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An Evaluation of Real-Time Deformation Monitoring Using Motion Capture Instrumentation and Its Application in Monitoring Railway Foundations

ABSTRACT: The purpose of this study is to evaluate the use of motion capture instrumentation to monitor the response of a railway embankment and the underlying soft peat mire foundation soils to freight train loading. Initial data sets were obtained from the motion capture system, called the ShapeAccelArray (SAA, Measurand Inc.), installed in a railway embankment. Review of the data sets from the site installation raised questions as to the ability of the SAA to provide accurate displacement measurements. Testing of the SAA in the laboratory confirmed that the output from the SAA system (inclusive of software) would not provide a true measurement of horizontal deformations during large cyclic motions. This inaccuracy was due to the magnitude of acceleration associated with the cyclical motion on the microelectromechanical systems (MEMS) accelerometers and the effect of this on the ability of the system to determine its shape. A method for determining the magnitude of cyclic displacement from the output of the MEMS accelerometers was developed from the laboratory testing data. This involved the double integration of the change in acceleration measured by the accelerometers to obtain a change in displacement. This method was applied to the data sets obtained from the field installation to obtain a profile of cyclic displacement with depth.

Introduction

Railway embankments over peat foundations are difficult to build and maintain. Many of the existing embankments in Canada were constructed over 100 years ago, for shorter, slower, and lighter trains. Large cyclic strains are produced within the peat foundation as a result of train loading. The large concentrated loads associated with trains are particularly destructive to rail-track structures due to the wear produced by large cyclic movements of the embankment and foundation.

A motion capture instrumentation system produced by Measurand Inc., called the ShapeAccelArray (SAA), was selected to obtain near continuous measurements of lateral deformation along vertical profiles within the embankment and underlying peat during cyclic train loading. This instrumentation was supplemented with more conventional geotechnical instrumentation (piezometers and extensometers). As this was the first time the SAA had been used for such an application its performance under these conditions required evaluation. In order to evaluate the performance of the SAA for the types of motion experienced in the field it was essential that it be calibrated under controlled conditions in the laboratory, as this was the first time the SAA had been used for such an application. This paper presents the results of a laboratory calibration and interpretation of real-time SAA measurements and demonstrates how these interpretation methods can be applied to monitored horizontal deformations of a railway embankment and underlying foundation at a field site.

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Background

The measurement of displacement within an earth structure during cyclic loading has traditionally relied upon the use of accelerometers, geophones, and extensometers. Extensometers accurately measure the displacement of the surface of the embankment relative to a fixed anchor installed at the base of a borehole. Accelerometers and geophones measure acceleration and double integrate acceleration to obtain displacement. This approach has met with varying degrees of success (Hall 2000; Heelis et al. 2000; Kaynia et al. 2000; Madshus and Kaynia 2000; Konrad et al. 2007). The resulting data from accelerometers and geophones are limited as they are installed at discrete depths and are restricted to a single axis (direction) of measurement.

The SAA is a microelectromechanical systems (MEMS)-based deformation monitoring system. The SAA consists of 305 mm (1 ft) rigid segments connected by a 2 degrees of freedom joint, which allows the joint to bend but not twist (Figs. 1 and 2). The three-dimensional (3D) coordinates of each joint (or node), and thus the 3D shape of the SAA, are calculated from the orientation and fixed length of each SAA section and the assumption that one of the ends is fixed in space (Abdoun et al. 2007). The SAA is not axially compressible and is often installed within a PVC access tube. Consequently, the array should not be used to measure vertical movement of the soil (Mikkelsen and Dunnicliff 2008). Interpretation of the data from a (near) vertically installed SAA can be used to measure the horizontal (two-dimensional) movement of

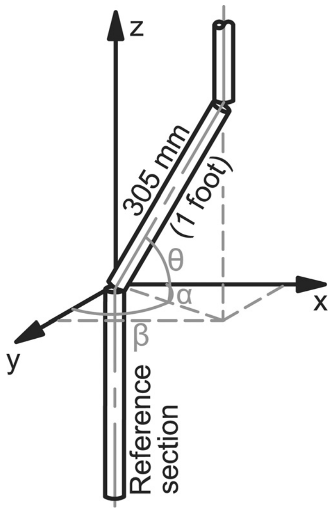

FIG. 1—*Calculation of 3D shape of array from orientation of sections.*

each joint along the length of the array in a similar manner to an inclinometer, but in near-real time as the earth structure deforms.

A Measurand Inc. research-grade SAA system along with a desktop computer for data processing was used in this study. This system allowed rates of data acquisition of up to 120 Hz. The system was modified for field use by installing the PCI card for data acquisition in a MAGMA external PCI to PCMI adaptor (MAGMA 2008). This alteration allowed the system to be run with a laptop computer. The use of the PCI to PCMI adapter resulted in slightly lower maximum data acquisition rates of up to 100 Hz. This reduced rate of data collection still provides sufficient resolution for the measurement of motion that occurs at frequencies less than 10 Hz.

FIG. 2—*SAA on spool (7.2 m (24 ft) array shown).*

The SAA was initially developed to measure long-term deformation and is often installed vertically to act as an in-place inclinometer or horizontally to measure settlement (Abdoun et al. 2005; Abdoun et al. 2007). The slow rate of movement in these applications allows many readings to be averaged to obtain an accurate measurement of displacement. The SAA has been the subject of several studies to ensure the accuracy of the measurements under near static and slow rates of deformation (Abdoun et al. 2005; Abdoun et al. 2007). These studies compared the displacement measured with the SAA at a single node compared to the same motion measured with a linear variable differential transformer (LVDT). The results from Abdoun et al. (2005) (Fig. 3) showed good agreement between the SAA and LVDT measurements for motions occurring at estimated frequencies ranging between 0.05 and 0.2 Hz. The results from Abdoun et al. (2007) (Fig. 4) also show a strong correlation between the data obtained from the SAA and the LVDT. The motion shows two different contributing frequencies. The first frequency is a very low frequency (estimated at 0.006 Hz), which contributes to the large overall motion. The error in the SAA in comparison to the LVDT as a percentage of overall displacement is estimated to be less than 2 %. A determination of the accuracy of the SAA measurement at the higher frequency (0.5 Hz), which produces the smaller oscillations, cannot be made from the data as it is presented, although it is comparable to the LVDT. The MEMS accelerometers contained within the SAA to measure the orientation of the SAA segments have been shown to provide measurements of acceleration with accuracy comparable to high quality piezoelectric accelerometers (Abdoun et al. 2005).

The response at higher frequencies has not yet been thoroughly tested. Based on the studies mentioned earlier the SAA does provide an accurate measurement of *cyclic* displacement at frequencies less than 0.5. Typical frequencies associated with embankment deformations during the passage of trains can be much higher than those at which the SAA had been previously tested. For example, for a train traveling at 110 km/h, the measurement frequency would be approximately 7 Hz (Hendry 2007).

Study Site

The CN mainline railway track runs east-west through Alberta, passing through Edmonton and Edson. The study site is located on a peat mire formation east of Edson between miles 101.4 and 102.6 (Fig. 5) of the Edson subdivision. The embankment was initially constructed in the 1920s, using a timber raft construction. The local terrain is flat (Fig. 6) and the embankment ranges from 1.6 to 2.0 m in height.

A ground investigation was conducted to determine the construction and composition of the embankment, and to provide

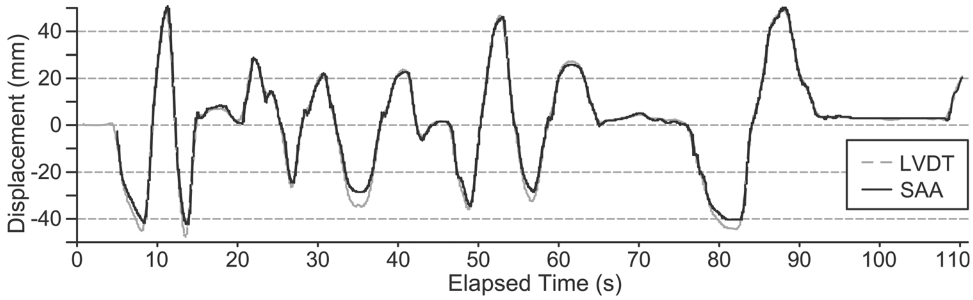

FIG. 3—*Comparison between lateral displacements (mm) measured using traditional displacement sensors (LVDT) and a ShapeAccelArray sensor (after Abdoun et al. 2005).*

information for the design and installation of a monitoring system. The embankment consists of ballast and sub-ballast to a depth of 1.2 m, underlain by approximately 1.0 m layer of peaty organic fill material, a timber corduroy log raft, and then approximately 3 m of intact peat overlying silty-clay (Fig. 7). The timber corduroy was found to be in very good condition as was evident by the difficulty in drilling through it and the well-preserved condition of samples obtained during drilling.

The "conventional" instrumentation installed at the site consisted of strain-gauge piezometers and extensometers (constructed by RST instruments). Both types of instruments are capable of reading at a rate of up to 90 Hz, although most measurements were taken at 50 Hz. Three piezometers were installed under the centreline of the track, at depths of 5.8, 4.7, and 3.1 m, to measure the generation of pore water pressure under train loading (Fig. 7). Three extensometers were installed approximately 0.6 m off the north end of the railway ties. The anchors of the extensometers were installed at depths of 7.46, 5.46, and 3.46 m (Fig. 7). The data from this instrumentation are not presented in this paper, with the exception of extensometer data, which are compared to the results from the SAA. The SAA was installed vertically in a PVC access tube 0.6 m off the north end of a railway tie (Fig. 7). A more detailed examination of the monitoring data from this instrumentation is presented in Hendry et al. (2008).

Preliminary Field Measurements

The horizontal motion of the embankment and peat measured by the SAA at the Edson subdivision site was resolved in two directions perpendicular and parallel to the rail (Fig. 8). Motion perpendicular to the rail is positive with deflections away from the rail, which indicates a horizontal expansion of the embankment. Motion parallel to the rail is positive in the direction of train travel.

Given that the wheel loads are applied and removed quickly it is reasonable to assume that the peat behaves in a nearly undrained manner during the passing of individual axles or grouping of axles. Due to the undrained behaviour of the soil, the vertical displacement should be strongly correlated to the horizontal displacements measured by the SAA. The SAA measurements of horizontal deflection and the extensometer measurements of vertical deformation are shown in Fig. 9. The data set in Fig. 9 shows the overall patterns of movement obtained using a 30 point moving average. The 30 point averaging was required as the raw data showed very large peaks in calculated displacement, which resulted in the data being unreadable. The 30 point average was the minimum number of averaged points, which revealed a correlation between the SAA displacements and the applied axle loads. A direct correlation between the extensometer and SAA data is apparent for node 1 but not for node 14 in Fig. 9. The perpendicular displacement measured at node 14 (Fig. 9) shows negative horizontal displacements, representing contraction of the embankment during train loading. The weights of locomotives and cars are routinely weighed by CN for billing purposes. The weights of the cars that comprise this train were used to determine the average axle loads shown in Fig. 9.

When plotted within the frequency domain (Fig. 10(*a*)) the frequency versus normalized magnitude plots of the extensometer data and the *parallel* SAA data (for node 14) show a strong correlation. The major frequencies contributing to these data sets range

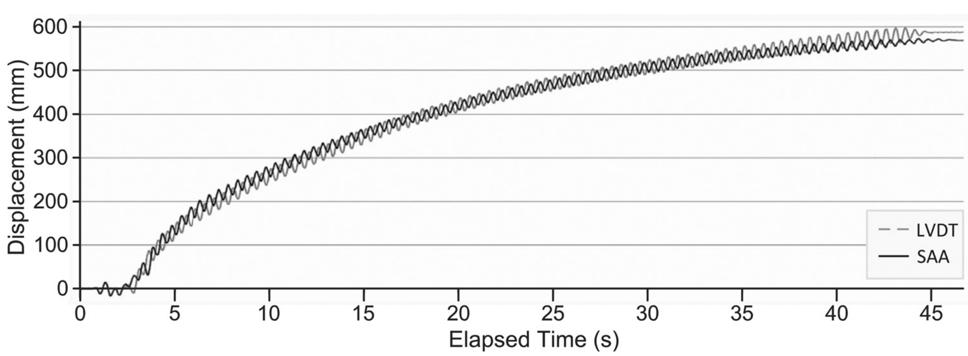

FIG. 4—*A comparison of the displacements measured by the WSAA (SAA) and a reference LVDT (after Abdoun et al. 2007).*

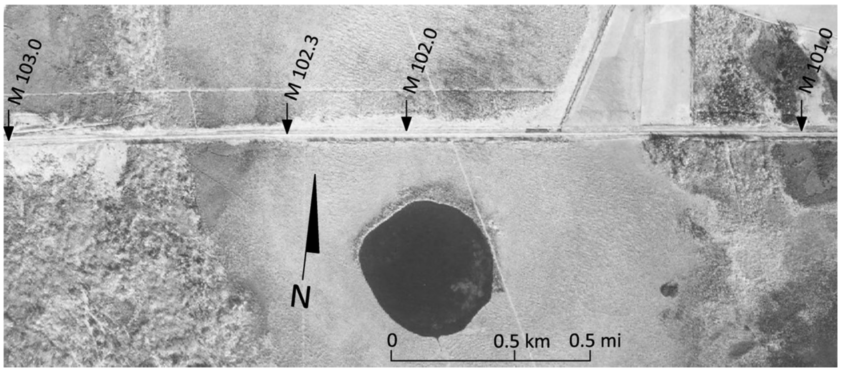

FIG. 5—*Arial photograph of the Edson Subdivision peat bog crossing. Instrumentation installed at Mile 102.0.*

from 0.4 to 0.7 Hz (Fig. 10(*b*)). From examination of the extensometer data and the train geometry, this corresponds to the frequency of the passage of groupings of four axles at the coupling point of two railcars. The extensometer data and the *perpendicular* SAA data show a similar strong correlation between 0.4 and 0.7 Hz (Fig. 10(*c*) and 10(*d*)), but also with higher contributing frequencies, ranging from 0.8 to 1.4 Hz, which have relatively large magnitudes. The application of a low pass filter at 0.7 Hz to the SAA data output data results in displacement versus time plots very similar to those shown in Fig. 9. These higher frequency deformations are unlikely to be due to "noise" in the measurements, as the distribution of the magnitude over the frequencies (or the shape of the graph) is very similar to that found between 0.4 and 0.7 Hz. It is most likely that these higher frequency responses are due to the higher frequency load applications of the loads from pairs of axles, which were not measured by the extensometer. The presence of this band of higher frequency (and magnitude of deformation) suggests that there may be exaggeration of the magnitude of deformation under higher frequency motion.

This preliminary evaluation of the SAA data sets highlighted concerns regarding the validity of the SAA measurements at higher frequencies. First, based on the literature review it was apparent that the SAA had not been tested at the frequencies and magnitudes of motions that were being measured within the embankments and peat subgrade at the Edson site. Second, the SAA measured negative horizontal displacements perpendicular to the track, representing a contraction of the embankment during train loading (Fig. 9). Finally, there were discrepancies between the nature of the measured vertical and horizontal (perpendicular) deformations within the peat. These discrepancies appear to increase with increasing frequency. Due to these inconsistencies between expected and measured behaviour of the soils, controlled testing of the SAA in the laboratory was undertaken to determine the accuracy and precision of the array.

FIG. 6—*Surface conditions at Mile 102.0 during installation of instrumentation.*

Laboratory Testing of SAA

The laboratory component of this study compared the controlled, cyclic, deformations of a PVC tube used to house the SAA to those measured using the SAA under a range of frequencies. The laboratory apparatus consisted of a schedule 40 PVC conduit (the same as was used in the field installation) with the locations of the SAA nodes marked on the outside of the conduit. The SAA was inserted into the tube with webbing to ensure a tight fit. The tube was clamped in a vertical orientation to the side of an I-beam (Fig. 11). The clamps were custom made from U-Bolts with rubber backs and were clamped to the PVC tube at the marked locations of nodes to provide known stationary points at which comparisons could be made. A linear hydraulic actuator was used to create the deformation of the PVC tube along with a LVDT to measure the motion. The linear hydraulic actuator was clamped to the PVC tube at a location corresponding to node 8. The LVDT measurements were collected to allow for a comparison between the resulting SAA data and a known displacement. The LVDT measurements were made at a rate of 120 Hz. The tests were carried out with sinusoidal functions of varying frequency and

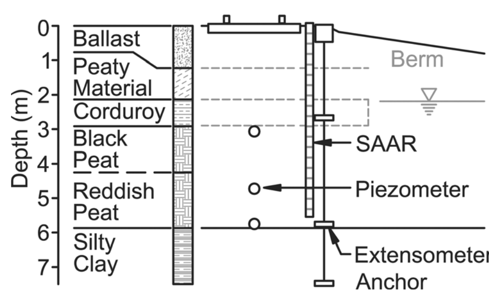

FIG. 7—*Cross section of embankment and foundation at Mile 102.0. Location and depths of the instrumentation are shown.*

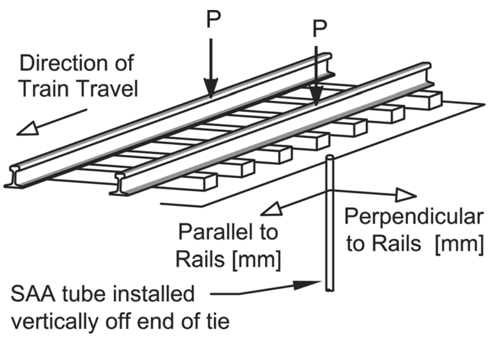

FIG. 8—*Directions of SAA measured displacements in the railway embankment and foundation.*

magnitude. The frequencies were varied between 0.1 and 4.0 Hz and the amplitude of the motion ranged from 1 to 41 mm.

Laboratory Testing Results

The difference between the displacements measured using the SAA and the LVDT during sinusoidal motion at a given frequency was expressed as a cyclic error factor (CE) defined as follows:

$$CE = \frac{M_{\mathrm{SAA}}}{M_{\mathrm{LVDT}}} \tag{1}$$

where:

M_{SAA} = amplitude of the cyclical displacements as measured by the SAA and

M_{LVDT} = amplitude of the cyclical displacements as measured by the LVDT.

A plot of CE versus frequency is presented in Fig. 12. These results clearly show increasing exaggeration of the magnitude of the motion with increasing frequency, diverging from a CE value of (near) 1 at very low frequencies to CE values and greater than 40 at a frequency of 4 Hz.

The observed discrepancy between the SAA and LVDT readings was hypothesised to be the result of the method by which the SAA software determines the direction of gravity and thus its vertical orientation from the MEMS accelerometer measurements and the acceleration due to the cyclical motion of the array.

The displacement and acceleration due to cyclical motion is described by the following equations, respectively,

$$d(t)_{\mathrm{cyclic}} = D\cos(2\pi f t - \phi) \tag{2}$$

$$a(t)_{\mathrm{cyclic}} = -(2\pi f)^2 D\cos(2\pi f t - \phi) \tag{3}$$

where:

$d(t)_{\mathrm{cyclic}}$ = displacement as a function of time, mm,
$a(t)_{\mathrm{cyclic}}$ = acceleration as a function of time, mm/s^2,
D = amplitude of the cyclic displacement mm,
f = frequency of motion Hz, and
ϕ = phase shift, rad.

The effect of the acceleration produced by the cyclic motion on the measured orientation of the SAA segment, as determined by the SAA system (inclusive of the software), can be large. The orientation of the SAA segments is calculated by assuming that the direction of gravity is in the direction of the resultant of the accelerations measured by the three orthogonal MEMS accelerometers.

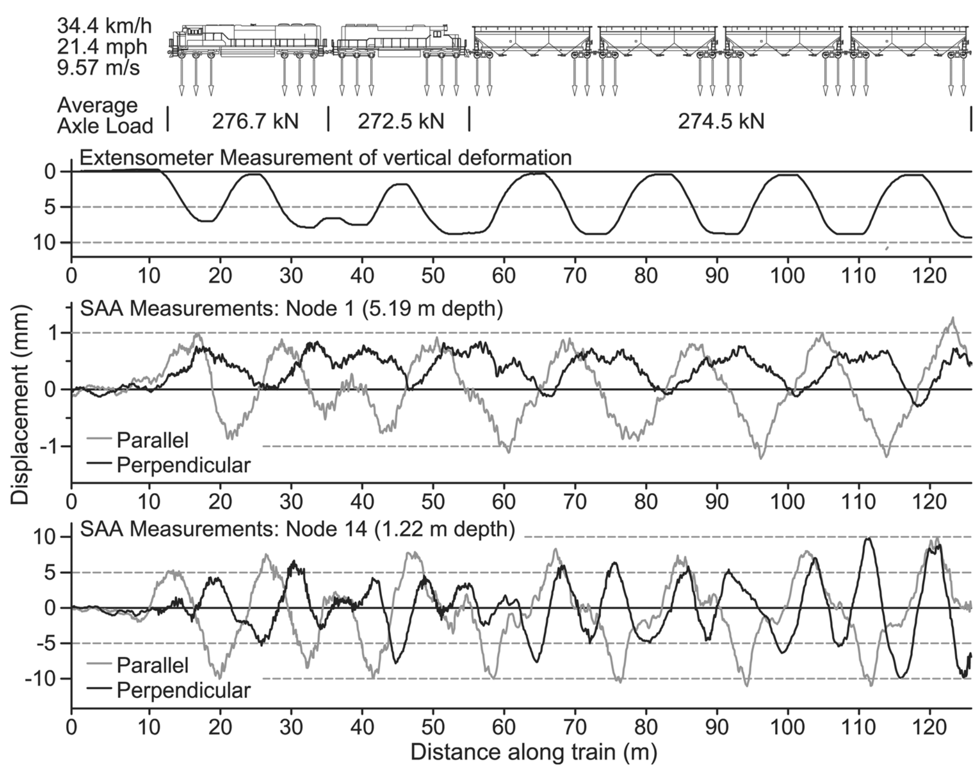

FIG. 9—*Vertical displacement of the embankment and foundation (extensometer data) and the horizontal displacement observed from the raw SAA data for both the perpendicular and parallel directions at two different depths. Note: data were smoothed using a 30 point average.*

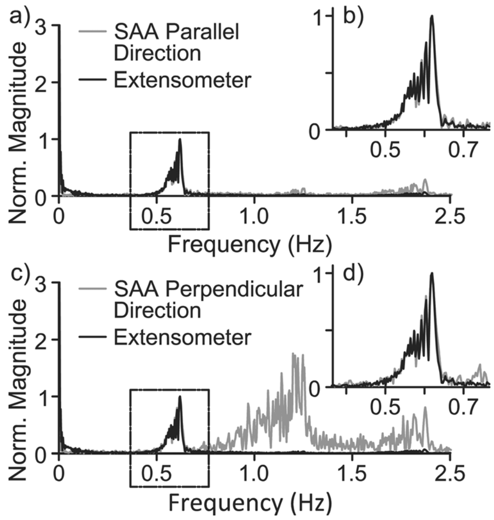

FIG. 10—*Comparison of the vertical displacement of the embankment and foundation (extensometer data) and the horizontal displacement from the raw SAA data in the frequency domain in the parallel (a) and perpendicular (b) directions. Note: Magnitudes of plots normalized to max value between 0.4 and 0.7 Hz for each data set.*

This assumption works well under slowly changing or static conditions, but not for cyclic motion as is evident in both the field and laboratory data. As shown in Fig. 13, the effect of the acceleration due to motion (***a***) on the orientation of the resultant acceleration (***R***) is a function of the magnitude of ***a*** and the orientation of the SAA segments (Fig. 13). The acceleration due to cyclic motion can thus result in an amplification (Fig. 13(*a*)), reduction (Fig. 13(*b*)) or event reversal (Fig. 13(*c*)) of the horizontal displacement.

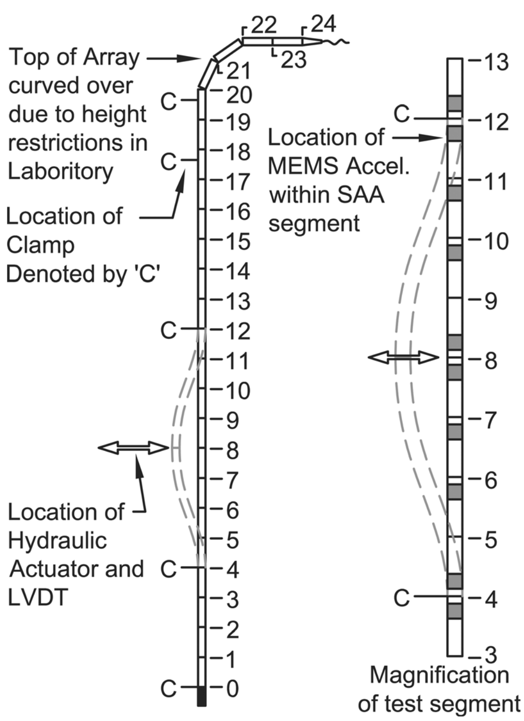

FIG. 11—*Schematic of testing of SAA in laboratory. Node (joint) numbers and locations of MEMS accelerometers are shown. MEMS accelerometers are located one quarter of the length of the SAA segments (0.076 m) from nearest node or joint.*

The horizontal displacement at node 8 was known from the LVDT measurements during each test. The *actual* shape and horizontal displacements of all of the remaining nodes was interpolated for differing frequencies from measurements taken at a frequency of 0.03 Hz. From the interpolated shape of the array it was possible to calculate the horizontal acceleration, and thus model the SAA output. Figure 14 presents a comparison of the interpolated (actual) shape of the SAA, the shape obtained directly from the SAA output and the modelled shape, for differing frequencies of motion. The modelled and measured SAA output show very close agreement. This suggests that the acceleration due to the cyclical motion is the cause of the erroneous SAA output.

It is apparent from the controlled testing in the laboratory that the SAA system cannot be used directly to provide accurate displacement measurements for cyclic displacements above 0.03 Hz. Several different approaches were of modifying the SAA output to directly provide accurate measurements; however these proved unsuccessful. As the error is a function of the magnitude and frequency of the motion, any attempt to modify the SAA software outputted displacement data set within the frequency domain does not take into account the effect of the orientation of the array segments (Fig. 13) and is consequently ineffective. An attempt to overcome the statically indeterminate nature of the forces on the accelerometers was attempted by assuming that the cyclical acceleration due to motion is occurring strictly in the horizontal plane (the same assumption used in the modelling of the laboratory data as described earlier) However, the variations in the magnitude of the output from one accelerometer to another were large enough to limit the ability to fully distinguish the acceleration due to gravity from the measured acceleration (due to both gravity and horizontal motion) without extensive calibration of each individual segment.

The method that proved most successful was using the MEMS accelerometers to directly measure the changes in acceleration due to motion. The accelerations can then be integrated with time to obtain velocity versus time and then again to obtain displacement versus time. This integrated displacement is calculated for the accelerometer within the SAA segment, not the nodes/joints of the array. This calculation is done with the assumption that the measured change in acceleration is due to translational motion, and thus the change in acceleration due to gravity as the section undergoes slight rotation with the horizontal motion is insignificant. The basis for the double integration method and the required baseline correction was drawn from Hall (2000). The double integration is conducted for various times resulting in a measurement of the change in displacement. The calculated displacement at any time is the sum of all changes in displacement which have proceeded that time. The resulting error in the displacement at any time is consequently the sum of the error that has proceeded that time.

In the case of sections that are not near vertical, the initial (static) output from the SAA provides the orientation of the sections and thus the orientation of the MEMS accelerometers with respect to vertical. This initial orientation measurement taken along with the 3D displacements from the double integration,

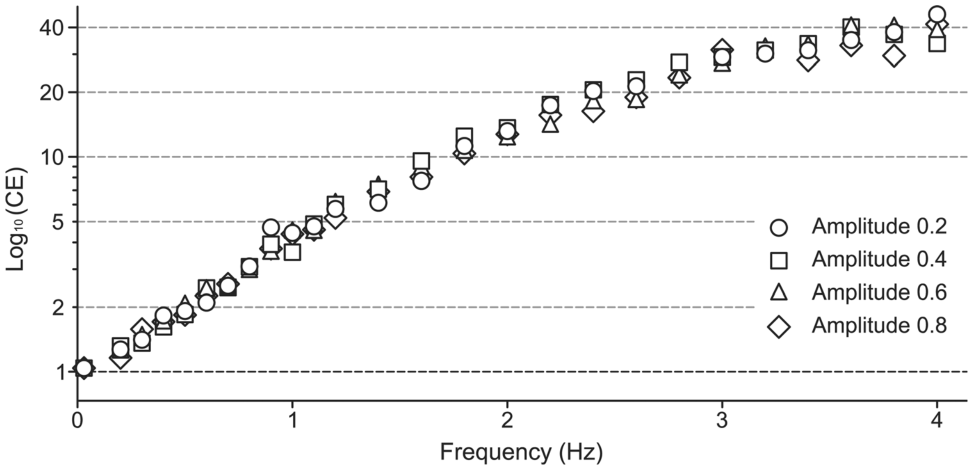

FIG. 12—*Resulting plot of error factor required for data sets (SAA/LVDT) versus frequency from laboratory testing data.*

allows for the rotation of the Cartesian axis of the integrated displacements into the horizontal plane, rather than relative to the orientation of the SAA section. The two resulting horizontal directions allow for rotation of the data about the vertical axis in post-processing in the event that the X and Y axes, defined by the SAA, are not in the ideal directions for the interpretation of the displacements. This would be the case when the X and Y directions of the SAA are not aligned with the perpendicular and parallel directions relative to the railway track.

Figure 15 shows the results of this interpretation of the SAA measurements as compared to the LVDT data. It is apparent from the start of each data set (before cyclic motion) that the hydraulic actuator generates a high frequency oscillation. The accuracy of the SAA measured data sets are thus affected by this high frequency oscillation and this results in some deviations of the SAA values from the measured LVDT values at any individual peak (standard deviation of ±2 mm). These deviations do appear to increase with increasing frequency of cyclic motion. However, the

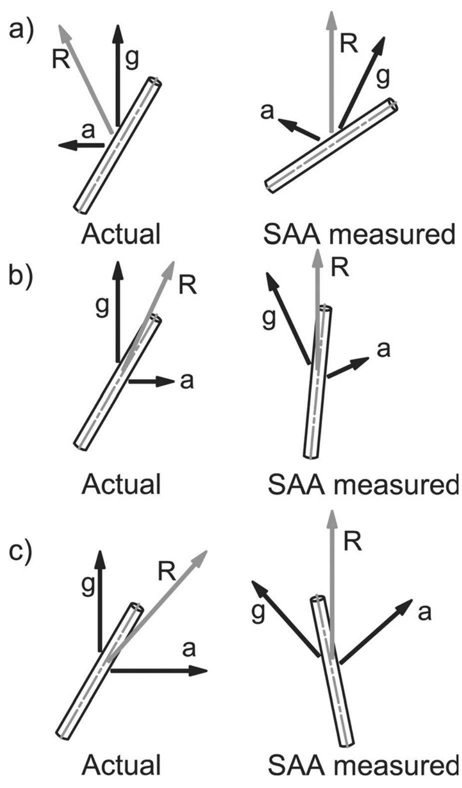

FIG. 13—*An illustration of (a) amplification errors, (b) reduction errors, and (c) reversal of direction errors in the measured orientation of the SAA section and the horizontal location due to the SAA software's interpretation of the horizontal acceleration (**a** is the acceleration due to motion, **g** is the acceleration due to gravity and **R** is the resultant of **a** and **g** the direction of which the SAA software interprets as the direction of **g**).*

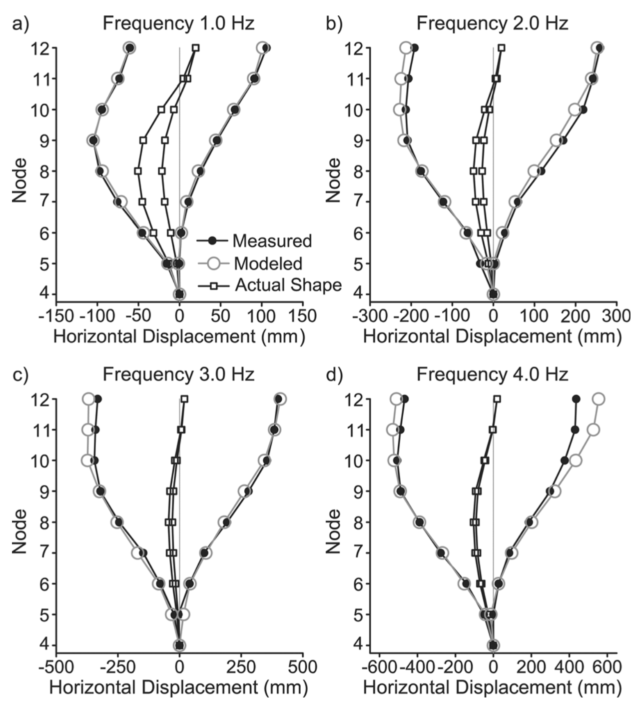

FIG. 14—*Comparison of the measured SAA motion as provided by the SAA software, the actual SAA shape and motion determined from the LVDT data, and the SAA output modelled from the actual SAA shape and motion and the orientation of the array with respect to gravity. Shown for cyclic frequencies of (a) 1.0 Hz, (b) 2.0 Hz, (c) 3.0 Hz, and (d) 4.0 Hz.*

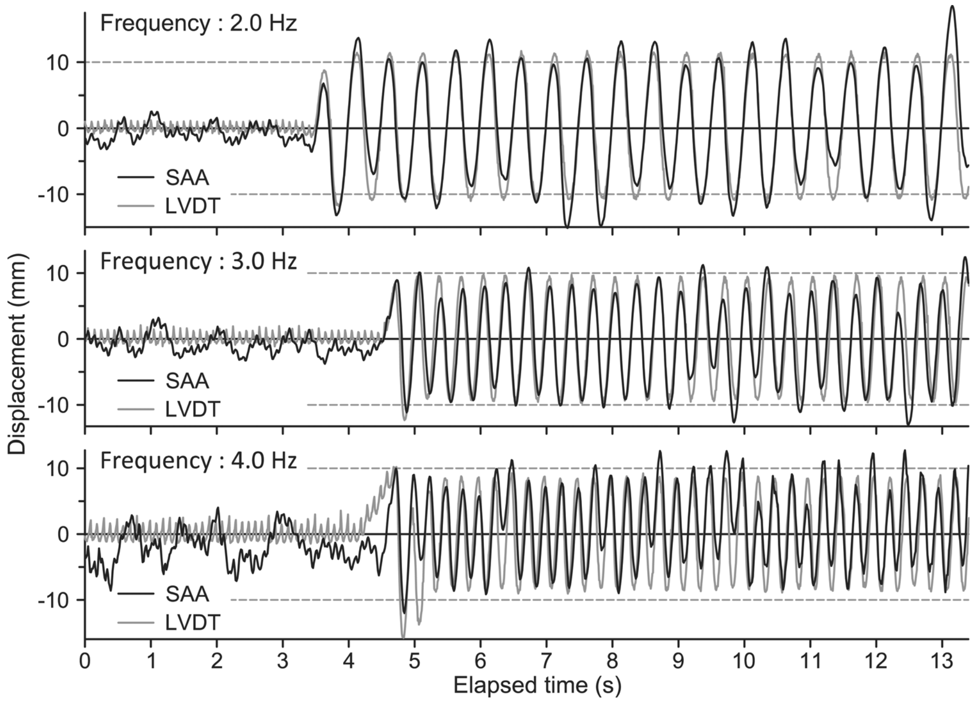

FIG. 15—*Comparison of measured (LVDT) displacements and displacements calculated from double integration of the SAA accelerometer output from the laboratory study. The graphs present a comparison of the motion of node 8 to the integrated displacement for accelerometer 8, which is located 76.2 mm (3 in.) above the node.*

overall pattern of movement taken over multiple peaks provides an accurate measurement of the LVDT motion with error between the median LVDT cyclic displacement and the corresponding SAA measured cyclic displacements ranging between 0.04 and 0.33 mm. This error expressed as CE values ranges from 0.92 to 0.97. This suggests that a statistical analysis of the *cyclic* displacements should provide reasonably accurate measurements of ground motion.

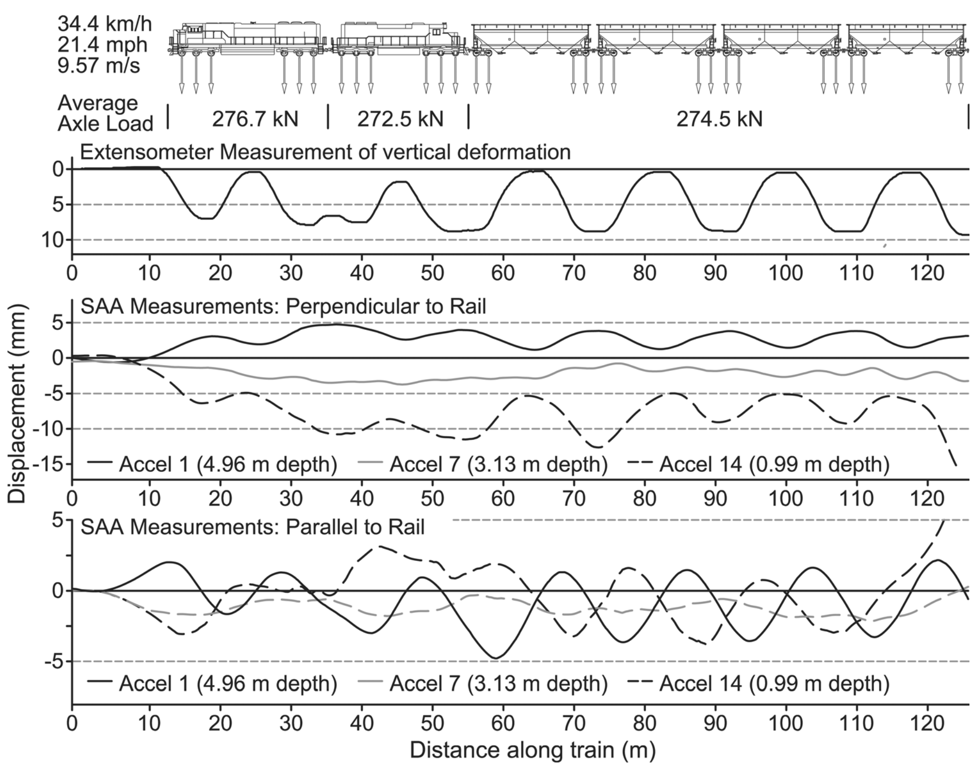

FIG. 16—*Vertical displacement of the embankment and foundation (extensometer data) and the horizontal displacement from the double integrated SAA data for both perpendicular and parallel directions at three different depths.*

Field Application

The proposed method for processing the SAA readings developed from the laboratory study was applied to the data sets collected at the Edson Subdivision site. Figure 16 shows the same data set as shown in Fig. 9, but with displacements obtained directly from double integration of the measured accelerations. The integrated displacements did not require filtering or smoothing, unlike the original SAA output. As the double integration calculation is cumulative, it is insensitive to these very high frequency and magnitude accelerations measured by the MEMS accelerometers which constituted the noise. The correlation between the extensometer data and the SAA data in Fig. 16 is now evident. The maximum and minimum deformations from the extensometer data and the perpendicular SAA data show a strong correlation with the applied axle loads. This data set is displayed as cyclic displacement versus depth in Fig. 17 for all accelerometers. Figure 17 shows the measured cyclic displacement of the embankment and foundation during the passage of grain cars from the last 30 cars of the data set. It is for the measurement of the cyclic displacement that the accuracy of the SAA has been determined.

The pattern of *cyclic* displacement shown in Fig. 17 is consistent with results from finite element modelling of the embankment and foundation as a simple linear elastic soil, although the magnitudes and distribution of the displacement are currently under investigation. The lower peat foundation material was found to spread laterally during the undrained (fast) loading, consistent with an undrained soil acting as an elastic solid. The embankment materials were measured and modelled to be rotating inwards with the formation of a deflection bowl on the surface. The measured peat responses in both perpendicular and parallel directions are very similar both in shape and magnitude. Considering the stiffness and negligible vertical strain (as measured with the extensometers) of the silty-clay base, the cyclic displacement of the deepest MEMS accelerometer suggests that there is a zone of significant shear at or near the interface between the peat layer and the underlying silty-clay. The differences in magnitude of the response of the embankment materials in the perpendicular and parallel directions are likely to be a result of the differences in geometry of the embankment in those directions. The rigidity of the PVC tube and SAA are assumed to smooth large gradients of displacement found in shear zones likely resulting from the contrasting stiffness of the fill and peat materials and the presence of the corduroy.

An alternative method to the double integration procedure is the use of a fast Fourier transform (FFT) to determine the major contributing acceleration frequencies and their magnitudes. The benefit of the FFT method is that the major contributing frequencies can be obtained from a sampling rate of only twice the frequency being measured. In the case of this train passage this would have required a sampling rate of only 1.24 Hz as opposed to the 100 Hz at which these measurements were taken. From Eqs 2 and 3 we can get the following equation, which shows the correlation between the magnitude of cyclic displacements and cyclic accelerations:

$$d(t)_{\text{cyclic}} = \frac{a(t)_{\text{cyclic}}}{-(2\pi f)^2} \tag{4}$$

A FFT was applied to a small segment of the data set in which there is consistent loading so that the frequency (f) and the magnitude of the cyclic acceleration can be determined. Figure 18 shows a comparison of the cyclic displacements determined using the magnitude of acceleration at the major contributing frequency (0.62 Hz) and the displacements determined from the double integration of the acceleration measured by all MEMS accelerometers. From Fig. 18 it is apparent that the FFT method overestimates the motion, likely due to the actual displacement pattern deviating from a sinusoidal shape, as is shown in the extensometer data in Fig. 16.

As the deformation of the soil is cyclic, with a consistent magnitude and frequency, a measurement can be made of the accuracy and consistency of the measurements in situ, in the form of a standard deviation of the horizontal displacements with depth. The results of this analysis are presented in Fig. 19. It is interesting to note that there is an increasing reliability in the readings with increasing depth as the standard deviation reduces from a range of 2–6 mm near the surface down to 0.3 mm within the peat. This is also apparent in Fig. 16 when comparing the consistency of the measured cyclic displacement from accelerometer 1 to that of accelerometer 14. As with the laboratory data, the upper section of the SAA is subject to higher frequency motion due to the dynamics of the train. The effect of this higher frequency

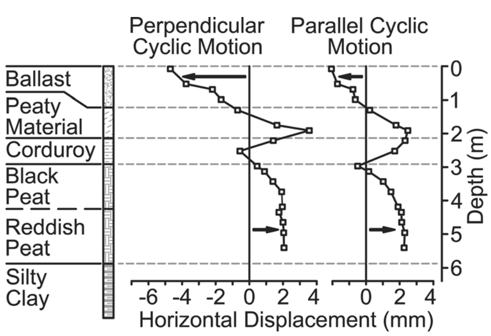

FIG. 17—*The magnitude and direction of the cyclic deformation measured by the SAA during train loading by the heavy grain train in both the perpendicular and parallel directions. Note: the cyclical displacement in parallel direction is calculated as one-half of the cyclic displacement as the displacement cycles between in front and behind the moving train loads.*

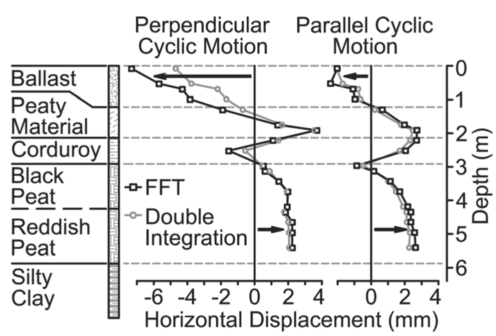

FIG. 18—*A comparison between the magnitude and direction of the cyclic deformation versus depth profiles determined by use of the fast Fourier transform (FFT) and by double integration.*

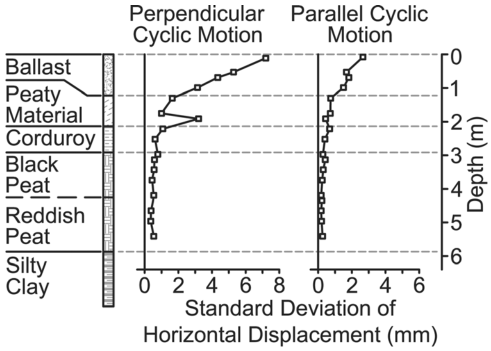

FIG. 19—*Standard deviation of the cyclic horizontal displacement as determined by double integration versus depth plots of for the cyclic horizontal displacements measured by the SAA during train loading by the heavy grain train.*

motion is decreased with depth resulting in increased reliability of individual measurements with increasing depth.

The linear baseline correction of the data during processing forces the final shape of the SAA to be the same as it was at the beginning of the data set. This baseline correction was done as only the calculation of the cyclic displacement from the SAA measured accelerations was determined to be accurate, and consequently does not allow for the measurement of non-recoverable horizontal deformation. However, as the array is not undergoing cyclic motion at the beginning (before the train) and at the end (after the train) of the data set the SAA can still function accurately as an in-place inclinometer, the original purpose of the instrument. The resulting change in shape of the array provides a measure of the distribution and magnitude of permanent deformation within the embankment. Unlike the displacements integrated from the accelerometers, the SAA change in shape is taken relative to the base of the instrument; thus the lower node is assumed static, similar to the assumption for interpreting slope inclinometer data. In the installation at the Edson site this is obviously not the case as the lowest section is known to move considerably (Fig. 17). For this data set the permanent horizontal displacement of the embankment and underlying peat relative to the deepest SAA section is shown in Fig. 20. This plastic deformation did not recover before the passage of the next train 14 min later.

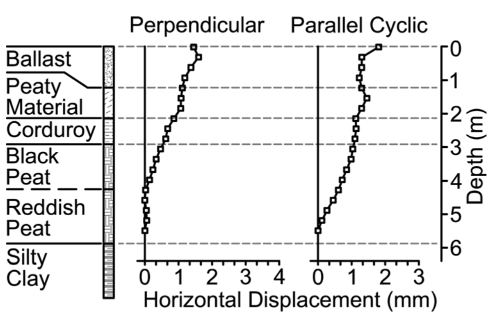

FIG. 20—*Horizontal deformations not recovered (relative to the lowest SAA section) as measured by the SAA before and after train loading by the heavy grain train.*

Conclusion

SAA output, when used as an in-place inclinometer, provides accurate measurements of displacement at very low frequencies of motion. However, results from the laboratory testing presented in this paper show that this accuracy is lost with cyclic motion at frequencies greater than 0.02 Hz. This loss of accuracy was shown to be due to the SAA software interpreting the acceleration due to the cyclical motion as a component of gravity, resulting in an incorrect determination of the orientation of the SAA segments and of the shape calculated from these orientations. The use of the SAA outputs for the displacement of the instrument at higher frequencies results in significant errors due to the large cyclical accelerations measured by the MEMS accelerometers in the SAA segments. When used as an array of accelerometers to directly measuring the magnitude of cyclic motion, the SAA becomes a useful and accurate instrument. The SAA was shown to have less than 0.33 mm of error for the measurement cyclic motion with consistent amplitude.

The spatial and temporal resolution of measurement and ease of installation of the SAA system made it possible to obtain measurements at the Edson site that are unique, and clearly show the distribution and magnitude of the horizontal cyclic displacement within the embankment and the soft peat foundation due to the cyclical heavy axle loads. Other available methods of measurement could not have produced this quality of data set. This technology is now being used to assess the foundation performance at various soft soil sites in Western Canada.

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