# Advanced Sensing for Real-Time Monitoring of Geotechnical Systems

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***Abstract***

Landslides, lateral spreading and other similar forms of ground failure due to natural disasters impact communities around the world. These ground failures continue to result in human suffering, billions of dollars in property losses, and environmental degradation. As our society becomes ever more complex and urban areas continue to spread, the economic and societal costs of landslides and other ground failures will continue to rise. Although our understanding of the mechanisms of failure and large ground deformation due to rains, floods and earthquakes have improved considerably over the last two decades; the goal of significantly reducing losses from ground failure due to natural hazards remains elusive. This state of affairs stems from the limitations of existing real-time sensing and monitoring tools as well as inadequate predictive capabilities of current computational models. Real-time monitoring programs are essential to develop warning systems of impending danger from active landslides in any site specific or regional hazard program. The current state-of-the-art in real-time monitoring of active slopes is either based on very expensive monitoring systems or on measurement of ground surface displacements.

The work presented in this paper constitutes a major step in the direction of establishing a low cost real-time monitoring system for active ground. A ShapeAccelArray sensor is being developed, taking advantage of promising new advances in the fiber optic and micro-machined electromechanical sensor (MEMS) technologies (Danisch et al., 2004). This sensor array is capable of simultaneously measuring acceleration and permanent ground deformation down to tens of meters of depth. The sensor array would be capable of measuring in situ (field) 3D ground deformation as well as 2D soil acceleration at 0.5 m to 1 m intervals. The paper presents the preliminary design of the new sensor array as well as preliminary results from tests aimed at validating and calibrating the accelerations and displacements measured using the newly developed sensor array. The accelerations and displacements measured using the ShapeAccelArray sensor are compared to those measured using traditional accelerometers and displacement sensors. Finally, conclusions are drawn on the effectiveness and accuracy of the new sensor array.



 

***Introduction***

The U.S. has continued to sustain very expensive natural disasters such as landslides, floods and earthquakes over the past 20 years, with great human suffering and many billions of dollars in losses. Much of the destruction is associated with ground failures and other geotechnical phenomena, and the loss exposure continues to rise due to expansion of urban areas and increasing complexity of our society. Landslides during the rainy season occur in essentially every state. The US Geologic Survey (USGS) estimates that landslides cause in excess of $1 billion in damages and about 25 to 50 deaths each year in the U.S. (Fig. 1), and worldwide they are responsible for thousands of fatalities and hundreds of billions of dollars lost. Failures of dykes, levees and dams during floods are also very dangerous and expensive. FEMA and the US Army COE estimate that at least twenty-five of these disastrous floods occurred during the 1988-2002 period with 911 deaths and economic loss of about $140 billion.

Figure 1: Aerial view of the 1995 La Conchita, CA Landslide

Figure 2: Photo of the San Fernando dam failure during the 1971 San Fernando earthquake

Earthquakes are another significant source of geotechnical problems. In addition to triggering landslides and failures of earth embankments (dams, coastal dykes, highways), the phenomenon of liquefaction of loose, water-saturated sands and other granular soils is a specific earthquake-related major hazard. There is scarcely a major seismic event affecting an urban or industrial area which does not cause liquefaction, including ground failure and significant permanent vertical deformations and lateral spreading. These ground failures are usually associated with very costly damage to port facilities, bridges, dams, buried pipes, houses and buildings of all types. For instance, the 1971 San Fernando, California earthquake caused more than five hundred million in damage (NRC, 1982), including a failure of the San Fernando dam (Fig. 2). The 1995 HyogoKen Nanbu earthquake in Kobe, Japan, caused more than one hundred billion in total damage, with about $10 billion attributed to soil liquefaction and ground deformation. The recent Turkey, Taiwan and Greece 1999 earthquakes also caused tremendous destruction.

Real time monitoring of active soil systems can detect early indications of a catastrophic movement. It can also provide a better understanding of the underlying geotechnical phenomena that can be used in modeling and predicting similar failures. Many State DOT's and federal agencies spend significant resources monitoring possible slope failures using manual slope inclinometers or slope inclinometer arrays. A slope inclinometer is a borehole, typically vertical, installed in the ground with flexible casing so that it follows the surrounding ground deformation. Such a system provides very limited monitoring capability and has proven to be expensive in the long run. A slope inclinometer array has an inclination sensor attached to each segment of the borehole that monitors the inclination at depths continuously with time. While slope inclinometer arrays can provide real time monitoring with good angular resolution capability, they are very expensive and inflexible. This high cost makes it impractical or impossible to install multiple arrays on a single slope, thus severely limiting the ability of conducting continuous real time monitoring.

Damage due to seismic excitation is often directly correlated to local site conditions. This correlation was evident during recent earthquakes in the form of motion amplification and liquefaction induced ground deformations (e.g., Mexico City, Seed et al. 1987; San Francisco during the 1989 Loma Prieta earthquake, Seed et al. 1990; and 1995 Kobe, Bardet et al. 1995, Comartin et al. 1995, Sitar 1995). The associated mechanisms of ground response are being monitored through a worldwide network of sites instrumented with accelerometer downhole arrays, often supplemented at liquefiable sites with pore pressure sensors and in some cases also with slope inclinometer arrays. Downhole acceleration records provide direct insight into the response mechanisms of instrumented layers within the ground. In the United States, early downhole data sets were recorded at the San Francisco Bay area (Aisiks and Tarshansky 1969, Joyner et al. 1976, Johnson and Silva 1981), and at Union Bay in Seattle, Washington (Seed and Idriss 1970a, Tsai and Housner 1970, Dobry et al. 1971). During the 1980s, data from downhole seismic arrays that include pore-pressure piezometers became available (e.g. Owi Island in Japan, Ishihara et al. 1987, Wildlife Refuge in CA, Holzer et. al 1989; and Lotung in Taiwan (Tang 1987).

In spite of the growing awareness of the importance of accelerometer downhole arrays, especially when combined with pore pressure sensors to capture poorly understood liquefaction and lateral spreading phenomena, these arrays still remain scarce due to their high cost. The recent advances in sensors and wireless networking technologies provide valuable opportunities for creating new knowledge and technology to assess the impact of natural disasters. The newly developed ShapeAccelArray sensor presented in this paper capitalizes on these recent advances in sensors and wireless networking technologies to develop a new low cost wireless sensor array (Danisch et al., 2004). The sensor array consist of several MEMS sensors installed in a flexible water tight casing and is capable of measuring the 3D ground deformation as well as 2D lateral soil acceleration every 0.5-1.0 m interval down to a soil depth of 30 m. Each sensor array will be connected to a wireless sensor node, to enable real time monitoring as well as remote sensor configuration (Fig. 3). The new system is designed to be easily inserted in the ground using the widely available Cone Penetrometer equipment (CPT) or can be placed in an traditional inclinometer borehole. Figure 4 presents a sketch rendering this vision of several ShapeAccelArray sensors installed in the ground and on a pile foundation at a bridge abutment site where the soil shakes, liquefies, slides and deforms during an earthquake.

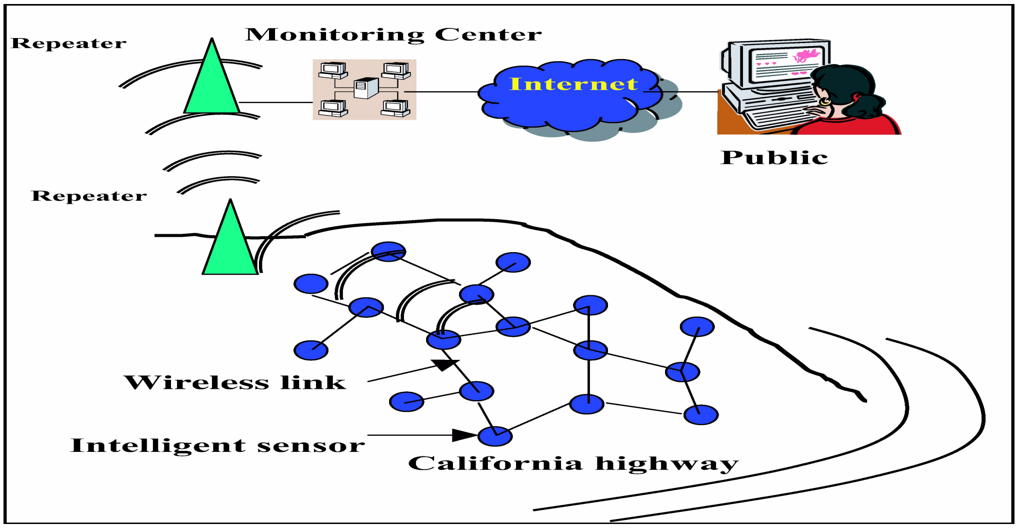


Figure 3: Wireless network for real-time monitoring of geotechnical systems

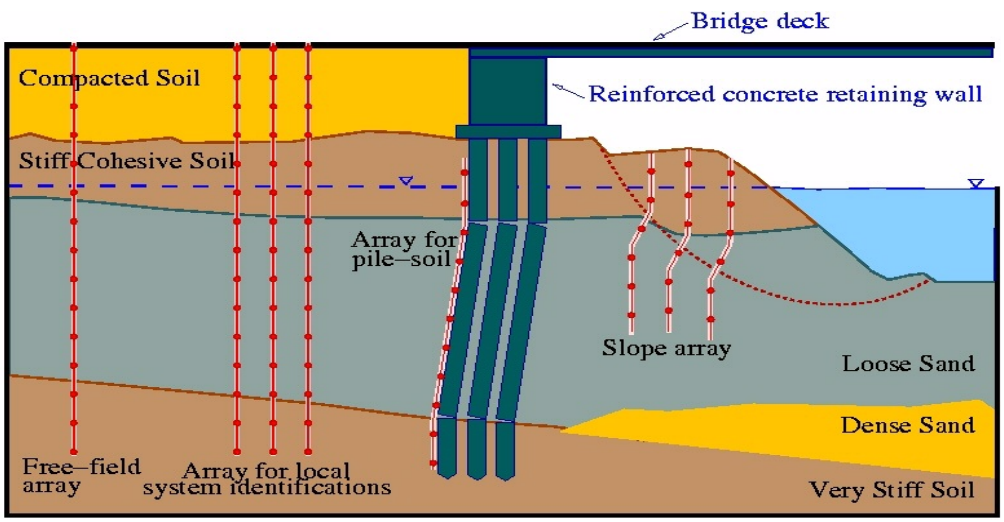


Figure 4: Sketch rendering the vision of installed ShapeAccelArray sensor in an active soil and soil-structure systems

## *Sensor Design*

The ShapeAccelArray sensor is currently being developed in collaboration with Measurand Inc. (www.measurand.com). The ShapeAccelArray sensor is designed to: (1) be low in cost when in volume production, (2) be capable of measuring the 3D soil deformation and 2D accelerations (two lateral directions), (3) provide high resolution measurement in time (sampling rate higher than 100Hz for dynamic measurement) and space (a sensing element every 0.5 to 1m), and (4) contain modular components to enable variable sensor spacing and multiplexing.

MEMS are good candidates for long-term stable measurements of curvature along a substrate. In the future, bipolar fiber optic sensors can be added to resolve torsional movements and near-pole conditions (Danisch 1998 and 2000; Danisch et al. 2003). The MEMS accelerometers can be applied to a flexible substrate at intervals, chosen to include at least two sensors within any expected monotonic curve that can be modeled as a circular arc (Fig. 5). The MEMS devices have sufficient resolution and accuracy for many applications, and it is possible to multiplex a large number of them using conventional CANbus or similar high-speed multiplexing technology (so that electrical interference can be minimized by converting to digital signals locally along an array). They also offer the possibility of measuring both differential tilt (bend) at low sampling rate, and, when needed, to measure acceleration at a higher sampling rate (100Hz or higher). Listed below is a summary of the current specifications of the sensor array.

- Diameter <35 mm
- Length of sub-arrays (arrays are formed by connecting sub-arrays): 1 & 3 m.
- Length of segments within a sub-array: 1 m (others available).
- Number of segments: <=100.
- Temperature is measured in each sub-array.
- Max. tilt: +/- 45 degrees from vertical, measurements
- Range of lateral acceleration: +/-2 G
- Waterproof to 100 m (water column on lowest segment).
- Operating and storage temperature: -20 to 50 deg c.
- Compatible with low-power long-term monitoring arrays
- Tilt measurements are average of 200 frames
- Absolute accuracy of tilt within 20 deg of vertical: 0.2 deg (3.4 mm/m)
- Resolution of tilt within 20 deg of vertical: 0.01 deg (.17 mm/m)
- Azimuth error: <2 deg.
- Bandwidth for vibration and real-time shape measurement: 20 Hz (100 Hz option).

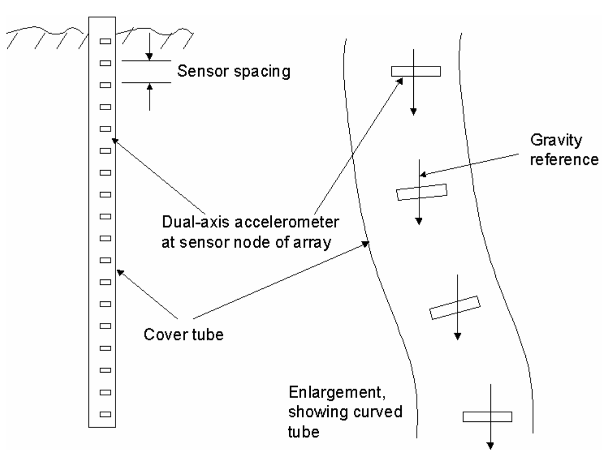


Figure 5: Design of ShapeAccelArray sensor

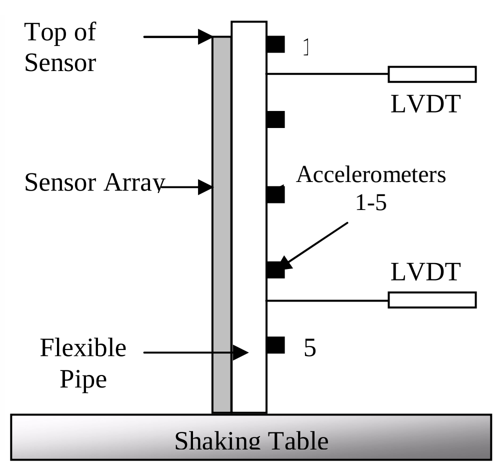


Figure 6: Setup for Testing the ShapeAccelArray sensor

***Sensor Calibration Tests***

A series of calibration tests using the shaking table facility at Rensselaer Polytechnic Institute (RPI) were conducted to evaluate the response of the 1st ShapeAccelArray sensor prototype. Figure 6 presents a sketch of the test setup. A 1.5 m long sensor array, which includes 6 sensing elements placed at 0.25 m intervals was attached to a flexible pipe and placed on RPI 1g shaking table. The response of the flexible pipe was also monitored using traditional accelerometers and displacement sensors (LVDT) as shown in Figure 6. The test setup was excited by different shaking amplitudes and frequencies using RPI's 1g shake table. Figure 7 presents two photos of the sensor array tested at RPI before and after attaching the sensor array to the pipe.

Figure 7: Photos of the 1st prototype of the ShapeAccelArray sensor

A limited number of representative tests measurements are presented in this paper due to page limitations. Figure 8, presents a comparison between accelerations time histories recording using the sensor array and external accelerometers located at vertex 1(top of the flexible pipe) and vertex 4 (mid height of the flexible pipe). Figure 9, presents a comparison between the lateral deformation time histories measured using the sensor array and an external displacement sensor at a 0.7m height from the shake table. Figures 8 and 9 show a very good comparison between the acceleration and lateral displacement measured by the traditional sensors and the sensor array. Figure 10, presents the profiles of the measured lateral displacement using the sensor array at different times during shaking. The lateral displacement profiles presented in Figure 10 demonstrate the ShapeAccelArray sensor capability in measuring internal soil deformation.

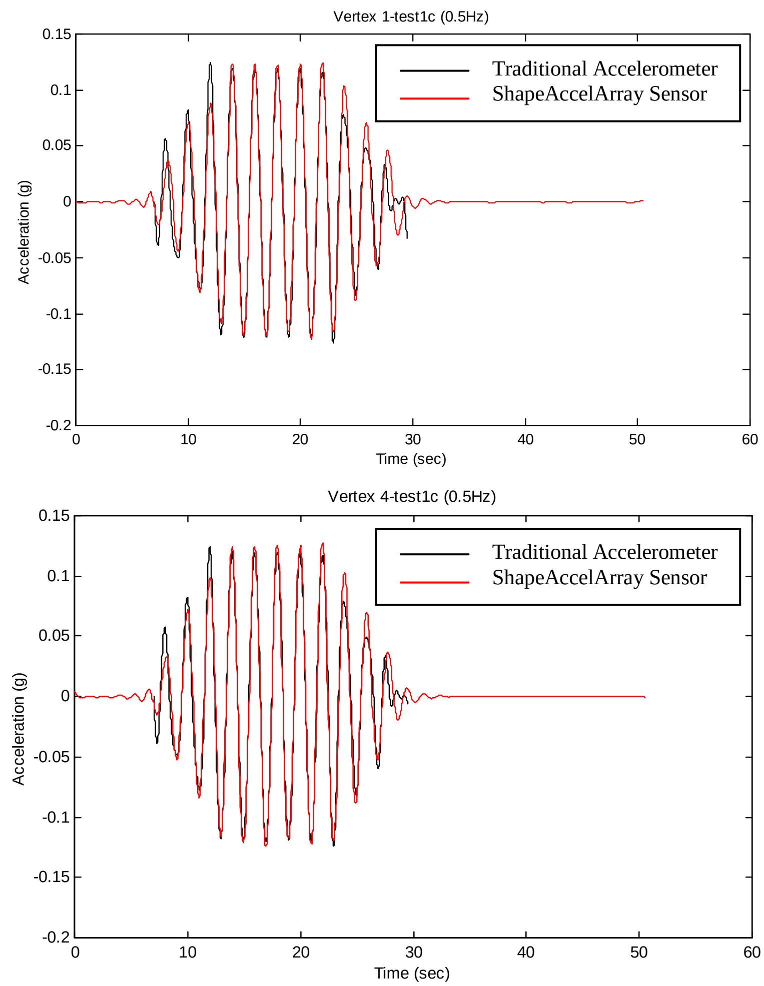


Figure 8: Comparison between acceleration measured using traditional accelerometers and ShapeAccelArray sensor.

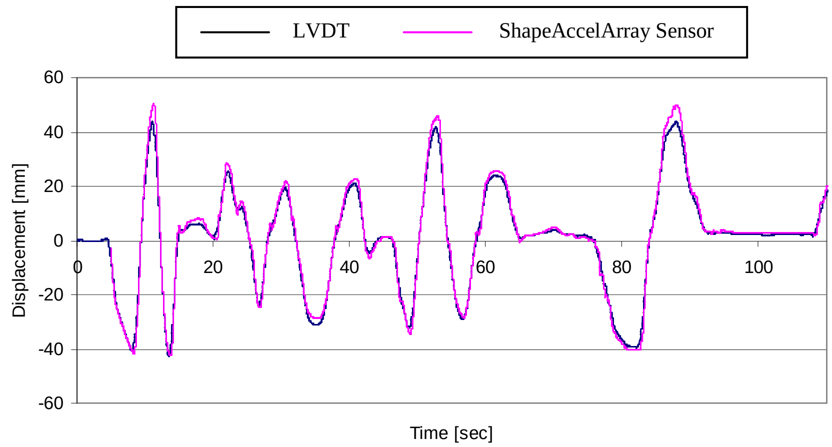


Figure 9: Comparison between lateral displacement measured using traditional displacement sensors (LVDT) and ShapeAccelArray sensor.

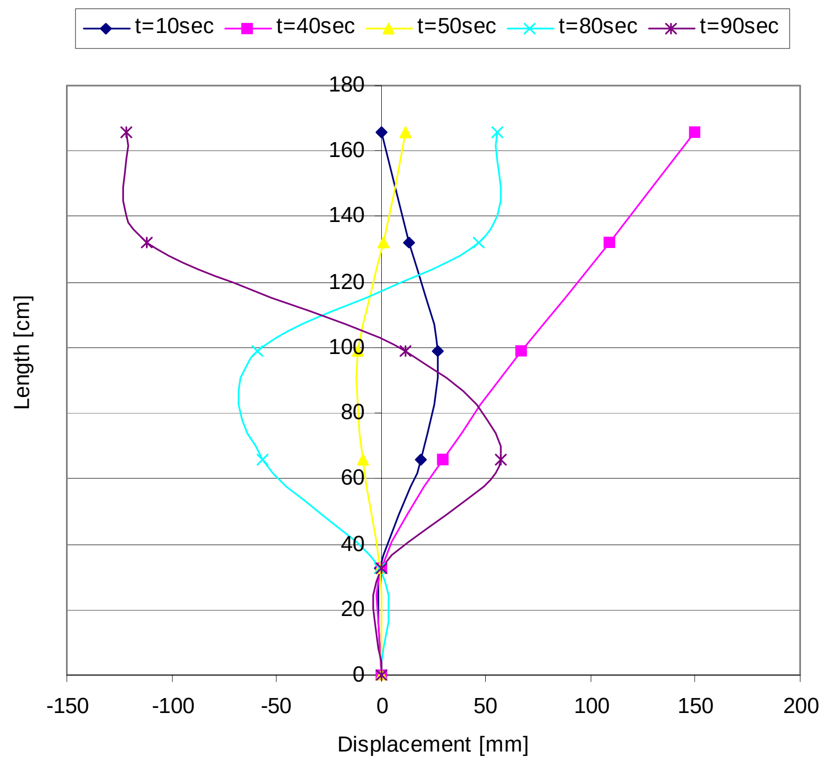


Figure 10: Measured lateral displacement profiles

## *Conclusions*

The work presented in this paper constitutes a major step in the direction of establishing a low cost real-time monitoring system for active ground. A ShapeAccelArray sensor is currently being developed, taking advantage of promising new advances in the fiber optic and micro-machined electromechanical sensor (MEMS) technologies. Preliminary test results demonstrate that the newly developed sensor array is capable of simultaneously measuring acceleration and permanent ground deformation down to several meters of depth.

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