologies and materials with unusual properties

(Srinivasan et al. 2001). For example, in traditional structure design against wind and earthquake risks, intensive efforts are put into code development (Cheng et al. 2008). Such endeavors are passive because in this way the structures can only rely on their stiffness to withstand earthquake force and on material and structural damping to dissipate dynamic energy. On the other hand, with the sensors and actuators added, structures can react according to the feedbacks from sensors and consequently improve the performance during earthquake and strong wind.

Future vulnerable slopes, as well as fields and structures subjected to soil liquefaction, can embrace the benefits of distributed sensors and actuators. With all information related with the health evaluation of a slope or a body of soil being available, early warnings and further countermeasure techniques can be expected. Note that while this paper focused mainly on the application of the proposed tracking system in laboratory-scale testing where the magnetometer array can be simply fixed on a wooden frame, more research and detailed design are needed in its actual field implementation.

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REFERENCES

Akeila, E., Salcic, Z., Kularatna, N., Melville, B. and Dwivedi, A. (2007). Testing and calibration of smart pebble for river bed sediment transport monitoring. Proceedings of IEEE Sensors, Art. No. 4388624, 1201-1204.

Akeila, E., Salcic, Z. & Swain, A. 2010. Smart pebble for monitoring riverbed sediment transport. IEEE Sensors Journal, 10 (11): 1705-1717.

Chen, X. & Orense, R.P. 2017. Development of magnetic tracking system for monitoring ground movements. Proceedings of 20th New Zealand Geotechnical Society Geotechnical Symposium, Napier, 23-26 November 2017, 8pp.

Cheng, F.Y., Jiang, H.P. & Lou, K. 2008. Smart structures: innovative systems for seismic response control. CRC Press.

Dai, F.C., Lee, C.F. & Ngai, Y.Y. 2002. Landslide risk assessment and management: an overview. Engineering Geology, 64 (1): 65-87.

Hu, C., Meng, M.Q.-H. & Mandal, M. 2006. Efficient linear algorithm for magnetic localization and orientation in capsule endoscopy. 2005 IEEE Engineering in Medicine and Biology 27th Annual Conference. IEEE.

Kaya, Y., Ventura, C., Huffman, S. & Turek, M. 2014. British Columbia smart infrastructure monitoring system. EWSHM - 7th European Workshop on Structural Health Monitoring, Nantes, France.

Lin, W., Nishie, S., Seko, I., Uchimura, T., Towhata, I. & Qiao, J.P. 2015. Case histories of slope failure and landslide disaster prevention by using a low cost tilt sensor monitoring system. Engineering Geology for Society and Territory, 2: 631-635, Springer International Publishing.

Makdisi, F.I. & Seed, H.B. 1977. Simplified procedure for estimating dam and embankment earthquake-induced deformations. ASAE Publication No. 4-77, Proceedings of the National Symposium on Soil Erosion and Sediment by Water, Chicago, Illinois, December 12-13, 1977.

Newmark, N.M. 1965. Effects of earthquakes on dams and embankments. Geotechnique, 15(2): 139-150.

Nyce, D.S. 2004. Linear position sensors: theory and application. John Wiley & Sons.

Orense, R.P. 2003. Geotechnical Hazards: Nature, Assessment and Mitigation, University of the Philippines Press, 510pp.

Schlageter, V., Besse, P.-A., Popovic, R.S. & Kucera, P. 2001. Tracking system with five degrees of freedom using a 2D-array of Hall sensors and a permanent magnet. Sensors and Actuators A: Physical, 92 (1): 37-42.

Srinivasan, A.V. & McFarland, D.M. 2001. Smart structures: analysis and design. Cambridge University Press.

Wartman, J., Bray, J.D. & Seed, R.B. 2003. Inclined plane studies of the Newmark sliding block procedure. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 129 (8): 673-684.