DYNAMIC DEFLECTION MONITORING OF EPS EMBANKMENT TO SUPPORT RAILWAY SYSTEM

3.1 Introduction

The amount of deflection of the rail caused by the passing of a locomotive or rail car is a significant safety issue for rail system operations. Large deflections could pose the risk of possible derailment, especially at higher speeds of operation. Dynamic rail deflections can occur on all types of embankment support systems.

The amount of deflection can be measured by using direct or indirect methods. For direct methods, measurement is usually done by via survey equipment, lasers, or other optical equipment (e.g., high-speed cameras) deployed in the field. When optical techniques are used, optical equipment are used to obtain images, and those images are subsequently processed to determine relative displacement. For indirect methods, the amount deflection is measured either by instrumentation and numerical interpretation. The most common indirect method involves the installation of accelerometers or geophones at the site. These sensors can provide time history data of acceleration or velocity. This information can be integrated to provide estimates of displacement of the rail versus time.

The use of optical techniques to measure the dynamic deflection on rails and sleepers that atop the embankment made from conventional materials have been carried out by
several researchers (Ho et al., 2006; Bowness et al., 2007; Lu, 2008; Pinto et al., 2009; Psimoulis and Stiros, 2013). The video graphic and image processing techniques were used to monitor the vertical displacements of rail sleepers with the passage of trains by Ho et al. (2006). Bowness et al. (2007) monitored the dynamic displacement of railway track using remote video monitoring system. Lu (2008) developed a system to measure track deflection from a moving railcar. The system was comprised of a loaded hopper car fitted with a camera/lesser sensor system which detected the vertical deflection of the rail relative to the wheel/rail contact point. Pinto et al. (2009) used an optical system for monitoring the vertical displacements of the track in high speed railways. The system was based on a diode laser module mounted away from the track. Psimoulis and Stiros (2013) measured the deflection of a short-span railway bridge using robotic total station (RTS).

The use of indirect methods to measure the dynamic deflection in the field have been carried out by several researchers (Madshus and Kaynia, 2000; Bowness et al., 2007; Chebli et al., 2008; Priest and Powrie, 2009; Ling et al., 2010). Madshus and Kaynia (2000) studied the motions of the track and embankment by installing the accelerometers in the field. In this study the displacement was calculated and the results were compared with numerical simulation. Bowness et al. (2007) monitored the dynamic deflection of railway tracks by placing the geophones on the sleepers. The field test results were then compared with the results obtained from an optical target method. Chebli et al. (2008) studied the dynamic response of high-speed ballasted railway tracks using a three dimensional (3D) periodic model and in-situ measurement. As an in-situ measurement, accelerometers were installed at various locations to measure the vertical acceleration and displacement. In this method, the accelerometers were placed on the sleepers. The in-situ measurement results
were then compared with the results obtained from 3D periodic model. Priest and Powrie (2009) evaluated the dynamic track modulus by measuring track velocity during train passage. In this method, geophones were attached to the sleeper outside the rail. Dynamic displacement was calculated from the measured velocity. Ling et al. (2010) studied train induced vibration response characteristics and dynamic stability of track structures by installing accelerometers on sleepers, rail and embankment slopes.

The use of EPS geofoam for railway embankments has not been studied to any great extent. O'Brien (2001) described the innovative solution for the replacement of an old railway bridge by using EPS geofoam embankment in United Kingdom (UK). From this study, one can understand the potential of using EPS geofoam as a lightweight fill material for railway embankment for short term and long term purposes. So far, there are no study focusing exclusively on vertical deflection monitoring of EPS embankment to support railway system. (WHAT ABOUT THE STUDY OF DEFLECTION IN NORWAY REFERENCED IN SHUN’S THESIS).

In the United States, EPS geofoam was recently incorporated in portions of the commuter and light rail systems in Salt Lake City, Utah by the Utah Transit Authority (UTA). The FrontRunner commuter rail south line extends from Salt Lake City to Provo, Utah. Along this line at Corner Canyon in Draper City, EPS has been used in the embankment in order to minimize the stress over a reinforced concrete box culvert. This location has both EPS geofoam and adjacent earthen embankment. Similarly, the light rail line (Green Line) extends from West Valley Central to Salt Lake City International Airport. In this line, EPS has been used in the embankment near Roper Yard, which is operated by
the Union Pacific Railroad. These two sites were selected to monitor the dynamic deflections of EPS geofoam embankment.

The main objectives of the study were to: (1) develop an optical technique to measure the dynamic vertical deflection, (2) evaluate the performance of the developed optical technique, (3) measure the vertical deflection during passage of trains using accelerometers and (4) compare the results of vertical deflection of EPS embankment with that of the earthen embankment.

3.2 Field Description

The FrontRunner commuter rail system in the Corner Canyon area in Draper City, Utah has rail embankment constructed of both EPS geofoam and conventional fill materials. The site is shown in Figure 3.1. This system consists of (from top to bottom): steel rail, ballast, sub-ballast, concrete reinforcing slab, EPS geofoam and sand. The slope of an embankment is 2H:1V. The cross-section of an embankment is shown in Figure 3.2. Similarly, a photo of the EPS embankment used to support light rail along Green Line near River Trail is shown in Figure 3.3. (SHOULD INCLUDE A X-SECTION OF THIS EMBANKMENT ALSO, SIMILAR TO THAT USED IN FIGURE 3.2).
Figure 3.1. Embankment with EPS geofoam and conventional fill materials in Draper city of Utah along FrontRunner line

Figure 3.2. Cross-section of an EPS geofoam embankment at corner canyon of Draper city of Utah
3.3 Equipment and Methods

3.3.1 Dynamic Deflection Monitoring

In the study, an optical target technique was developed for measuring the dynamic deflection of the rail, but this technique was not deployed in the field due to poor weather conditions (high winds). However, an accelerometer array was installed in the field and the data from these were interpreted to provide estimates of rail deflections.

3.3.1.1 Development of Optical Technique

In this method, a paper target (Figure 3.4) was developed and used for laboratory testing of the system and optical interpretation. The target was attached on a wooden frame and kept on the MTS machine as shown. The MTS machine has an actuator that can be controlled to produce a systematic and controlled vertical displacement. A LVDT was used to measure the linear displacement versus time. A loading protocol was set up in the MTS
machine for cyclic loading of a frequency 0.5 Hz and peak to peak amplitude of 7 mm. The protocol was written to yield time and displacement as output.

![Target set-up on MTS machine](image)

Figure 3.4. Target set-up on MTS machine

Bowness et al. (2007) considered the minimum distance between target and camera to be 10 m in order to minimize the effects of train vibration on the camera. This recommendation was used for this study, where video was recorded by setting a Go-Pro™ camera and telescope at a 10-m distance from the target as shown in Figure 3.5. The Go-Pro™ camera was able to take pictures and videos at a rate of 120 frames per second, and had a Wi-Fi system which could connected to another electronic devices to display the target. The target was made with black and white squares in order to make analysis easier. After recording the video, an image processing technique was employed to find the vertical deflection.
In this method, the video recordings were converted into several still frames. The first frame was taken as the base image. The center of the target was determined in terms of pixel number for each frame. The displaced position of center of the target in the vertical direction was determined in terms of pixels and was converted into linear distance.

For the analysis, an algorithm was developed in MATLAB. The algorithm is given in Appendix A. In this process, all images were uploaded initially. The central black square box of the target was chosen as the region of interest. The region was selected to make sure that the total displacement of the square still remains within the peripheral white region. A matrix was created with zeros in all rows and columns. The region of interest was then replaced by the matrix with zero values. Therefore, this region became completely different from the peripheral zones. A histogram was made for the linearly spaced vectors, which were prepared from a one-dimensional (1D) matrix. The 1D matrix was obtained from the rows and columns of the selected region. The threshold value of the pixels in the region was then determined. Values smaller than threshold were made zero. Similarly, values greater than threshold were set equal to one.

Figure 3.5. Camera-telescope set up for video recording
The total number of rows where the values were non zero represented the length of the square. Thus, the total number of pixels along the length of one small square was determined. The identity of the center region was then determined in terms of its pixel number. The pixel numbers for the center region of subsequent images were determined in similar manner. Once the minimum pixel numbers were determined, then each pixel number was subtracted from this. (The pixel numbers represented the distance in terms of the number of pixels from the minimum value.) A linear scale was used to measure the side of the big square. The total number of pixels at one side of the big square were also calculated. A conversion factor was determined for converting pixels into corresponding linear displacement. The time was calculated by dividing the frames to the number of frames in one second. For example, if there were 200 frames in 10 seconds then the 20 frames were obtained in 1 second. From this, a plot was made between displacement and time. The total displacement was then determined from the plot. The displacement versus time from both optical techniques and data extracted from MTS machine was plotted on the same graph for comparison (Figure 3.6).
After laboratory verification, a similar instrument was developed for field implementation. At the Corner Canyon embankment site, there is no level ground around for a distance of 10 m from the target on the rail to where the embankment slope begins. The embankment slopes away from the rail on a 2H:1V side slope. Therefore in order to measure the deflection on sloped ground, a modification of the set-up was introduced. A telescoping rod was fixed on a survey tripod, and the telescope with a Go-Pro™ camera was mounted at the top of the rod. The rod and camera attached was able to rotate (Figure 3.7). The target could be seen using a Wi-Fi device such as smart phone or tablet using the Wi-Fi system of the Go-Pro™ camera. Unfortunately, however, this technique proved to be very sensitive to vibration for wind and other ambient sources.
3.3.2 Accelerometers for Dynamic Deflection Monitoring

Five accelerometers of model 4630A (Figure 3.8) were used in the sites for deflection monitoring. The triaxial accelerometers were cubical in shape with dimension of 25.4 mm. The dynamic range of the accelerometers was \( \pm 2\text{g} \) to \( \pm 100\text{g} \) with an operating temperature of \(-55^\circ\text{C}\) to \(125^\circ\text{C}\). Data from the accelerometers were collected at a sampling interval of \(1 \times 10^{-3}\) sec (1000 Hz). The accelerometers were glued on the concrete tie (i.e., sleeper) to measure the deflection. Figure 3.9 shows the orientation of the accelerometer on the sleeper.
As shown in Figure 3.9, the Z axis was oriented along the vertical direction, the Y axis was parallel to the rail and the X axis was perpendicular to the rail. The spacing between the accelerometers were installed using the live load configuration provided by American Railway Engineering and Maintenance-of-Way Association (AREMA) manual (AREMA, 2007) for the train locomotive (Figure 3.10).
In Figure 3.10, the letters A, B and C denote the position of the accelerometers. The maximum axle load was exerted by a locomotive is 75 K (kips). The configuration of accelerometers was chosen in such a way that the maximum load could be recorded by the sensors. Similarly, Figure 3.11 shows the positioning of accelerometers at A, B and C in the sleepers along the light rail line. A similar orientation and positioning was used for the light rail measurements.

The FrontRunner train had three double decker passenger cars, one single decker car and a locomotive as shown in Figure 3.12 (locomotive is shown at far left of photo). The
train is southbound in this case and is enroute to Provo, Utah. The light train had two cars as shown in Figure 3.13.

![Train Image](image1)
Figure 3.12. Front runner heading towards south on the route with three double deck cars, one single deck car and a locomotive

![Train Image](image2)
Figure 3.13. Light rail heading towards the West Valley Central with two passenger cars

Two accelerometers were glued at positions A and B where the maximum axle load would be exerted on the sleeper. A third accelerometer was glued at position C which lied in between A and B. The accelerometers were then connected to the data logger to extract data. The data logger to be used in the instrumentation was CR9000X is shown in Figure
3.14. The basic CR9000X system consists of CR9011 power supply module, a CR9032 CPU module and CR9052DC Anti-Alias Filter Module with DC Excitation.

The filter module connector has a number of channels. Each input channel consists of both regulated constant voltage excitation (VEX) and regulated constant current excitation (IEX) channels. There are five ports for excitation with high voltage input, low voltage input, return and ground. Each accelerometer has five colored wires namely: red, green, white, black and silver and were connected to the five ports on data loggers: excitation (VEX or IEX), high side of the differential voltage input (VIN+), low side of the differential voltage input (VIN-), return (VRTN or IRTN) and ground respectively.
The RTDAQ™ (Real-time Data Acquisition) software was used for the collection of data and was connected to the USB serial port. In RTDAQ, there are three tabs for operation: clock/program, monitor data and collect data. The recorded time in the data logger and pc was synchronized by using the update and check button. The monitor data tab is important for the collection of data. It consists of a ports and flags window. In this window, the flag should be turned on during collection of data. The green light on flag denotes the flag is turned on. Once the train approached the embankment, the flag was turned on. Shortly after the train passed through the embankment array, this flag was turned off.

The data between time of flag being turned on and being turned off was recorded. The collection data tab was used for data collection. In this tab, there are three collection options: collect mode, file mode and file format. All the data options were used in the collect mode. In the file mode and file format, append to end of file and ASCII table data were selected. The start collection tab was used for the collection of data.

After data collection, the next step consisted of the analysis of the field accelerometer data. This was done using the commercially available software SeismoSignal™. This software has filtering and baseline correction routines which can be used to convert the input acceleration time history to velocity and displacement time histories.

The collected data was impacted by high frequency noise (i.e., vibration) which created spurious baseline errors. Therefore, the baseline correction and frequency filtering features of this software were employed to re-baseline the measurements and to remove unwanted high frequency signal. The available baseline corrections methods were: constant, linear, quadratic and cubic. For this study, the linear baseline correction function was chosen.
because it provided the most reasonable adjustment to the trend in the data. After completing the base line correction, Fourier and power spectra were plotted for each of the train events. The Fourier amplitude spectrum shows the distribution of amplitude of motion with frequency and the power spectrum reveals the power spectral density with respect to frequency. The frequency band for filtering was determined based on plots of the Fourier and power spectrum (Figure 3.16). These plots suggest that much of the signal above about 60 Hz is high frequency noise from vibration, which is not of interest for estimating the deflection of the rail from the moving train.

In addition, the SeismoSignal™ software has four types of filter configurations: lowpass, highpass, bandpass and bandstop. For the creation of the filter configurations, three filter types are available: Butterworth, Chebyshev and Bessel filters. In this study, a Butterworth filter type was used which featured a flat response in the pass band. The Bandpass filtering configuration was applied in the study which allows signals to pass through the given frequency range. The lower frequency in the Bandpass was chosen to be large (10 seconds) based on the time required during the passage of the train and the high frequency was selected based on the frequency and power spectrum plots (Figure 3.16). The baseline corrected and filtered time series provides records of the acceleration, velocity and displacement time history of the rail ties. The vertical displacement of the tie was used to estimate the vertical deflection of the rail because there little opportunity for relative vertical movement between the rail and the rail ties.
3.4 Results from Field Measurements

3.4.1 Optical Technique

The results from the test of the laboratory optical technique matched well with the MTS results. This proved that the optical technique, as developed, was able to give reliable results in controlled conditions. However, subsequently this technique was not deployed in the field due to field geometrical constraints and weather conditions. The technique so developed for the field did not perform to its fullest capacity because the study site was windy during the field testing. In addition, it was not possible to gain additional access to the site at a later date when more favorable weather conditions might have prevailed due to the time limits placed on the deflection monitoring by the UTA track access permit. Therefore, the technique was not used for field measurements at the Corner Canyon site.

Nonetheless, the developed technique and algorithm may be useful for future projects or for laboratory measurements for cases where the ambient conditions are more favorable. In short, the optical technique presents a very low cost alternative when compared with the expense required to deploy an accelerometer array and its corresponding high-speed data acquisition system; hence because of this, the optical technique merits further consideration and development.

3.4.2 Accelerometer Array

The orientation of the accelerometers and their locations are shown in Figures 3.9 and 3.11. The possible influence that filtering might have on the vertical displacement results was studied by using various values for the upper frequency of the band pass filter. The estimated displacement time history corresponding to an upper band pass frequency of 30, 60 and 90 Hz are shown in Figure 3.15. This parametric change revealed that the selected
displacement record was not significantly altered by the selection of the high frequency for the band pass filter.

The displacement results from the accelerometers positioned at points A, B and C in the EPS embankments for the along commuter rail line and light rail lines are described separately in the following sections.

3.4.2.1 Commuter Rail Line

The Fourier amplitude and power spectra of the recorded data from accelerometers positioned at A, B and C were analyzed in order to finalize the filtering process and to select the upper frequency in the band pass filtering. The Fourier amplitude and power spectrum of A, B and C positions are shown in Figures 3.16, 3.17 and 3.18, respectively.

![Figure 3.15. Vertical displacement record using different levels for the upper frequency in the Bandpass filter](image)
Figure 3.16. The record of accelerometer at position A along commuter rail line
(a) Fourier amplitude and (b) Power spectrum
Figure 3.17. The record of accelerometer at position B along commuter rail line
(a) Fourier amplitude and (b) Power spectrum
Figure 3.18. The record of accelerometer at position C along commuter rail line
(a) Fourier amplitude and (b) Power spectrum
Based on these plots, it was concluded that the average value of frequency beyond which significant noise started was about 70 Hz in both the Fourier amplitude and power spectra. Thus, the highest upper frequency for the band pass filter to selected to be 70 Hz. The time taken for trains to pass the sensors was less than 10 sec and the lowest level of frequency to be considered was 0.1 Hz.

The train bound to Salt Lake City from Provo will be referred to as the north bound (NB) train, and that bound from Salt Lake to Provo will be referred to as the south bound (SB) train hereafter. The train shown in Figure 3.10 was a SB train. In the study, three NB trains named 1, 2 and 3 were monitored for estimating the vertical deflection of rail atop EPS embankment. Three NB trains were named 4, 5 and 6 were monitored for the determination of vertical deflection of rail atop earthen embankment. The accelerometers were placed on the sleepers adjacent to the NB train track; whereas the SB train track was located 1.5 m distance from the position of the accelerometers. The NB trains were used for measuring vertical deflection because the vertical stress on embankments was assumed to be higher under the NB train track due to the placement of the accelerometers directly on this track. However, one NB and one SB train were monitored to compare the results in terms of the vertical deflections.

The input acceleration and the vertical displacement of three trains on EPS embankment are shown in Figures 3.19, 3.20 and 3.21. Figure 3.19 reveals the input acceleration and the vertical displacement measured by the accelerometer at position A due to trains 1, 2 and 3. In Figure 3.19, a somewhat higher peak displacement occurred at the beginning of the record when the train had just entered over the EPS embankment at about 8 seconds of elapsed time. The maximum displacement for this spike was found to be 6
mm. However, a typical average displacement of about 2 mm was observed for many of the deflection events (Figure 3.20 and 3.21).
Figure 3.19. The record of accelerometer position at A of EPS embankment along commuter rail line (a) Input acceleration and (b) Vertical displacement.

(a)

(b)
Figure 3.20. The record of accelerometer position at B of EPS embankment along commuter rail line (a) Input acceleration and (b) Vertical displacement
Figure 3.21. The record of accelerometer position at C of EPS embankment along commuter rail line (a) Input acceleration and (b) Vertical displacement

Figure 3.20 shows the input acceleration and vertical displacement of the EPS embankment recorded at position B for trains 1, 2 and 3. The third train produced acceleration spike once it had left the EPS portion of the embankment. The maximum and average displacement were found to be around 4 mm and 2 mm, respectively.

Figure 3.21 shows the input acceleration and vertical displacement of EPS embankment measured by an accelerometer at position C for trains 1, 2 and 3. Figure 3.18 shows the maximum and maximum average vertical displacement of EPS were around 4 mm and 2 mm, respectively. The second train produced a spike at the end when it crossed the embankment. The combined accelerometer records for positions A, B and C for trains 1, 2 and 3 are shown in Figure 3.22. These records show that the maximum and average vertical displacement were around 6 mm and 2 mm, respectively. These vertical displacement results are similar to those measured on sleepers for an earthen embankment railway track using geophones by Bowness et al. (2007). These authors report a maximum and average displacement of around 6 mm and 3.5 mm.

For one event, two trains passed over the EPS embankment array simultaneously, one in the NB direction and one in the SB direction. The displacement was monitored for this event. In this analysis, the record of NB train and SB train was denoted by AN and AS for the accelerometer position at location A. Similar notations were used for accelerometers positioned at B and C. The input acceleration of both trains while passing the array is shown in Figure 3.23. The analysis was done separately for each of the accelerometers and trains.
Comparative plots of the input acceleration and vertical displacements of the EPS embankment recorded by accelerometers A, B and C are shown in Figures 3.24, 3.25 and 3.26, respectively.

Figure 3.22. Vertical displacement recorded by accelerometers at positions A, B and C for trains 1, 2 and 3 in the EPS embankment along commuter rail line
These figures show that the maximum and average vertical displacements for the NB train are about 4 mm and 1.5 mm, respectively; whereas about 1 mm and 0.75 mm was recorded for the SB train, respectively. The lower values for the SB train was due to its greater distance from the position of the accelerometer array placed on the NB rail.

The input acceleration and vertical displacements for three train events named as 4, 5 and 6 on the adjacent earthen embankments are shown in Figures 3.27, 3.28 and 3.29, respectively. Figure 3.27 shows the maximum displacement occurred when the train 4 just entered this portion of the embankment. There was an initial displacement spike at the beginning of this passing, followed by lower displacements a few seconds afterward. The maximum and maximum average displacements were about 12 mm and 3 mm, respectively for the earthen embankment.
Figure 3.28 shows the maximum displacement occurred when trains 5 and 6 just arrived on the earthen portion of the embankment. The maximum and average displacements were around 13 mm and 5 mm, respectively.

A high displacement event occurred when train 6 entered onto the earthen embankment. Figure 3.29 shows a maximum and average displacement of around 22 mm and 5 mm, respectively. The combined displacement results for records at positions A, B and C for trains 4, 5 and 6 are shown in Figure 3.30. This combined plot shows a maximum vertical displacement and maximum average vertical displacement of about 22 mm and 7.5 mm, respectively. These results are higher than those reported by Bowness et al. (2007) for earthen embankment. The difference in results might be due to differences in the embankment materials, construction, geometry, train loads, and from experimental error.

In summary, the maximum and average vertical displacements for the earthen embankment were found to be higher than those of the EPS embankment. The measurements suggest that EPS embankment, as constructed at this site, is performing as well as, or slightly better that the earthen embankment in terms of rail deflections.
Figure 3.24. The comparative plot of record on EPS embankment by accelerometer at position A (a) Input acceleration and (b) Vertical displacement
Figure 3.25. The comparative plot of record on EPS embankment by accelerometer at position B (a) Input acceleration and (b) Vertical displacement.
Figure 3.26. The comparative plot of record on EPS embankment by accelerometer at position C (a) Input acceleration and (b) Vertical displacement
Figure 3.27. The record of accelerometer position at A of earthen embankment along commuter rail line (a) Input acceleration and (b) Vertical displacement
Figure 3.28. The record of accelerometer position at B of earthen embankment along commuter rail line (a) Input acceleration and (b) Vertical displacement.
Figure 3.29. The record of accelerometer position at C of earthen embankment along commuter rail line (a) Input acceleration and (b) Vertical displacement
Figure 3.30. Vertical displacement recorded by accelerometers at positions A, B and C for trains 4, 5 and 6 in the earthen embankment along commuter rail line

3.4.2.2 Light Rail Line Array

The Fourier amplitude and power spectrum for the A, B and C positions are shown in Figures 3.31, 3.32 and 3.33, respectively, for the UTA light rail system (i.e., TRAX). The average frequency beyond which significant noise started was about 80 Hz for both Fourier amplitude and power spectrum. Thus, the highest frequency considered in the data interpretation was 80 Hz. The time taken for trains to pass the sensors was less than 10 sec and the lowest level of frequency to be considered was 0.1 Hz.
Figure 3.31. The record of accelerometer at position A along light rail line
(a) Fourier amplitude and (b) Power spectrum
Figure 3.32. The record of accelerometer at position B along light rail line
(a) Fourier amplitude and (b) Power spectrum
Figure 3.33. The record of accelerometer at position C along light rail line
(a) Fourier amplitude and (b) Power spectrum
The westbound (WB) train bound to West Valley Central Station from Salt Lake City International Airport was monitored for this study. The train from the West Valley Central Station to Airport will be referred to as the east bound (EB) train hereafter. The train shown in Figure 3.13 is the WB train. In this study, five WB trains named as 1, 2, 3, 4 and 5 were monitored for the determination of the vertical deflection of concrete rail ties (i.e., sleepers) constructed atop a large EPS embankment. The WB train were selected for the monitoring and the accelerometers were placed on the sleepers for the WB rail. At this location, the EB track was about 1.5 m distance from the position of the accelerometers on the WB rail.

The acceleration time histories and the vertical displacement of five trains traveling on the EPS embankment are shown in Figures 3.34, 3.35 and 3.36. Figure 3.34 shows the input acceleration and the vertical displacements estimated by the accelerometer at position A due to trains 1, 2, 3, 4 and 5. The process of converting the acceleration time history to displacement was the same as that used for the FrontRunner system, discussed previously, except the upper frequency for the band pass filter was set to 80 Hz. In Figure 3.34, the maximum displacement was estimated to be about 0.6 mm. Figure 3.35 shows the input acceleration and vertical displacement of the EPS embankment recorded for the position of accelerometer at B for trains 1, 2, 3, 4 and 5. The maximum displacement was about 0.5 mm. Figure 3.36 shows the input acceleration and vertical displacement of the EPS embankment measured by accelerometer at position C for trains 1, 2, 3, 4 and 5. Figure 3.34 shows the maximum vertical displacement of EPS was about 0.7 mm.

The records on accelerometers at positions A, B and C for trains 1, 2, 3, 4 and 5 show the average vertical displacements were about 0.6 mm. This value is approximately 4 times
smaller than the maximum average vertical displacements that occurred in EPS embankment along the FrontRunner commuter rail line.
Figure 3.34. The record of accelerometer position at A of EPS embankment along light rail line (a) Input acceleration and (b) Vertical displacement
Figure 3.35. The record of accelerometer position at B of EPS embankment along light rail line (a) Input acceleration and (b) Vertical displacement
Figure 3.36. The record of accelerometer position at C of EPS embankment along light rail line (a) Input acceleration and (b) Vertical displacement

3.5 Conclusions

The FrontRunner commuter rail south line extends from Salt Lake City to Provo, Utah. UTA used EPS in the embankments along this line at Corner Canyon in Draper, Utah in order to minimize the vertical stress and subsequent consolidation settlement of the foundation soils underlying a concrete box culvert. This site was selected in this study to monitor the dynamic rail deflection because the site has both EPS geofoam and earthen embankments. Similarly, the light rail green line at River Trail was selected to monitor dynamic deflection. Accelerometer arrays were deployed to measure the acceleration time histories of several trains passing through this area. Subsequently, these time histories were baseline corrected and filtered to produce estimates of the displacement time history.
In addition, a low cost optical technique for vertical deflection measurement was developed. The method was used to measure the deflection in the laboratory and the deflection was compared with LVDT results. The percentage difference of results from these two methods was around 2 percent. However, this method had some limitations in the field. Wind, elevation of site and vibration from trains were major constraints for obtaining accurate results; hence the optical technique was not successfully used to obtain field estimates of deflection. However, this method may still prove to be applicable for laboratory use, or for situations where the conditions for field deployment are more favorable.

Results from the accelerometer array show the maximum and average displacements for the sleepers positioned on the EPS embankment was about 6 mm and 2 mm, respectively for the FrontRunner system. The same system constructed on earthen embankment underwent a maximum and average displacement of 22 mm and 7.5 mm, respectively. Therefore, the average displacement occurring on the EPS embankment was about 25 percent of that incurred by the earthen embankment.

The average value of the vertical displacements occurring atop the EPS embankment for the light rail (i.e., TRAX) line were about 0.6 mm. This average value is almost four times smaller than the average displacement value measured for the FrontRunner system. This suggest that deflections of rail systems on EPS embankments is relatively small and has a similar or better performance than that of earthen embankments.
3.6 References


