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REAL-TIME MONITORING FOR GEOSYNTHETIC REINFORCED SYSTEMS

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ABSTRACT

Real-time monitoring of civil infrastructure provides valuable information to assess the health and condition of geotechnical systems. This paper presents the recently developed Shape Acceleration Array (SAA), which constitutes 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 in two field installations; within a plantable geosynthetic reinforced (PGR) retaining wall and a bridge replacement site. The PGR wall, with a 6V:1H battered wall face, is about 2.4 km (1.5 mile) long. The wall height varies from 7 m (23 ft) to about 21.8 m (71.5 ft), with an average wall height of about 16 m (52.5 ft). This wall is the first of its kind, with a state-of-the-art concrete facing design. Thus, in order to fully capture the response of this design to seismic activity and other vibrations, the wall was heavily instrumented with accelerometers, piezometers, and in-place inclinometers. The instrumentation plan for the bridge replacement site included the use of two SAA systems, oriented vertically and horizontally, to monitor the lateral deformation and consolidation settlement, respectively, of a 30 m (98 ft) soft soil deposit beneath geosynthetic embankment surcharge. The comprehensive site instrumentation included traditional inclinometers, piezometers, and settlement gages. The geosynthetic embankment surcharge fill is used as an applied vertical stress (preload), prior to completion of the final permanent construction load. The paper will present data recorded with the developed in-place inclinometer-accelerometer system (SAA) and compared data measured with state-of-the-practice instrumentation. These comparisons were extremely favorable and justified the future use of this instrumentation for many geotechnical applications.

Keywords: Autonomous monitoring, MEMS, geosynthetic reinforced retaining wall, PVDs

INTRODUCTION

The evaluation, health monitoring and response prediction of soil and soil-structure systems during construction and due to extreme hazard conditions are on the verge of a paradigm shift due to new sensing technologies and recent advances in information technology related to wireless sensor networking. For the last two decades, much of the innovation in instrumentation and sensing has been driven by the availability of more compact and less expensive sensors. The relative abundance of data is improving the design and construction of soil-structure systems, and the strategies for mitigation of geohazards.

Real-time monitoring of active construction sites can provide early indications of deviations from design, in addition to providing valuable information on in situ health status. State departments of transportation and federal agencies spend significant resources monitoring possible slope failures using manual slope inclinometers or slope inclinometer arrays (commonly known as in-place inclinometers). Typically, manual slope inclinometer systems use a vertical borehole, with a flexible, grooved casing to guide a tilt-measuring instrument positioned at intervals by a field technician. Operating costs can be high and important information can be missed between the periodic measurements. A slope inclinometer array has an inclination sensor attached to each segment of the borehole and monitors the inclination at depths continuously with time. While slope inclinometer arrays can provide one-dimensional deformation in real time with good angular resolution, they are expensive and require grooved boreholes to maintain torsional alignment of the array. These limitations make installation of multiple arrays on a single site relatively rare, thus limiting the ability to conduct pervasive real-time monitoring in a sensor network system.

The development of robust geotechnical instrumentation able to capture local site conditions is crucial to employing the observational method and inverse modeling at active constructions sites (Finno and Calvello 2005). In spite of the growing awareness of the importance of such geotechnical instrumentation, these comprehensive arrays still remain scarce due to their limited measuring capabilities per sensor and high cost. The recent advances in sensors and wireless networking technologies have made it possible to make in situ measurements with much higher sensor density, at shorter intervals and without visiting the site, enabling better understanding and control of soil and soil-structure systems exposed to natural forces or construction activities. The wireless Shape-Acceleration Array (SAA) system (Danisch et al. 2004), manufactured by Measurand Inc, presented in this paper was developed in an effort to combine recent advances in the miniaturization of sensors and electronics with an established wireless infrastructure to enhance geotechnical monitoring. This sensor array has demonstrated its potential to deliver measurements robust enough for use in a health assessment framework, at a lower cost per measurement point. This paper provides an assessment of this array's performance in two field installations; within a plantable geosynthetic reinforced (PGR) retaining wall owned by California Department of Transportation (Caltrans) and a New York State Department of Transportation (NYSDOT) bridge replacement site.

SENSOR SPECIFICATIONS

The SAA system uses triaxial temperature-calibrated MEMS (Micro-Electro-Mechanical System) accelerometers within 30 cm (1ft) long rigid segments connected by composite joints that prevent torsion but allow flexibility in two degrees of freedom. Arrays are constructed by connecting subarrays of eight segments end-to-end. Microprocessors, one per subarray, collect data from groups of sensors and transmit this digital data to the surface using just two communication wires. The SAAs are factory-calibrated and completely sealed, requiring no field assembly or calibration and are capable of measuring three-dimensional ground deformations at 30 cm (1 ft) intervals to a depth of 100 m (330 ft). Because each segment of the SAA contains three orthogonal sensors, arrays can be installed vertically or horizontally as shown below in the New York State Department of Transportation (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 are transported to the jobsite on an 86 cm (34 in) diameter reel, see Fig. 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 Measurand 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 (Abdoun et al. 2007), (Bennett et al. 2009). Similar studies have been conducted with different MEMS-based systems (Uchimura et al. 2011), (Lemke et al. 2008).

Fig. 1 32 m (104 ft) SAA on shipping reel.

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 resolution of the deformation measurement is +/- 0.5 mm for 32 m SAAs. The accuracy of the deformation measurement of the SAA is +/- 1.5 mm per 30 m. This system has been operating in the field with stable readings for over five years to date (Dasenbrock, 2012). In addition to maintaining stable data readings over half a decade, the flexibility and durability of the construction have allowed for very large displacements to be recorded. In one example, more than 0.77 m of slow creep has been observed over three years and the array continues to function properly.

The following section presents data that was collected during a full-scale lateral spreading experiment conducted in a laminar container at the University of Buffalo (Dobry et al. 2011). The laminar container 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 holding 150 tons of sand. The results from two SAAs installed in this experiment provide an example of the range and type of data that can be collected by this system, which has since been utilized in many field installations worldwide.

After this laminar container was instrumented and filled with loose sand and water, two 100-ton hydraulic actuators were used to induce 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 Fig. 2. This data was collected during a sloping ground test, where the base of the box was inclined 2°.

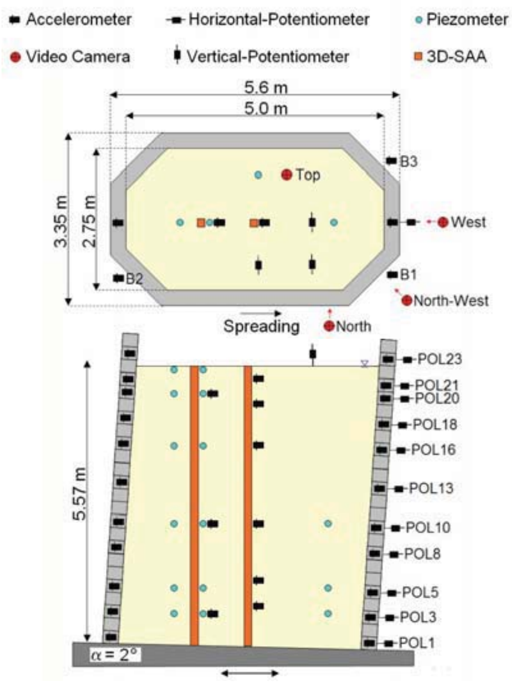

Fig. 2 Sensor layout of liquefaction test at University at Buffalo (modified from Dobry et al. 2011).

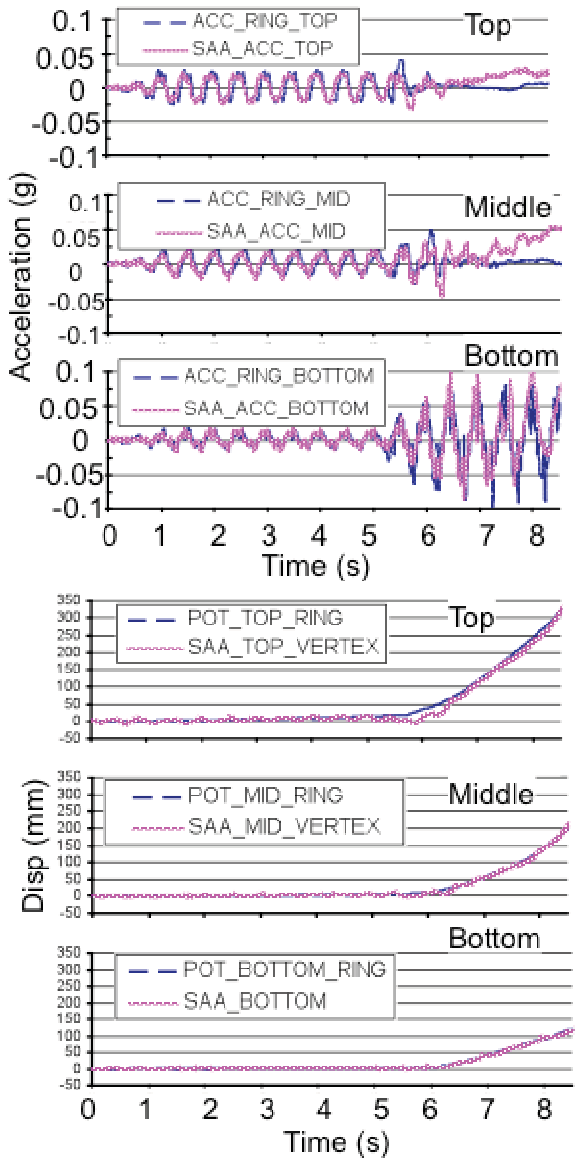

Fig. 3 Acceleration (g) and lateral displacement comparison (mm) between SAA and laminar ring accelerometers and potentiometers, respectively, at the soil surface (0 m depth), mid-depth (2.8 m depth) and bottom of soil deposit (5.6 m depth); ACC_RING = Accelerometer on Laminar Ring, POT = Potentiometer on Laminar Ring, SAA = Shape Acceleration Array.

At the end of the input shaking event, nearly the whole soil deposit was liquefied, and the ground surface displacement at the top of the laminar container had reached 32 cm, as seen in Fig. 2. 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 Fig. 2. This full-scale lateral spreading experiment provides a unique example of the simultaneous acceleration and permanent lateral displacement data captured by the SAA system. For more information on this full-scale experiment see Dobry et al. (2011).

NYSDOT BRIDGE REPLACEMENT SITE

An early application of the SAA system was at a NYSDOT bridge replacement site over the Champlain Canal in upstate New York, see Fig. 3. 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, including a slope inclinometer and settlement plates. As shown in Fig. 3, SP is settlement plates, SAAH is the horizontal SAA, SAAV is the vertical SAA, and PVDs are prefabricated vertical drains.

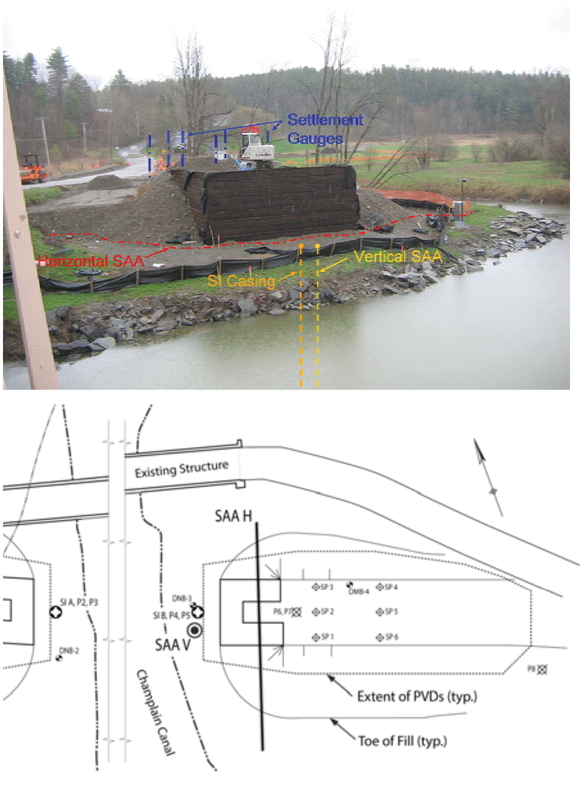

Fig. 4 Bridge replacement and realignment over the Champlain Canal, NY.

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-six meter deep soft clay deposit. Based on soil strength and consolidation testing performed on undisturbed boring samples, it was decided to employ prefabricated vertical drains (PVDs), Fig. 4, and surcharge fills to accelerate the consolidation and strength gain of the clay layer prior to driving piles for the bridge.

Fig. 5 Installation of vertical SAA (SAAV) at NYSDOT soft clay site.

The vertical SAA installed at this site was 32 m (104 ft) long, in order to extend below the very soft silty clay layer. 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 Fig. 5. A 50 mm (2.0 in) diameter polyvinyl chloride (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. 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 (Abdoun et al. 2008). This recommendation method had not been developed yet at the time of this installation. The consequential effect is the appearance of spurious displacements resulting from movement of the sand backfill rather than actual lateral movement of the clay deposit.

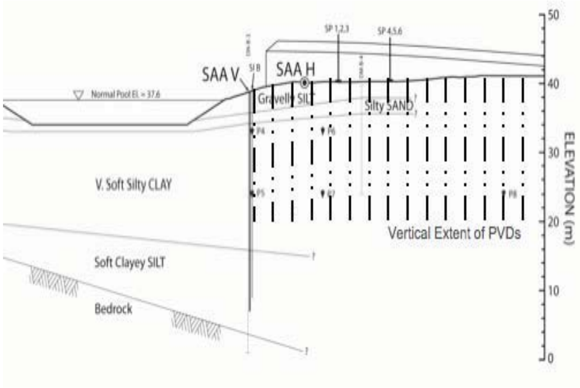

Fig. 6 Soil profile and location of vertical SAA at Champlain Canal site.

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 began to accumulate and the lateral displacement of the foundation soils could be discerned. The zone of lateral squeeze can be seen in Fig. 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, i.e. May 2007 is used as the zero reading. The trends from are both methods of instrumentation are similar. Figure 7 shows the continuous displacement profile from the SAA system software for the four-month monitoring period after surcharge fill placement. Total displacements measured by both systems were less than 18 mm (0.71 in), but the general trends are discernible.

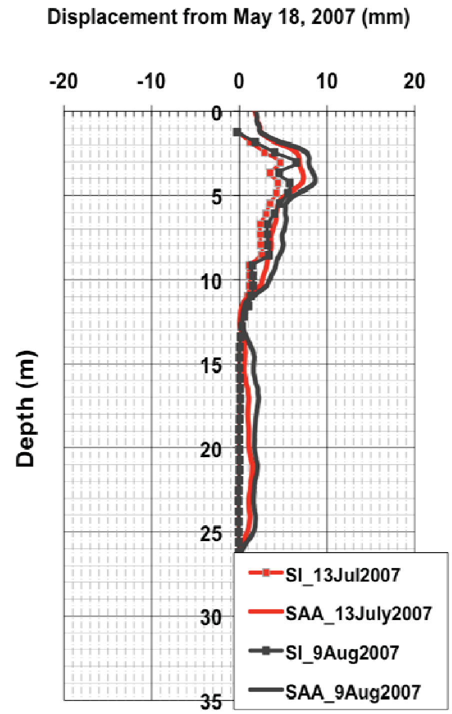

Fig. 7 Comparison of vertical SAA and traditional slope indicator displacement data during surcharge loading.

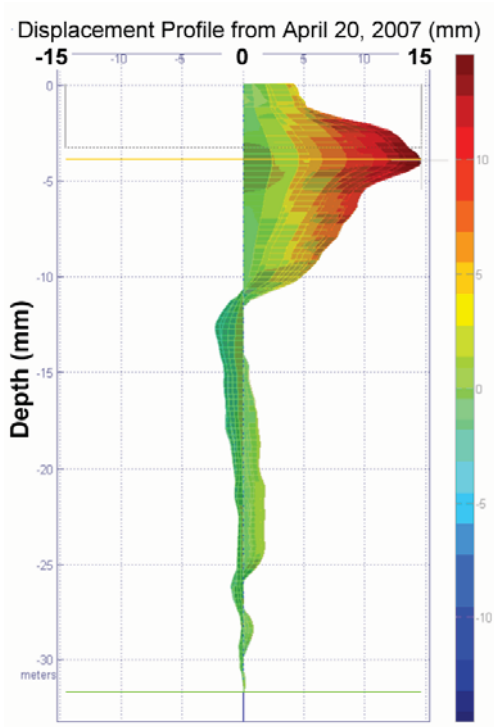

Fig. 8 Continuous displacement profile from SAA system; maximum observed displacement was 15 mm at 4 m depth.

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 west-most 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 glued together 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 into the full length of PVC conduit with relative ease, even in spite of having to install the array against 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.

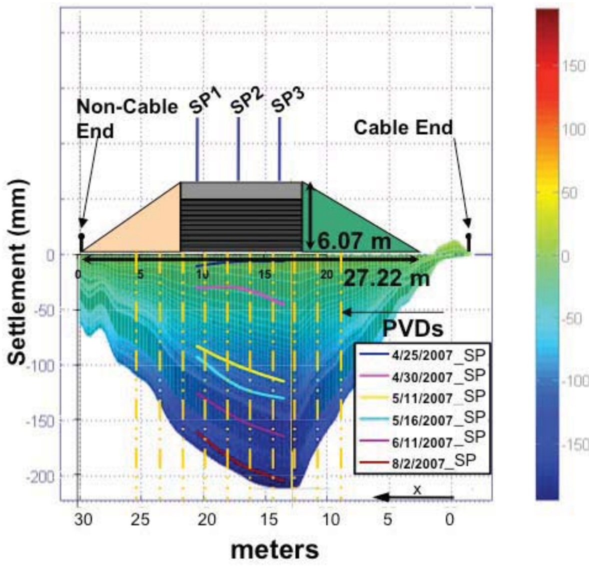

Fig 9 Settlement profile from horizontal SAA (contour plot) and nearest set of surface settlement plates (discrete lines).

Figure 8 shows the settlement profile from the horizontal SAA and a row of settlement plates (SP1, SP2 and SP3). This figure includes the horizontal SAA settlement data shown as a contour plot 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 8, 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 Fig. 9 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. The x-values shown for the SAA and the SPs correspond to the position of the measurement on Fig. 8, measured from the cable end of the SAA.

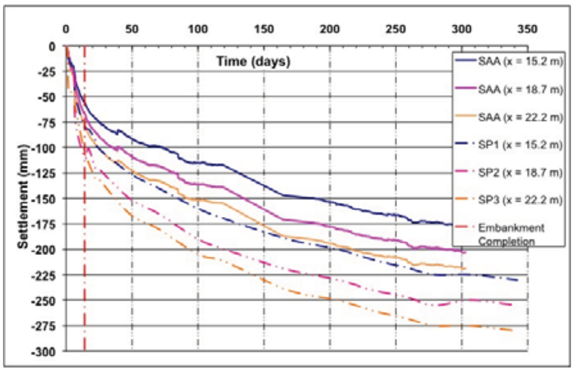

Fig. 10 Time history of displacement from three SAA and surface settlement plate locations (consolidation data).

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 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.

PLANTABLE GEOSYNTHETIC REINFORCED RETAINING WALL IN SAN DIEGO, CA

The SAA system was also installed within a plantable geosynthetic reinforced (PGR) retaining wall at the intersection of southbound interstates 5 and 805 in San Diego, CA, see Fig. 10. The PGR wall, with a 6V:1H battered wall face, is about 2.4km long. The wall height varies from 7m to about 21.8m, with an average wall height of about 16m. This wall is the first of its kind, with a state-of-the-art concrete facing design. Thus, in order to fully capture the response of this design to seismic activity and other vibrations, the wall was heavily instrumented with accelerometers, piezometers, and in-place inclinometers. This collection of instruments potentially provided an excellent opportunity to compare the response of the SAA system to traditional instrumentation.

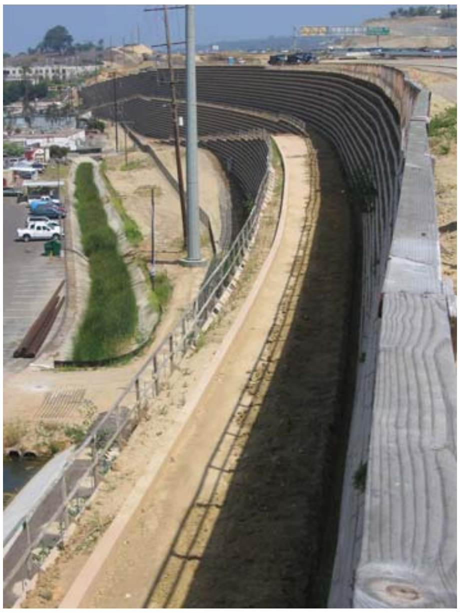

Fig. 11 PGR retaining wall in San Diego, CA.

The array was 31.7m (104ft), in order to capture a full profile of vibration within the wall. The borehole was located in the shoulder of the new roadway, approximately 2.5m from the PGR facing, near a previously-installed communication line conduit. This conduit served to pass the communication and power line between the top of the SAA and the solar panel cabinet at the base of the PGR wall, see Fig. 11. This cabinet was installed during the construction of the wall and houses the power for the wide range of other sensors. The solar panel is used to recharge a 12V battery that was installed along with the earthquake alarm and the wireless modem for the SAA system. A lithium battery on the circuit board at this communication end is used to keep the clock going even in the case of a power failure. The WSAA system in San Diego was set to upload to the FTP server once a day for the first few weeks after installation. This value can be changed remotely at anytime via the FTP server. Site preparation and drilling at the San Diego site took approximately three hours, installation of the PVC casing and WSAA took two hours, installation of communications cable in the existing conduit took four hours, and installation of the earth station equipment in the solar panel cabinet took two hours. The first data sets were uploaded to the FTP server by wireless cellnet modem within a few minutes of establishing a connection between the earth station and the WSAA.

Fig. 12 Solar panel cabinet with WSAA earth station components highlighted in yellow.

During the first weeks of data collection at this site, the deflection plot of the SAA system showed noticeable zigzag movements of many segments, presumably due to settlement of the sand within the casing. Some minor additional deflections were measured over the following months (up to 10 mm (0.4 in)) specifically in the upper 12 m (39 ft) of the SAA, see Fig. 12. These movements occurred both suddenly and at more modest rates. Since these differential deflections were not in response to an external static or earthquake loading, it was concluded that they were likely due to backfill effects and not indicative of true ground deformation. Green and Mikkelsen (1988) identified that granular backfills around inclinometer casings are more prone to bridging than grout and that "incomplete backfilling or backfill settlement causes spurious casing movements that are best avoided." Based on the displacement profile at this site, it seems likely that the coarse sand settled to the bottom 20 m (66 ft) of the PVC casing, perhaps leaving very little sand backfill in the top 12 m (39 ft). With no backfill support, the sensor array may have become stabilized on the side of the PVC casing. The measured displacement of less than 10 mm (0.4 in), as seen in Fig. 12, is a reasonable value considering the 76.2 mm (3 in) inner diameter of the PVC casing and the 25.4 mm (1 in) diameter of the SAA. Figure 13 shows a plot of x-displacement versus y-displacement at the depth of maximum observed displacement, 9 m (30 ft) in this case. From this plot, the direction of displacement is observed to be primarily in the –y direction, or northwest.

Despite high expectations about the opportunity to compare the SAA measurements at this site with previously installed instruments, namely in-place inclinometers and accelerometers, this data did not become available. The SAA at this site continues to collect data and has been functional for nearly four years.

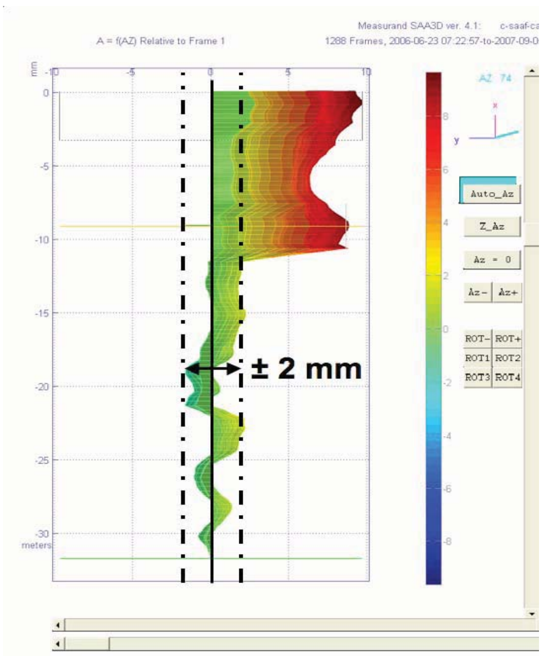

Fig. 13 Fourteen months of displacement data from a 32 m (104 ft) long ShapeAccelArray at the San Diego PGR site.

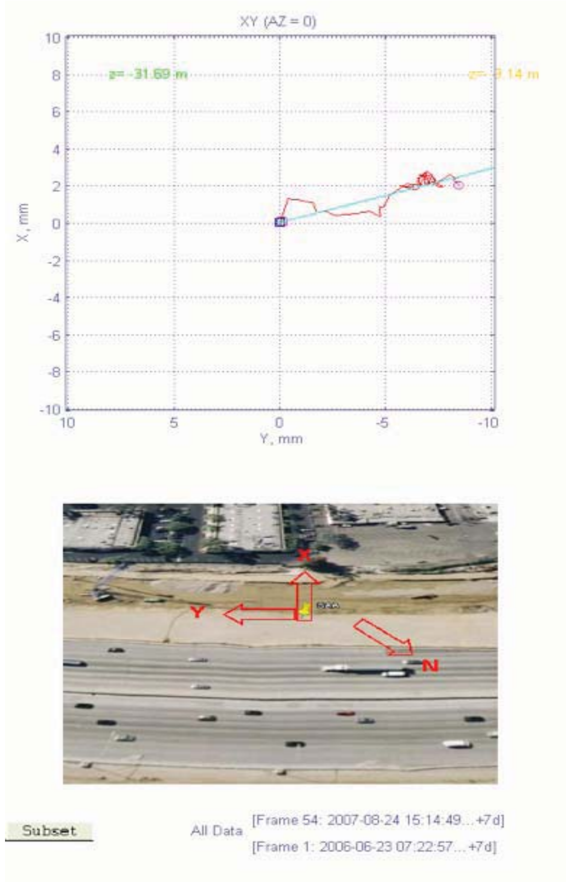

Fig. 14 x-displacement versus y-displacement after fourteen months of SAA data at the San Diego site.

CONCLUSIONS

The NYSDOT and Caltrans geosynthetic drained/reinforced field sites were excellent opportunities for field installation of the MEMS-based inclinometer-accelerometer system. The Shape-Acceleration Array data was comparable to traditional inclinometer data at the bridge replacement site and showed typical sensor stability at both sites. These field installations provided useful experience in developing the best practices for installation and retrieval of this new system. SAA data from these field sites confirmed the necessity for complete sand compaction or a different installation method for best conformance of the sensor array to actual ground displacements. Since these installations, several successful installations have been completed using the 25 mm casing method. Field data confirms that the SAA instrumentation system is also a viable solution for use in monitoring and assessing levees and other earthen structures. This system now includes an integrated pore pressure measurement and shows promise for incorporation into early warning management systems for civil infrastructure in New

Orleans, The Netherlands, and other locations. The instrumentation has just been implemented at one site in New Orleans in 2012 through the collaboration of Rensselaer and Geocomp Corp. in development of a multi-scale monitoring and health assessment framework. The site will be monitored as part of future work and more installations will follow. Ultimately, data collected from these sites will be used in a safety assessment, potentially anticipating failures before they occur.

ACKNOWLEDGEMENTS

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