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TECHNICAL NOTE

Integrated Subsurface Investigation of the Misaligned Reinforced Soil Retaining Wall

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Abstract The paper presents an integrated approach in subsurface investigation of the existing geotechnical structure using ground penetrating radar (GPR), seismic survey and by drilling a limited number of boreholes. These methods are used to investigate the RE wall, which is a part of the rail over bridge (ROB) on the National Highway. Information about the detailed survey, testing procedure and data analysis are presented in this paper. Geophysical investigation using GPR and Multichannel Analysis of Surface Waves (seismic survey) and a borehole test were carried out without disturbing the traffic flow and structure. Compaction quality, homogeneity of soil layers, static and dynamic properties of the backfill materials and foundation soil have been determined from the geotechnical and geophysical tests. The results obtained from the study are used to comprehend the reason for the misalignment of RE wall (present position). The study shows that integrated subsurface exploration can be used to assess the geotechnical structure's integrity, properties, and also to understand its performance under static and dynamic loading.

Keywords Subsurface investigation · GPR · Seismic survey · Material properties · Performance

Introduction

Estimation of geotechnical properties of the existing geotechnical structure plays a vital role in performance assessment studies. Assessment of properties of the geotechnical structure requires detailed subsurface investigation without disturbing its integrity and utilities. The widely used investigation methods for geotechnical structural assessment are geological methods, geotechnical methods and geophysical methods. The popular geotechnical methods are standard penetration test (SPT), dilatometer test (DMT), pressure meter test and seismic cone penetration test (SCPT); among these SPT is widely used. Multichannel analysis of surface wave (MASW) is a surface wave method that is commonly used for geophysical applications. Even though SPT and 1-D surface wave methods can provide information on the dynamic properties of soil, they are point/average informations. These tests have limited capability to measure the spatial variation of subsurface properties on the site. Ground penetrating radar (GPR) can be used to map the spatial variability and to study the hidden anomalies/deviations below the surface. In this study, these three methods were used to investigate the existing geotechnical structure and to estimate the properties of the structure for performance assessment. This paper, presents a brief summary of the integrated subsurface investigation methods viz. SPT, MASW and GPR and application of these tests for the investigation of misaligned RE wall.

A recently constructed rail over bridge (ROB) RE wall is out of plumb along the vertical direction at a specific segment. Vehicles are moving on the road over bridge which includes the misaligned RE wall section. In order to check the performance of the RE wall section against static and dynamic loads, an attempt has been made in this study to estimate the subsurface properties and its spatial variation using integrated subsurface investigation. A detailed study has been carried out using GPR, MASW and SPT testing. The results are used to understand the spatial variation of the subsurface layer thickness, strength and

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presence of reinforcement of RE wall. Investigation results are used to understand the possible reason for the distress in the form of the wall misalignment.

Integrated Subsurface Investigation

National Highway Authority of India (NHAI) noted that RE wall which is a part of the ROB located on the National Highway 7 is not perfectly vertical and it is out of plumb by 210 mm inwards. The position of misalignment and ROB are shown in Fig. 1. The vertical alignment of the RE wall stretches approximately 49 m in length (on one side) and is found to be out of tolerance (allowable is 12.5 mm per 3 m height) over a distance of 40 m in the RE wall. The misaligned part was predominantly noticed at about 2/3rd the height (at 6.5 m from ground level) and observed at a maximum offset of 210 mm inwards. It was also observed that beyond an inward movement, there is an outward alignment of correcting action with an offset of 50 mm. Figure 2a shows inward and outward movement of the RE wall portion and schematic sketch is shown in Fig. 2b. To minimize the physical damage in the structure, integrated subsurface exploration has been attempted in this study. Integrated subsurface exploration combines many geophysical and geotechnical testing with the least amount of disturbance to the structure. In this study, GPR has been used to identify the subsurface condition of the soil, reinforcement in the RE wall sections and homogeneity of the layers. Surface wave method of MASW is used to measure the shear wave velocity of the RE wall section. The SPT result is used to get subsurface material type and depth, to compare with MASW result and also to get in situ density.

Integrated investigation using SPT, MASW and GPR has been adopted to assess the condition of RE wall section. Two boreholes were drilled in such a way that it does not affect the intactness of the ROB roads in between RE walls. First borehole (BH1) was drilled at the ground level close to the misaligned RE wall section to know the foundation soil properties. Second borehole (BH2) was drilled at the top of RE wall and the centre of the road, i.e., median such that no reinforcement was affected due to this investigation. Both the tests were carried out as per the SPT procedures. Figure 3 shows a plan view of RE wall and SPT test locations. The boreholes were drilled with a diameter of 150 mm as per IS:1892 [1] and N-SPT values were measured regularly at 1.5 m interval as per IS: 2131 [2]. Disturbed and undisturbed samples were collected at possible depths as per IS:2132 [3]. Data on SPT N values, depth of sample collection and soil type identification, etc., were logged during field tests. Both the boreholes were drilled up to refusal i.e. SPT N value is more than 50 for 15 cm penetration. Refusal stratum at 6.0 m depth in BH1 and 9.0 m depth in BH2 containing hard rock pieces. The borelog (BH2) data on the top of the RE wall is shown in Fig. 4. The physical properties were measured in the laboratory using disturbed soil samples as per IS:1498 [4] and used for soil classification.

Borehole gives subsurface information on only drilled locations. In order to measure the average Young's modulus and shear modulus for performance analysis, the seismic surface wave survey of MASW was carried out. Four MASW surveys were carried out i.e., three at the top of RE wall and one close to the foundation of RE wall. Figure 3 shows the location of the MASW on the site. MASW system consisting of 24 channels Geode seismograph with 24 geophones of 4.5 Hz capacity are used in this investigation. The seismic waves were created by impulsive source of sledgehammer weighing 15 pounds with 300 mm × 300 mm size hammer plate with ten shots. These waves are captured by the vertical geophones/receivers and further analyzed by inversion. Twenty-four geophones were arranged linearly and the sources were kept on one side of the MASW line. Geophone spacing of 1 m and source distance of 4, 8 and 12 m were being used. In order to enhance the signal to noise ratio, movement of vehicles on the roads on ROB was completely stopped during MASW recording period. Surface wave records were used to extract dispersion curve and to estimate the shear wave velocity. A dispersion curve is generally displayed as a function of phase velocity versus frequency. The phase velocity is calculated from the linear slope of each component on the swept frequency record. A typical dispersion curve is shown in the Fig. 5. Each dispersion curve obtained for corresponding locations had a very high signal to noise ratio of about 80 and above. The SWV profile was calculated by an iterative inversion process that requires the input of the dispersion curve developed earlier.

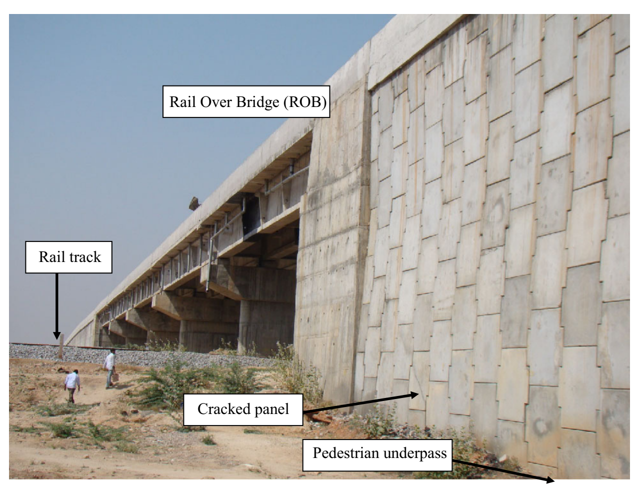


Fig. 1 Misalignment of the reinforced earth wall close to the rail over bridge

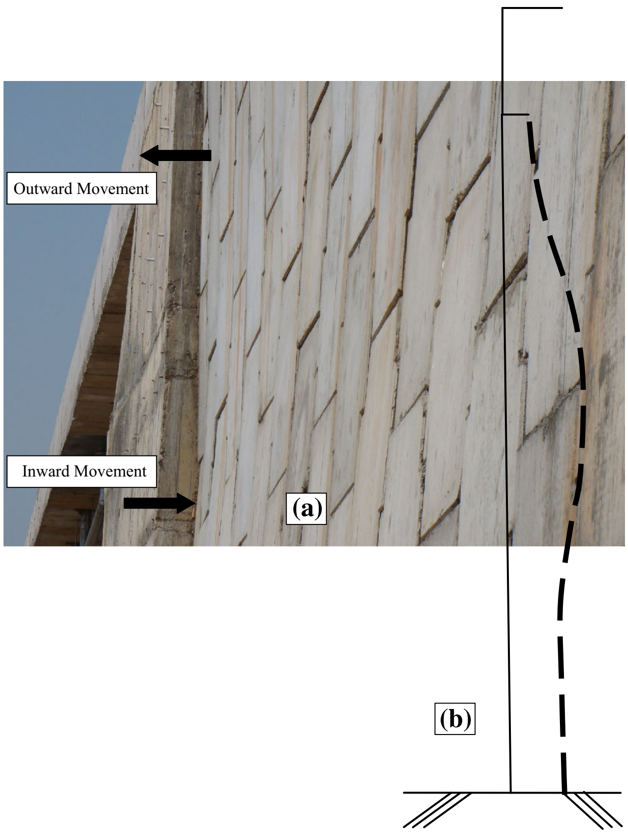


Fig. 2 Inward and outward movement of misalignment of the reinforced earth wall **a** Photo and **b** Schematic line diagram

A typical model of shear wave velocity and an actual dispersion curve associated with the Rayleigh wave is shown in the Fig. 6.

Ground Penetrating Radar (GPR) Survey

GPR is an electromagnetic pulse reflection method based on physical principles similar to those of reflection seismic surveys. Ground Penetration Radar is an electromagnetic reflection method in which an electromagnetic signal is emitted via an emitter in the form of a built in antenna into the structure under inspection. The emitted waves are reflected due to changes in material properties in sub-structures, which will be received by a receiver inbuilt in the antenna. This wave is recorded in the control unit, displayed in monitor and further analyzed in the computer. Frequency of emitted and received electromagnetic waves plays an important role in resolution and depth of information. Using high frequency antennas results in high resolution data, but reduces the depth of penetration. Low frequency antennas provide greater depth of penetration at the expense of lower resolution. Electromagnetic waves received from layers can be utilized to estimate dielectric properties of subsurface layers, which is very important for different non-destructive evaluation techniques. Dielectric properties are usually influenced by the volumetric properties of the subsurface layers. The electric permittivity (dielectric constant) ‘ε’ and the electric conductivity ‘σ’ are Petro physical parameters which determine the reflectivity of layer boundaries and penetration depth. GPR is a well-established non-destructive method for investigating the internal composition of many naturally occurring materials such as rocks, earth and gravel, and man-made materials like concrete, brick and asphalt. It can also be used to detect metallic and non-metallic pipes, sewers, cables, cable ducts, voids, foundations, reinforcing rods in concrete, and a whole host of other buried objects [5].

GPR is applied in a wide range of geotechnical engineering surveys as a non-invasive method, to explore the hidden underground patterns and discontinuities. Application of GPR for subsurface soil survey investigations was first demonstrated in Florida by Benson and Glaccum [6] and Johnson et al. [7]. Since then, many GPR soil surveys were performed to validate the method and to increase the efficiency and the frequency of observations, to extend the depth of observation [8]. GPR is being used to study the presence, depth, and lateral extent of each subsurface soil layers and is further used to classify soils. The abrupt boundaries due to a contrast of overlying soil in physical (texture, bulk density, moisture) and chemical (organic carbon, calcium carbonate, sesquioxide contents) properties are helping in producing strong reflections at interfaces and recognizable GPR imagery [9]. Geotechnical testing of SPT and geophysical methods of MASW and GPR is widely used independently in several geotechnical subsurface explorations and forensic geotechnical investigations. However, very limited studies have used the above methods together to obtain subsurface data for the performance assessment of geotechnical structures. The next section describes SPT, MASW and GPR testing in the geotechnical structure of RE wall.

GPR study has been carried out to image the homogeneity of soil layers in-between RE wall. An initial GPR survey is carried out in order to calibrate GPR setting so as to penetrate the required depth by a few trial surveys. Survey parameters are frozen for the clear waveform signature with a penetration depth of 2.5 m for 500 MHz, 10 m depth for 100 MHz and 15 m for 25 MHz antenna. GPR survey was carried out parallel to the RE wall and perpendicular to the RE walls. All three antennas are used in the same locations to get a radargram of the subsurface. Figure 3 shows the GPR survey location and line numbers for different antennas. Recorded GPR waveform data were processed and used to get radargram. The raw data were processed using data processing steps. The aim of this

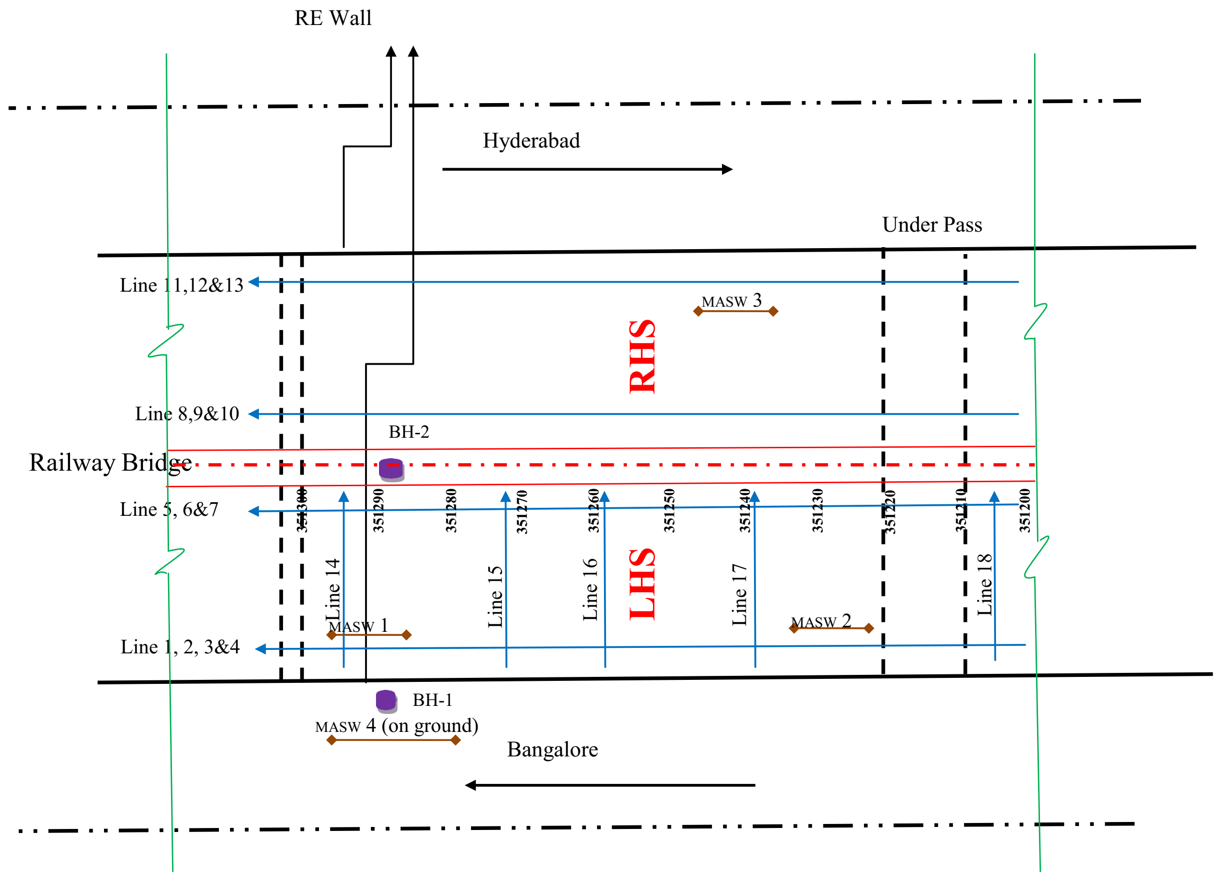
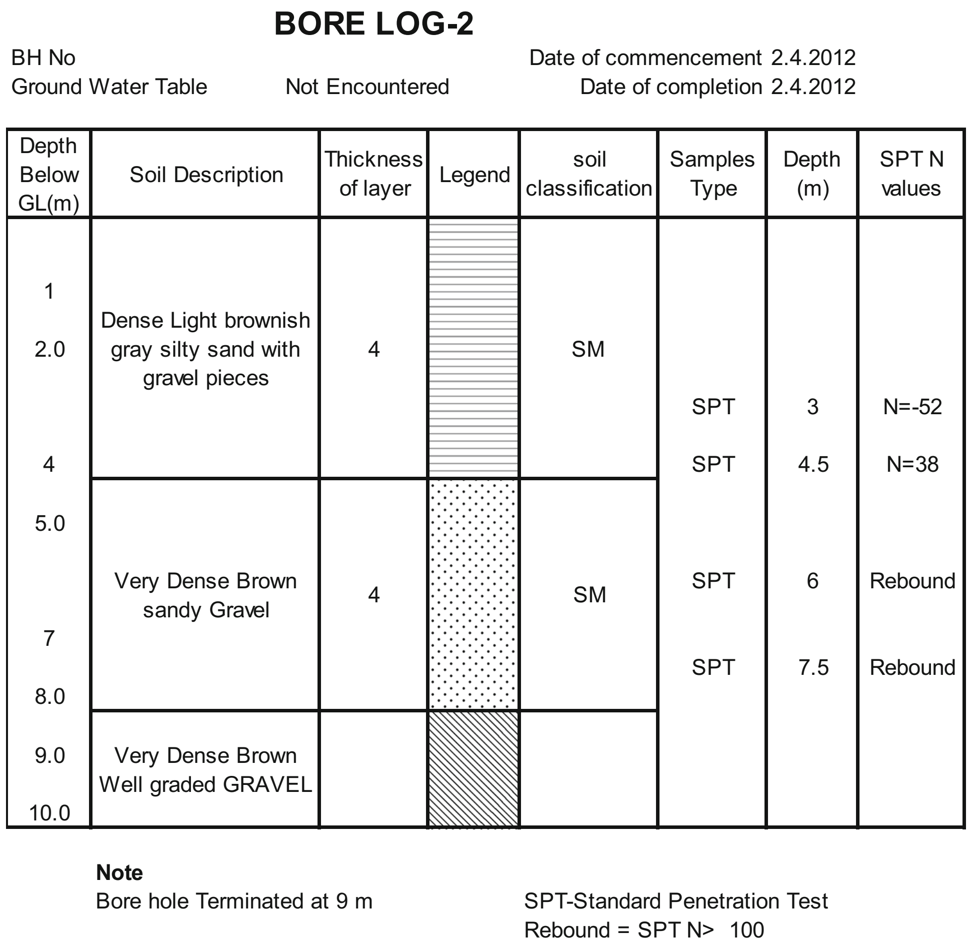


Fig. 3 MASW, GPR and SPT test locations in misaligned RE wall. *Line* 1,5,8, and 11 are taken with 25 MHz GPR antenna; *Line* 2,3,6,9,12,14,15,16,17 and 18 are taken with 100 MHz GPR antenna; *Line* 4,7,10 and 13 are taken with 500 MHz GPR antenna

processing is to enhance signal–noise ratio, highlight interfaces and radargram textures. The processing includes a band pass filtering, DC removal, subtract mean trace and gain control. Only very fundamental filters are applied to the raw data to avoid introducing artificial textures into the radargram. Wave character/radargram image quality depends mainly on the dielectric properties of the materials which is a function of density, moisture content and porosity. Typical GPR radargram obtained from 500 MHz is shown in Fig. 7 with the non-uniform layer may be due to variation of moisture/density/porosity. Detailed interpretation of the GPR data and final recommendations of soil properties are given in the next section.

Discussion of MASW and Borehole Results

This section presents selected results of two boreholes and four MASW surveys. Borehole 1 shows that all layers have SPT N values of more than 100, which reveals that the RE wall foundation is placed on the firm ground; also no weak or loose layer was noticed and soil density increases with increasing depth at the drilled location. The BH2 shows that up to 4 m, sandy silt with gravel pieces with SPT N values of 38–52, and for 4–8.0 m, similar materials with SPT N values of more than 100 and beyond 8.0 well graded gravel were noticed. Borehole was terminated at 9.0 m depth due to the presence of very dense material and stones. It can be noticed here in Fig. 4 that top layers are denser than layer at 4.5 m where SPT N value is 38. This borehole result is compared with typical shear wave velocity from top of RE wall as shown in Fig. 6. Pavement and soil layers in between RE walls have dense surface layers (pavement and subgrade) with the shear wave velocity of more than 360 m/s and is followed by medium dense layers (compacted soil) with lowest shear wave velocity being 195 m/s. Lower shear wave velocity is observed in the 1-D MASW survey close to railway bridge abutment. These values are noticed soon after the pavement layers and extend to more than 6 m from surface. After 6.0 m, shear wave velocities are increasing with depth (See Fig. 6). Shear wave velocity (SWV) profile



BORE LOG-2

BH No — Date of commencement 2.4.2012

Ground Water Table — Not Encountered — Date of completion 2.4.2012

Depth Below GL(m)	Soil Description	Thickness of layer	Legend	soil classification	Samples Type	Depth (m)	SPT N values
1	Dense Light brownish gray silty sand with gravel pieces	4		SM			
2.0							
					SPT	3	N=-52
4					SPT	4.5	N=38
5.0	Very Dense Brown sandy Gravel	4		SM			
					SPT	6	Rebound
7							
					SPT	7.5	Rebound
8.0							
9.0	Very Dense Brown Well graded GRAVEL						
10.0							

Note

Bore hole Terminated at 9 m

SPT-Standard Penetration Test

Rebound = SPT N> 100

Fig. 4 Borelog of borehole drilled in the middle of the RE wall section

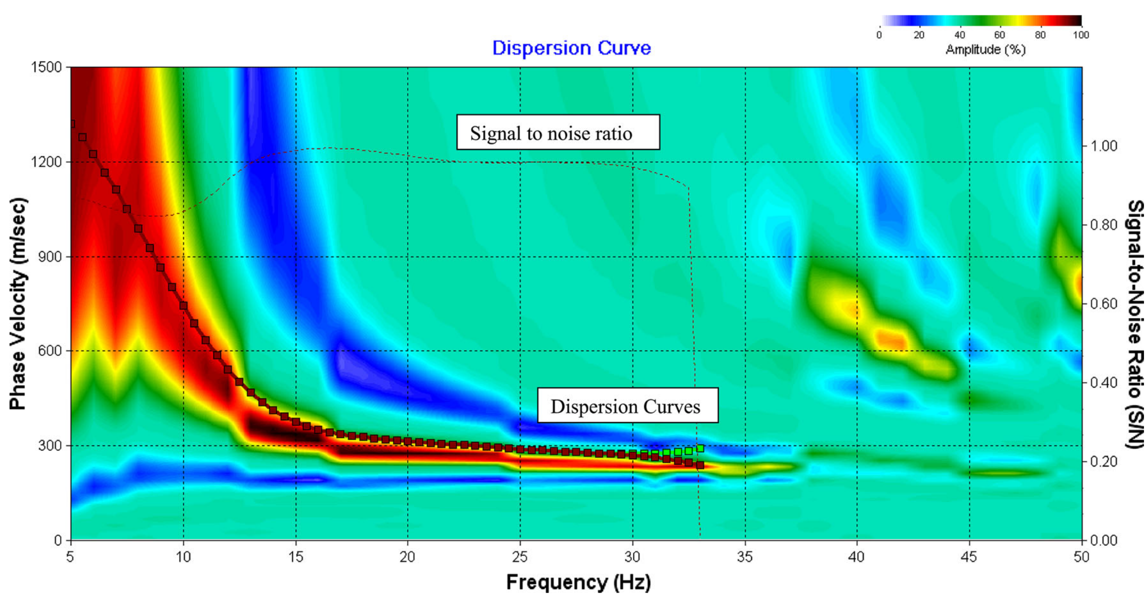


Fig. 5 Typical dispersion curve of the compacted embankment at the ROB

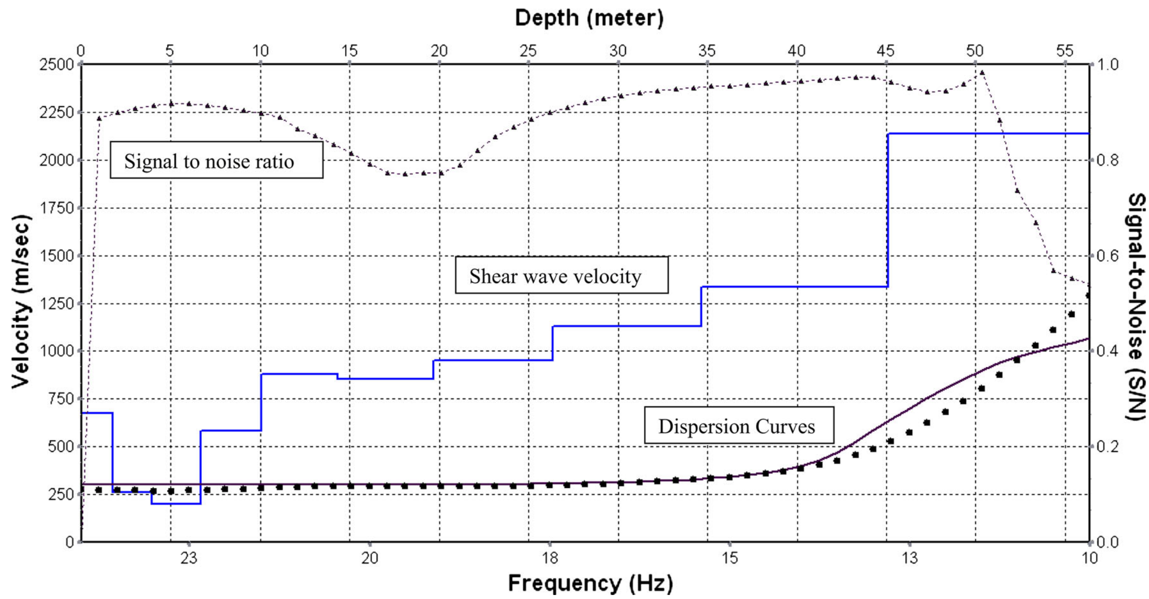


Fig. 6 Typical shear wave velocity profile for the embankment of soil layers

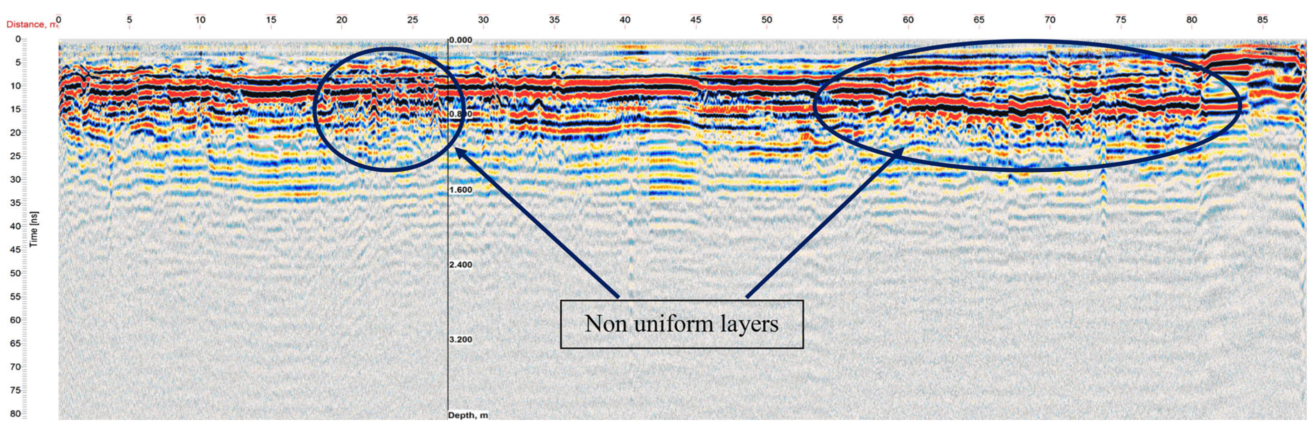


Fig. 7 Typical GPR result using 500 MHz antenna along the road (parallel to RE wall)

from MASW line 2 is slightly more than MASW line 1 values, i.e., about 5 % for respective layers. SWV from MASW line 3 is about 15 % more than MASW 1. MASW 4 close to borehole 1 shows that layer up to 1.5 m is having SWV of more than 400 m/s indicating very dense layer, 1.5–4.0 m is having SWV of 250–360 m/s indicating dense layer and 4.0–6.0 m is having SWV of 360–550 m/s. After 6.0 m, shear wave velocities are than 760 m/s indicating rock layers. This information matches very well with borehole (BH1) data.

GPR Results and Discussion

In this study, GPR surveys have been carried out at about eighteen locations (see Fig. 3) and the selected results are discussed here. GPR results show the continuous 2-D subsurface information in the form of radargram along survey lines. Top layers of the RE wall were investigated using 500 MHz antenna. Typical GPR radargram up to a depth of 2.5 m is shown in Fig. 7. Figure 7 shows higher resolution radargram for the length of about 10 m and interpretation over a depth of about 1 m. Figure 7 shows non-uniformity in the soil layers within a depth of 1.6 m. Among these, non uniform waveform sections close to Railway Bridge are predominant and also contain randomly spaced hyperbolae. Several hyperbolas are noticed within non-uniform sections close to Railway Bridge, which might be attributed to presence of stone/gravel/rock pieces which are bigger than the materials around. The special processing steps are applied and radargram is generated to interpret soil reinforcement detail, which is shown in Fig. 8. Figure 8 shows continuous

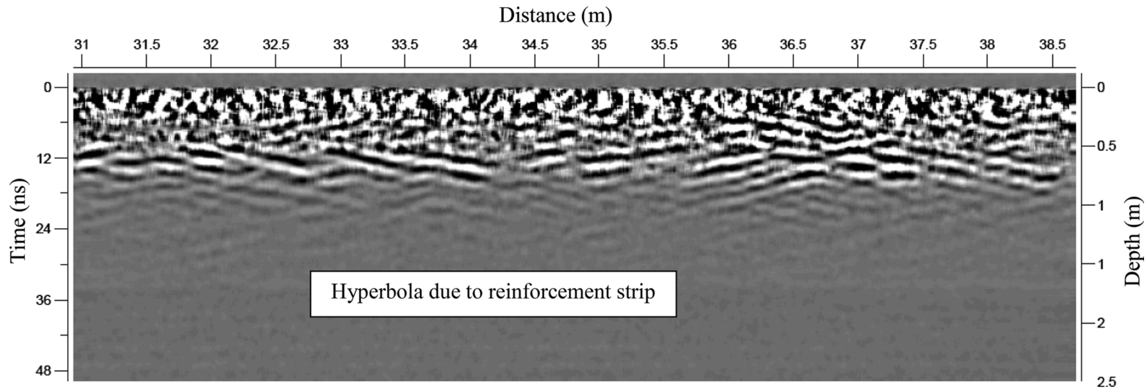


Fig. 8 Typical GPR study results using 500 MHz (Hyperbola at regular interval indicates presence of reinforcement in soil layers)

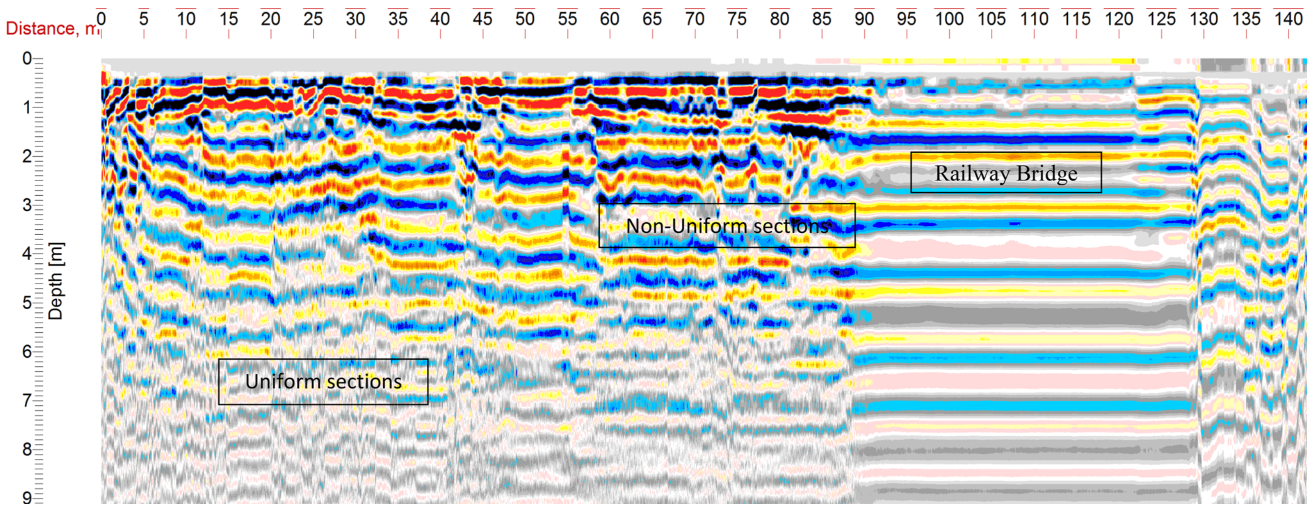


Fig. 9 Typical GPR study results using 100 MHz

hyperbolas at constant intervals below a depth of about 0.55 m. This constant interval hyperbola may be indicative of the reinforcement strip in the soil layers. Figure 9 show radargram of RE wall soil layers using 100 MHz antenna parallel to the RE wall alignment (line 1). 100 MHz antenna radargram also shows non uniform wave forms similar to 500 MHz radargram (Fig. 7) in the misaligned location. Irregular wave forms are noticed for wider distance and at deeper depths close to Railway Bridge. Further, waveforms are recorded perpendicular to the road, i.e. mid of road to RE wall. Radargram across the road is shown in Fig. 10 (between the RE wall to the median of the road). It can be noted that close to RE wall, waveforms are uniform when it approaches the median and the waveforms are slightly distorted with hyperbola pattern. Distorted signals with hyperbola may be due to presence of loosely compacted soil layers with stone/gravel/rock pieces. No hyperbola is noticed in the 100 MHz radargram similar to 500 MHz radargram (Fig. 7), this means that whatever hyperbola is

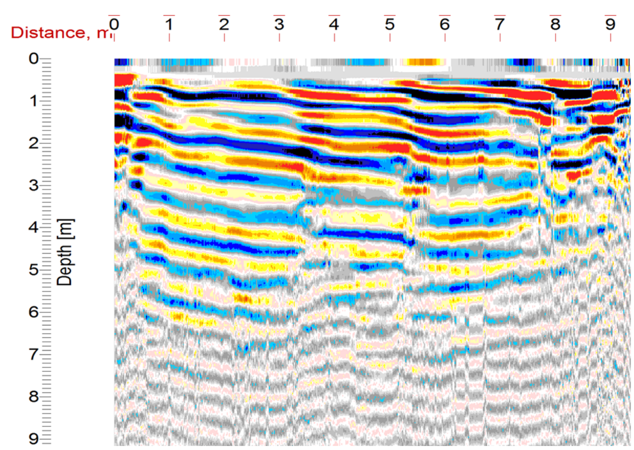


Fig. 10 Typical GPR result using 100 MHz antenna across the road (Perpendicular to RE wall)

noticed in the 500 MHz antenna radargram is due to smaller objects such as stone/gravel/rock pieces and their size may not be larger than 0.5 m. Radargram close to RHS for

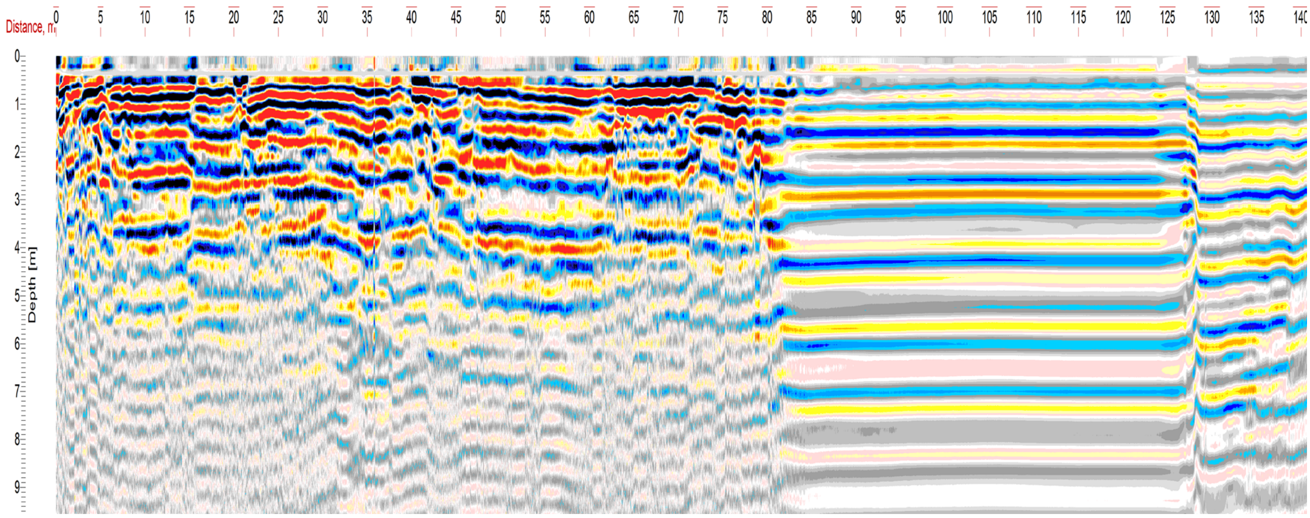


Fig. 11 Typical GPR result using 100 MHz antenna along the road (parallel to RE wall)

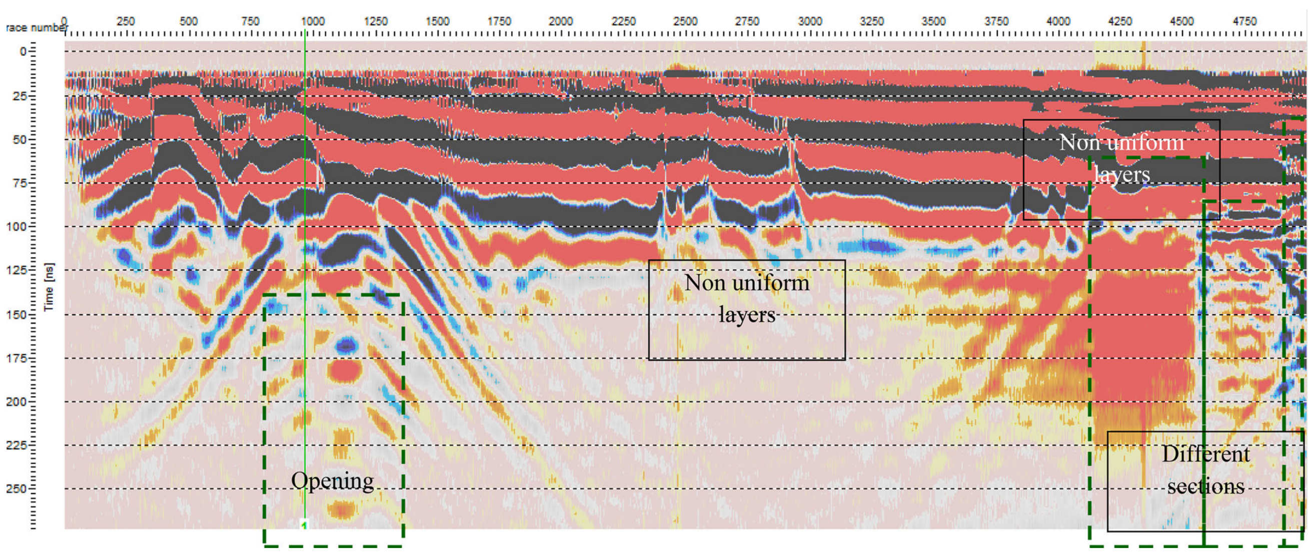


Fig. 12 Typical GPR study results using 25 MHz

line 12 i.e. RE wall without any misalignment is shown in Fig. 11. This radargram shows that soil layers are relatively horizontal and uniform when compared to radargram close to misaligned RE wall section LHS. Figure 12 shows radargram from 25 MHz antenna. Non uniform layers are also noticed in this radargram. Wave reflections and wave form characteristics clearly highlight the presence of the underpass and ROB below road RE wall section and other non-uniform sections. Location of the underpass and ROB below road RE wall in the GPR radargram (Fig. 12) are very well matching with field observation.

From the above discussion, it is clear that compacted soil layers thickness and properties are not uniform throughout the RE wall section; non uniform layers are predominantly noticed close to the misaligned RE wall section. Seismic testing at misaligned location also shows a low shear wave velocity. It can be inferred from the GPR results that the misalignment of RE wall may be due to settlement of the embankment after construction of the wall. This settlement may be attributed by poor compaction close to ROB approach. Pavement and soil layers in-between RE walls has dense surface layers (pavement and

Table 1 Low strain shear and young's modulus for RE

Depth (m)	Vs (m/sec)	Density (kN/m^3)	Shear $\times 10^3$ kN/m^2	Poisson's Ratio	Young's Modulus (E) $\times 10^3$ kN/m^2
0–0.5	675	21.58	1,002	0.30	2,606
0.5–1.75	500	20.60	525	0.30	1,365
1.75–3.9	260	19.62	135	0.30	352
3.9–7	195	15.70	61	0.30	158
>7.0	580	21.00	720	0.30	1,872

subgrade) with the shear wave velocity of more than 360 m/s and followed by medium dense layers (compacted soil) with a lower shear wave velocity of 195 m/s. Lower SWV is observed in the 1-D MASW survey close to railway bridge abutment. These values are noticed soon after the pavement layers and they extend more than 5 m from surface and below that, this velocity is found to be increasing. This result is also comparable with the borelog data and SPT test results. Shear wave velocity of 195 m/s and SPT N value of 38 corresponds to medium dense layer. Shear wave velocity arrived from MASW is used to estimate the shear modulus and young's modulus of embankments and are given in Table 1.

Summary

The paper presents the results and interpretation of integrated geophysical and geotechnical investigation of the misaligned reinforced soil retaining wall. SPT and MASW test were carried out and static and dynamic properties were estimated for the performance analysis of misaligned RE wall. It is noted that SPT N values and Vs are relatively lower, close to the misaligned sections of RE wall. GPR results show a uniform wave pattern in the intact RE wall section and non uniform/scattered wave pattern with hyperbolae close to misaligned RE wall section. GPR scattered wave pattern along misaligned sections are attributed to the post construction settlement of poorly compacted soil layers. Modulus values were also estimated in the misaligned RE wall for the further performance analysis.

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