MEMS Based Real-Time Monitoring System for Geotechnical Structures

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ABSTRACT

Real-time monitoring of civil infrastructure provides valuable information to assess the health and condition of the associated systems. This paper presents the recently developed Shape Acceleration Array (SAA), which constitute a major step toward long-term effective health monitoring and analysis of soil and soil-structure systems. The sensor array is based on triaxial MEMS (Micro-Electro-Mechanical System) sensors to measure in situ deformation (angles relative to gravity) and dynamic accelerations up to a depth of one hundred meters. This paper provides an assessment of this array’s performance for geotechnical instrumentation applications by reviewing the recorded field data from a full scale shaking test and a bridge replacement site.

1. INTRODUCTION

The health and state of the aging and overburdened civil infrastructure in the United States has been subjected to renewed scrutiny over the last few years. The American Society of Civil Engineers reports that this state threatens the economy and quality of life in every state, city and town in the nation. As one example, the United States Army Corps of Engineers noted in early 2007 that nearly 150 United States levees pose an unacceptable risk of failing during a major flood. Additionally, losses associated with failures of soil systems continue to grow in the USA and elsewhere in view of increased development in hazard-prone areas. The control and mitigation of the effects of these failures requires a better understanding of the field response of soil systems. In order to overcome these problems, the performance of these systems needs to be reliably predicted, and such predictions can be used to improve design and develop efficient remediation measures. The use of advanced in situ monitoring devices of soil systems, such as the SAA system described below is essential to achieve these goals.

The answer to this challenge partly resides in the development of tools for short- and long-term health monitoring of existing civil infrastructure along with data reduction tools of systems identification and inverse problems. The knowledge gained from this monitoring and analysis would aid in planning for maintenance and rehabilitation of these infrastructure systems and will improve the design, construction, operation and longevity. Critical soil-structure elements of the civil infrastructure which are important to monitor include bridge foundations, abutments and support systems; retained, reinforced or stabilized rock and earthen embankments and levees, slopes and mechanically stabilized earth (MSE) walls; tunnels and tunnel linings; etc. This paper presents a newly developed sensor array. The array is capable of measuring in situ deformation and acceleration up to a depth of one hundred meters and is essentially an in-place inclinometer coupled with accelerometers. The frequency and spatial abundance of data made available by this new sensor array enables tools for the continuous health monitoring effort of critical infrastructure under a broad range of static and dynamic loading conditions.

The concept of the presented MEMS-based, in-place inclinometer-accelerometer instrumentation system is centered on measurements of angles relative to gravity, using triaxial MEMS (Micro-Electro-Mechanical Systems) accelerometers, which are then used to evaluate inclinations (i.e. deformations). The same MEMS accelerometers also provide signals proportional to vibration during earthquakes or construction activities. Three accelerometers are contained in each 30 cm (1ft) long rigid segment for measuring x, y, and z components of tilt and vibration. The rigid segments are connected by composite joints that
are designed to prevent torsion but allow flexibility in two degrees of freedom. These rigid segments and flexible joints are combined to form a sensor array. The array development was partially funded by the National Science Foundation (NSF) and is manufactured by Measurand, Inc. The system, called Shape Acceleration Array (SAA), is capable of measuring three-dimensional (3D) ground deformations at 30 cm (1 ft) intervals and 3D acceleration at 2.4 m (8 ft) intervals to a depth of 100 m (330 ft). The system accuracy of the SAA is ±1.5 mm per 30 m; an empirically derived specification from a large number of datasets. More detailed information on the design of the SAA is available in [7] and [8].

The following sections present: (1) a brief description of the SAA technology, (3) a case history of the application of the SAA system, both vertically and horizontally, at a bridge replacement site in New York State, (3) a case history of the application of the SAA system at a full-scale levee testing facility in the Netherlands, and (4) a newly developed local system identification (SI) technique to analyze the response of active soil systems using the dense measurements provided by a network of SAAs. The developed SAA and local SI technique constitute a major step in the direction of establishing long-term monitoring and analysis tools capable of providing a realistic picture of large deformation response and pending failure of soil and soil-structure systems.

Sensor Description

The Shape Acceleration Array (SAA) system uses temperature-calibrated MEMS accelerometers within 30 cm (1ft) long rigid segments connected by composite joints that prevent torsion but allow flexibility in two degrees of freedom. The SAAs are factory-calibrated and completely sealed, requiring no field assembly or calibration. Because each segment of the SAA contains three orthogonal sensors, arrays can be installed vertically or horizontally as shown below in the NYSDOT bridge replacement case history. The intended array orientation does not need to be specified prior to installation. Orientation can be selected in the software. Each sensor has an output that is the sine of the angle of tilt over a range of 360 degrees. The sensor arrays arrive at the jobsite on an 86 cm (34 in) diameter reel, see Figure 1, and can be lowered into vertical, or pushed into horizontal, 25 mm (1 in) casing. The initial shape of the installation, or the absolute deviation of the installation from a virtual vertical or horizontal line, can be immediately viewed on a computer. An SAA is modeled as a virtual multi-segment line in the software, with x, y, and z data representing the vertices of this polyline. In the case of near-vertical installations, the vertices correspond to the joint-centers of the array in 3D. For near-horizontal installations, the vertices show vertical deformation only versus horizontal position [7, 8].

![Fig. 1: 32 m (104 ft) SAA on Shipping Reel](image1)
A microprocessor and other circuitry on a small printed circuit board (PCB) are built into the array, at intervals of eight segments. The microprocessor services the triaxial MEMS (Figure 2). 3D orientation is derived from the MEMS readings along the substrate using 3D transforms, as described in the next section, and the built-in geometric constraints of the joints. Dynamic acceleration is measured in the horizontal plane at multiple points to provide signature data for earthquakes.

![Fig. 2: Schematic Drawing of Vertical field Version of the Wireless ShapeAccelArray](image2)

The SAA system is built in subarrays, as presented in Figure 2. A subarray is a contiguous grouping of eight 0.305 m rigid segments (in the standard design), with a microprocessor that collects data from triaxial MEMS accelerometers in each segment. This design enables calibration of a subarray individually prior to concatenation of subarrays into a full sensor array of a length determined by the end user. A calibration subroutine allows adjustment of the torsional offsets between subarrays during
concatenation. When fully assembled, the array is already calibrated to measure in situ 3D permanent ground deformation at 0.30 m intervals and 3D soil acceleration at 2.4 m intervals. High flexibility and high sensor density result in enhanced spatial resolution along the array and the ability to capture even significantly distorted displacement profiles. Torsional constraint, and 3D pre-calibration of the complete SAA, eliminates the need for torsional alignment systems, such as grooved borehole casings, which are typically used with traditional probe and in-place inclinometer systems.

Wireless SAA data transmission is made possible by the use of an on-site data acquisition system, called a wireless earth station. Similar to traditional probe and in-place inclinometers, data from the SAA represents deviations from a starting condition or initial reading. These data are sent wirelessly, over a cellular telephone network, to an automated server, where data are made available to users through proprietary viewing software and an internet connection. Long-term system automated monitoring using SAAs typically collects data once or a few times a day but this collection frequency can be re-specified remotely by the user and changed at any time, through the same wireless interface used to receive the data. The SAA system is capable of collecting data at a sampling frequency rate of up to 128Hz, which makes it suitable for dynamic and seismic measurement. Each array is equipped with a trigger sensor that would automatically switch the SAA from slow to fast sampling rate in the case of a seismic event. Limiting the use of fast sampling rates to specific dynamic events significantly reduces the power consumption as well as data storage and transmission requirements.

Figures 2 and 3 present an example of the range and type of data which can be collected by the SAA system. This data was collected during a full-scale lateral spreading experiment conducted at the University of Buffalo. The laminar container at the University of Buffalo facility is 5 m (16.4 ft) long, 2.75 m (9.0 ft) wide, and 6 m (19.7 ft) high and is capable of containing 150 tons of sand, see Figure 2 [9].

Fig. 2: Assembly of Laminar Container at the University at Buffalo

Fig. 3: Lateral Acceleration and Displacement from one SAA System and Traditional Accelerometers and Potentiometers
After this laminar container was instrumented and filled with loose sand and water, two 100-ton hydraulic actuators were used to input predetermined motion with a 2 Hz frequency to the base of the box. The resultant soil liquefaction and lateral spreading was monitored using accelerometers within the soil deposit and on the ring laminates, potentiometers (displacement transducers) on the laminates, pore pressure transducers and two SAAs within the soil deposit. Each of the SAAs was 7 m (23.0 ft) long and contained 24 3D sensing elements. The acceleration and lateral displacement data from the SAA compared to the ring accelerometer and potentiometer data, respectively, are presented in Figure 3. This data was collected during a sloping ground test, where the base of the box was inclined 2°.

At the end of the input shaking event, nearly the whole soil deposit was liquefied, and the ground surface displacement had reached 32 cm, as seen in Figure 3. Some discrepancies are observed between the SAA data and the ring accelerometer data after 6 s, which is when the soil deposit began to liquefy. As the soil liquefied, the upper part of the SAA moved downslope with respect to the bottom of the array, thus the accelerometers were tilted with respect to their initial condition. This resulted in a slight DC component bias in the SAA acceleration readings. By filtering this low frequency component, the acceleration readings from both types of instrumentation would match even more closely. Since this was a dynamic test, the dynamic component of the displacement was removed by filtering to obtain the results presented in Figure 3. This full-scale lateral spreading experiment provides a unique example of the simultaneous acceleration and permanent lateral displacement data capture provided by the SAA system. For more information on this full-scale experiment see [10].

SAA Field Installation at NYSDOT Bridge Replacement Site

The SAA system was recently installed in California, through collaboration with Caltrans [7], and a bridge replacement site over the Champlain Canal in upstate New York, see Figure 4, through collaboration with the New York State Department of Transportation (NYSDOT). These two sites highlight the array capabilities as an infrastructure health monitoring tool. A brief site history and description of the installation process of the NYSDOT site is provided below along with a comparison between the vertical and horizontal SAA systems and traditional instrumentation.
The instrumentation plan for this site included the use of two 32 m (104 ft) long SAAs. One SAA was oriented horizontally and the other vertically to monitor the settlement and the lateral displacement, respectively, of a thirty meter deep soft clay deposit. The site instrumentation installed by NYSDOT included traditional inclinometers, vibrating wire piezometers and surface settlement plates. Based on soil strength and consolidation testing performed on undisturbed boring samples, it was decided to employ prefabricated vertical drains (PVDs) and surcharge fills to accelerate the consolidation and strength gain of the clay layer prior to driving piles for the bridge.

The vertical SAA installed at this site was 32 m (104 ft) long, in order to reach a stable soil layer beneath the very soft clay deposit. The SAA was installed in a vertical borehole located approximately 3 m (9.8 ft) from the edge of the Champlain Canal and approximately 2.5 m (8.2 ft) from a traditional inclinometer casing, in the area between the surcharge fill and the canal, see Figure 5. A 50 mm (2.0 in) diameter PVC well casing, grouted into place using the same weak grout mix used for the inclinometer casing, housed the vertical SAA. To enable future retrieval of the SAA, silica sand was used to fill the annulus between the 25.4 mm (1.0 in) approximate diameter sensor array and the inner wall of the casing. The sand would later be jetted out with water to free the instrument. The fine sand backfill was placed by pouring from the top of the casing. In future installations requiring the use of sand backfill to facilitate array retrieval, the sand placement should be completed similarly to traditional monitoring well placement where a weight is lowered into the annulus to compact the sand at set intervals. This increase in compaction is recommended to overcome the possible formation of sand bridges during backfill placement which can lead to measurement of ancillary movements. Historically, similar difficulties have been experienced when sand is used to backfill inclinometer casing. The recommended installation method for the SAA now includes direct insertion into a 25 mm (1 in) inner diameter casing, which is grouted into place prior to the array installation [11].

Prior to the start of construction activities in April 2007, the observed SAA displacements were presumably due to settlement of the fine sand backfill and the sensor array itself within the PVC well casing. Beginning in April 2007, a 4.5 m (14.8 ft) high, geosynthetic reinforced earth wall was constructed on the east bank of the Champlain Canal to mimic the load of the proposed bridge abutment, upon which an additional 1.5 m (4.9 ft) of fill was placed. With the surcharge in place, ground displacements, much greater than those measured by the SAA during the first six months, began to accumulate and the lateral displacement of the foundation soils could be discerned. The zone of lateral squeeze can be seen in Figure 6 with displacements approaching 20 mm (0.79 in), from 3 to 5 m (9.8 to 16.4 ft) depth after April 2007. Figure 6 shows a comparison between the displacement measurements from a traditional inclinometer and the vertical SAA system for a three month period of monitoring following the surcharge fill placement, in addition to the continuous displacement profile from the SAA system for the four month monitoring period after surcharge fill placement. Cumulative displacements measured by both systems were less than 18 mm (0.71 in), but the general trends are discernible. These trends in Figure 6 are comparable.

Fig. 5: Soil Profile and Location of Vertical SAA at Champlain Canal Site

Fig. 6: Comparison of Vertical SAA and Traditional Slope Indicator Displacement Data During Surcharge Loading
The horizontal SAA was installed after the PVDs had been driven, just prior to the construction of the surcharge embankment, approximately 5 m (17.5 ft) east of the westmost extent of the embankment and approximately 0.3 m (1 ft) west of a row of PVDs. The array was pushed into ten sections of 25.4 mm (1 in) diameter PVC conduit, which had been connected with PVC cement prior to the array insertion. Cable-pulling lubricant was used to assist the array insertion. However, the 32 m (104 ft) length was inserted with relative ease, in spite of a slight upward grade. The array-conduit assembly was placed in a small trench, approximately 0.3 m (1 ft) deep, within a previously placed gravel drainage layer. The displaced drainage material was backfilled around the conduit. The initial position of the horizontal SAA was obtained by laptop connection within minutes of the installation. The earth station for wireless data collection was installed a few days later, coinciding with the start of the embankment construction. The horizontal SAA transmitted wireless data every four hours, after an initial evaluation period where data was collected every hour. After 119 days of monitoring, the wireless modem was removed for use at a different site, though data collection continued via laptop downloads through day 302 (after initial embankment construction).

Figure 7 shows the settlement profile from the horizontal SAA and the west-most row of settlement plates (SP1, SP2 and SP3). This figure includes the horizontal SAA settlement data through February 2008, at which time the array was extracted prior to the pile installation at the site. The settlement plate profile is only provided through August 2007 in Figure 7, though it can be seen that the shape and values of the profiles from both methods of instrumentation is quite similar. It can been seen from the time history plots of displacement in Figure 8 that the settlement plates (SP1, SP2 and SP3) experienced greater total settlement, approximately 280 mm (11.0 in) versus 225 mm (8.9 in) maximum observed SAA settlement. This difference is attributable to the fact that the settlement plates were located approximately 4 m (13.1 ft) east of the horizontal SAA, a location bearing more of the surcharge load.

Although the traditional site instrumentation was not ideally located for direct comparison with the vertical and horizontal SAA readings, this project demonstrates the usefulness of SAAs for construction monitoring. The information provided by these two SAA systems helped NYSDOT engineers evaluate the effectiveness of the geotechnical treatments utilized at this site, namely surcharge loading and prefabricated vertical drains (PVDs). Information from the horizontal installation, especially, helped engineers make decisions about the surcharge waiting period during construction. Specifically, the settlement profile beneath the embankment and the lateral squeeze of the underlying soft clay layer were available in real-time. Had it been necessary, the construction schedule at this site might have been accelerated based on interpretation of the real-time settlement and rate of settlement information provided by the horizontal SAA.

At the end of monitoring, both SAAs were successfully retrieved for reuse on other projects. The same methodologies applied at this site could be used for longer-term monitoring of foundation soils of permanent structures.
2. CONCLUSIONS

This paper presented two successful field applications of the Shape Acceleration Array (SAA) system, demonstrating how this system could be utilized for real-time health monitoring of civil infrastructure. A new local identification technique to characterize the response and assess the properties of soil and soil-structure systems was also presented. The developed identification technique provides an effective tool to locally analyze and assess the static and dynamic response of soil and soil-structure systems using the acceleration and deformation measurement provided by the SAA. This technique does not require the availability of boundary condition measurements, or solution of a boundary value problem associated with an observed system. Studies are planned to capitalize on the capabilities of the SAA and identification technique to analyze the mechanisms of large deformation and lateral spreading of soil and soil-structure systems.

ACKNOWLEDGEMENTS

This research was supported by the NSF sensor program; this support is gratefully appreciated. The authors wish to thank Measurand, Inc. for their contribution to these projects, including their efforts toward all the field installations. The authors would also like to express their gratitude to the engineers, drillers and maintenance staff who participated in these field installations, without whom this research would not have been possible. The authors would like to acknowledge the contribution of Dr. C. Oskay and Dr. A. Elmekati to the development of the local system identification technique.

REFERENCES


