Determination of soil deformations using gpr under bridge approach slabs

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ABSTRACT

Ground penetrating radar (GPR) is one of the non-destructive technics that provide high-resolution information to a greater depth of soil strata. It works on the principle of reflection/refraction of an electromagnetic wave that occurs when there is a change in dielectric properties of two adjacent layers across a soil boundary, or a material interface. GPR is an effective tool for subsurface inspection and quality control, whose applications are very wide and include locating buried objects, detection of voids or cavities, locating re-bars in concrete slabs and applications in archaeological surveys.

The objective of this study is to determine the subsurface soil deformations under a bridge approach slab using GPR. Multiple GPR surveys were performed over a bridge section on a national highway near Hyderabad. The aim of this study is to detect the layers of low-density soil located at different regions throughout the bridge approach embankment and quantify the volume of road material involved in the settlements. A broad range antenna of 500MHz frequency having highest signal-to-noise ratio has been employed to generate a wave with a controlled velocity of 0.15m/ns. The radargrams were analyzed along with an image processing software to explore the defective ground pockets and soil deformations with a great success. The total volume of soil deformed under the bridge approach slabs were found to be as high as 72 m^3. The qualitative data obtained from the GPR radargrams were verified with the lightweight deflectometer (LWD) data.

INTRODUCTION

Bridge approach slabs are the structures constructed to provide a ramp or a gradual transition between the bridge superstructure and the pavement embankment. The approach slabs are constructed in order to reduce the abrupt bump created at the end of the bridge. The approach slabs along with the approach embankment often tend to settle or heave with respect to the bridge deck. The amount of approach embankment settlement along with various other distresses caused has to be determined to avoid further damage to the service life of the bridge structure. In addition, the bump at the end of the bridge not only leads to damage of the deck but also cause severe inconvenience to the users and responsible for frequent vehicle maintenance. The estimated maintenance cost of bridges with the bump issue sums upto $ 6.3 million per year (2001) in Texas alone in USA and over $100 million in the entire country (Ha et al. 2002). Quantification of the bump or distress is a crucial parameter in retrofitting the structure. There are number of destructive and non-destructive testing (NDT) techniques including profilometers, radar technics etc. available to determine the fault locations in the approach embankment and pavement structure. The NDT methods are generally preferred over the conventional destructive techniques as they are advantageous in evaluation of the subsurface conditions of the structure without causing any damage to the structure (Chen & Scullion, 2006). Ground penetrating radar (GPR), falling weight deflectometer (FWD), profilometers are few such NDT methods employed to check for the subsurface conditions and merging of their test data can be useful for pavement condition assessment (Scullion & Saarenketo, 2000).

The GPR technique applies a short pulse of energy in the form of radio waves into the material from the antenna and the waves are reflected from the materials or layers below to the antenna (Maser, 2000). The arrival time and the amplitude of the reflected waves depend upon the dielectric constants of the materials and the subsurface pavement conditions are evaluated based on these reflected waves (Chen & Wimsatt, 2010). For a typical pavement survey with the ground coupled antenna, the transmitter sends the waves through the layers and a part of the waves are reflected back, when it hits the interface as shown in Fig. 1 and they are recorded as two way travel time and the amplitude of the wave. The thickness of the pavement layers can be determined using the velocity and the two-way travel time of the radar wave through a given layer using Eq. 1.

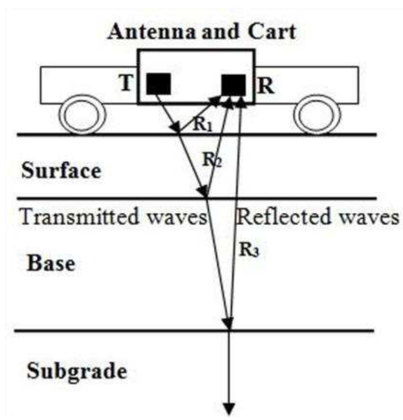

Figure 1. Principle of GPR

$$H = \frac{\Delta t \times c}{2\sqrt{\varepsilon_r}} \qquad (1)$$

Where, H is the layer thickness, c is a speed constant (speed of light in air = 0.3m/ns), Δt is the two-way travel time through the layer i.e. the time difference between the reflected wave (R_1) and the reflected wave (R_2) as seen in Fig. 1 and ε_r is the relative dielectric constant of the material or layer.

BACKGROUND

The NDT methods generally consist of applying electromagnetic radiation, ultrasonic pulse and radio waves to evaluate the condition of the material. NDTs provide instant solution to the problems and due to this reason; they have various applications in the field of concrete structures and pavements.

Among the various non-destructive test methods referred above, various researchers have identified anomalies in the sub-soil structures and pavements have adopted GPR successfully.

According to Miller (1996), GPR is an efficient, precise, non- destructive tool, which is effective in determining the human made subsurface subsidence along with its shape, its precise location and the depth of distress. A void under continuously reinforced plain concrete pavements in an Interstate Highway was identified by Chen and Scullion (2007) using the GPR technology. Besides, Uddin and Hudson (1994) evaluated the performance of various NDT methods like dynamic deflectometer, proof roller, Benkelman beam, GPR, FWD and transient dynamic response (TDR) to determine the voids under concrete pavements and advocated that the GPR technic is most useful in determining the location and extent of the voids precisely. Chen and Wimsatt (2010) have made a similar observation when they detected various anomalies and the presence of moisture in the flexible pavements along with the voids detected using GPR technic.

Besides, Park (2004) and Scullion, and Saarenketo (2000) have advocated that the GPR technic have a potential to evaluate the structural performance of the pavements and FWD to re-estimate the stiffness of the pavements after identifying the distresses. The distress locations estimated using GPR were cross-checked by coring and found that the GPR results correlated well with the cores excavated with an average error of less than 2.5% (Samer and Al-Qadi 2007). Maierhofer (2003) used GPR for the evaluation of the concrete infrastructure, whereas Chen et al. (2007) used GPR to determine the various causes for the failure of bridge embankment with cracked approach slabs. Similarly, Rister and Hopwood (2008) reported the use of GPR to investigate the presence of voids and cracks on the Interstate highway-275 twin bridges over the Ohio river in Kenton county.

The literature suggests that the NDT methods, especially GPR, would provide a clear information about the distresses and their location in various civil engineering projects spanning from pavements to embankments when used with care. To date, the NDT methods were used mostly for qualitative analysis of the projects. However, to quantify these destresses, one needs to compliment the NDT methods with other technics. The objective of this study is to investigate the causes of the soil deformations under a bridge approach slab along National Highway near Hyderabad, India and to quantify the zone of distress and using GPR, LWD and high definition image processing technics.

SITE LOCATION AND GPR SURVEY DETAILS

Severe bridge approach embankment settlements are noticed on either side of a bridge along Hyderabad - Pune highway near Hyderabad, which are causing intolerable discomfort to the users. It is a two span 60m long bridge with 6.0m high approach embankments, crossing a creek, oriented towards East-West directions. To plan on appropriate maintenance activities and remedial measures, it is necessary to understand the problems and accurately estimate the deformed zones of embankment. To avoid any traffic congestions along the highway, non-destructive test methods are proposed to employ to map the distresses. A 100 m long stretch of the embankment has been considered to cover the undisturbed zones of embankment on either side of the bridge deck, zones covering the settled approach slabs and the firm bridge section. It has been physically noticed that the pavement was settled for about 10.0m long on either side of the approach slabs. The Google image of the bridge site and the test sections are presented in Fig. 2, which includes the west side approach embankment (0.0 to 17.0 m), approach slab (17.0 to 21.5 m), bridge deck (21.5 to 78.5 m) and approach slab and embankment portion on the east side (78.5 to 100.0 m). The stretch of the approach slab from 20m to 21.5m rests on the wing wall and the bridge abutment and the remaining length rests over the embankment soil. The bridge deck spans from 21.5m to 78.5m with three expansion joints present at 21.5m, 50m and 78.5m, respectively. The whole stretch is symmetrical about the centrally located expansion joint as shown in Fig. 2. To investigate, identify and quantify the soil deformations in each layer accurately, a series of GPR surveys were conducted on the test stretch using a 500 MHz frequency ground coupled antenna along both directions i.e. west to east and east to west with a radar wave velocity of 0.15m/ns. Along the GPR survey track, lightweight deflectormeter (LWD) tests were also carried out to verify/quantify the in-situ deformation modulus of the test sections. The LWD data would provide the reduced modulus of the deformed stretches. The GPR surveys and LWD tests were repeated for three times to avoid errors in the measurement. Important physical features of the test section viz., start and end points of approach slabs, expansion joints, start and end points of bridge deck were marked on the ground and cross verified during the GRP surveys. These marks as flags can be seen in the radargrams (Fig. 3), which validates the survey data.

ANALYSIS OF RESULTS AND DISCUSSION

The series of radargrams obtained from the GPR surveys are first filtered to minimize the unwanted disturbances and noise caused due to the ringing effect of radar waves. In the current study, background removal, static correction, F-K filter with migration algorithm and linear gain function filters are adopted. Figure 3 presents the typical processed radargram of the test stretch after adopting the appropriate noise filtering techniques. A series of strong kinks noticed in the radargram are due to strong reflection of electro-magnetic waves from the iron sections placed at the expansion joints i.e. at 21.5m, 50m and 78.5m. The bridge deck spanning from 20m to 80m has shown strong reflections compared to the other areas owing to its stiff and dense material nature (Fig. 3). The rebars along the length of the bridge deck can also be visualized in the radargram if an appropriate high frequency antenna (about 1 to 2 GHz) is employed (Ha et al. 2002, Chen and Wimsatt, 2010, Chen and Scullion, 2006). However, the antenna used in this study is a 500 MHz medium range frequency antenna and hence, the rebars could not be traced with high resolution. The depth of the study depends upon the frequency range of the antenna used. Greater the depth of interest, lesser should be the frequency of the antenna and vice-versa.

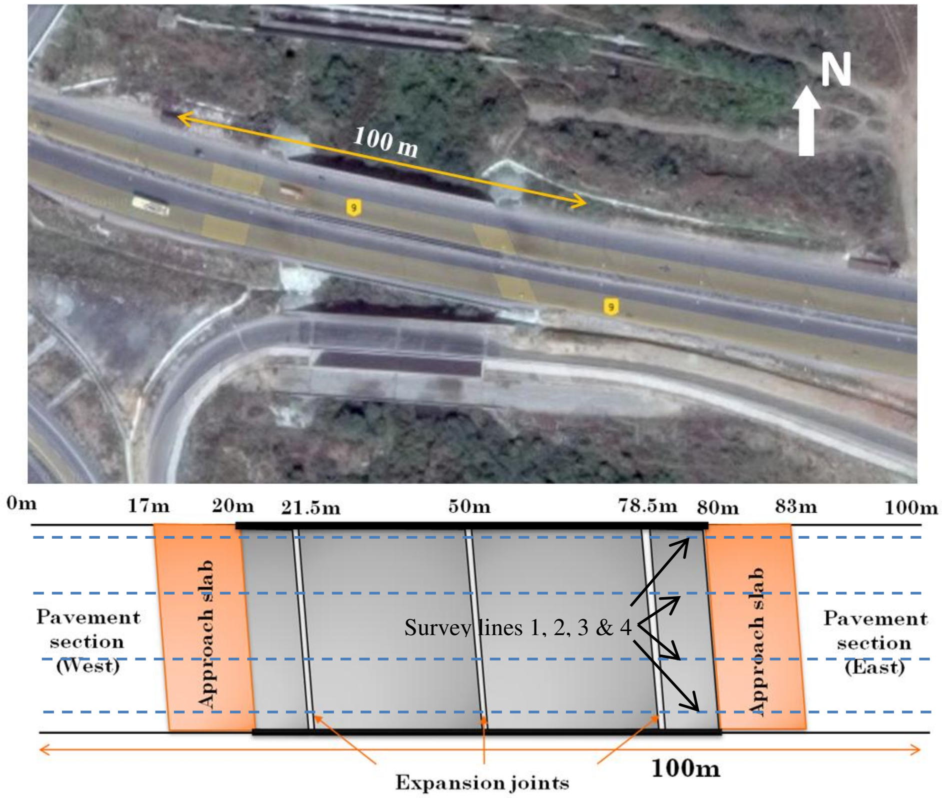

Figure 2. Google Image and plan view of the test location.

It is now important to identify the thickness of each pavement layer that would provide more information about the anomalies and distresses in the compacted embankment material. The thickness of the bound pavement layer i.e. asphalt concrete, can be calculated using ASTM D4748-10, a standard test method to determine the thickness of bound and unbound pavement layers using short pulse radar. The thickness of asphalt concrete layer can be calculated from Eq. 1 using the velocity and two way travel time of the radar wave. From the radargram, the two-way travel time of the radar wave is found to be 2ns and hence, the thickness is found to be 0.175m approximately. The thickness of the bridge deck excluding the asphalt surface is approximately 0.25m to 0.30m. The bottom of the bridge can be seen in Fig. 3 at a depth of about 0.4m to 0.45m. The thickness of the unbound pavement layers are found to be 0.275m total thick, which can be visualized from Fig. 3 that these layers are compacted in two lifts of 0.15m and 0.125m, respectively. It can be clearly seen that the compacted soil has extensively disturbed/deformed stretches between 15m and 17.5m and between 83m and 91m. Further, multiple surveys were carried out along these deformed stretches to quantify the distresses/settlements. Figure 4 shows a processed radargram of the deformed test stretch from 100m to 78.5m traversed from east-west direction. The reasons for the soil settlement under the approach slabs may be attributed generally to inadequate compaction of the embankment material and specifically the adopted lift thicknesses in this region. It can be observed that the lifts are of unequal depths especially under approach slabs. It is also noticed that an asphalt overlay was placed over the deformed test sections on either side of the approach slabs as a measure to retrofit the sections and improve the ride quality (Figs. 3 and 4).

A void was also detected underneath the approach slab on the test stretch between 81.5m to 83m, as visualized in Fig. 4. Chen and Scullion (2006) and Chen and Wimsatt (2010) observed similar type of voids under the continuously reinforced plain concrete pavements in IH 40, IH 35 and IH 90 respectively. Rister and Hoopwood (2008) reported the possibility of a void approximately one or two inch in depth under the approach slab of a bridge on I-275 in Kenton County, USA. Based on thorough analysis of various radargrams from these studies and the present study, a void is identified in the Fig. 4, which is denoted by a clear change in the radargram near the void location, due to the change in the dielectrics of the material. The extent of voids formed and the volume of the deformed soil are quantified using an image processing and analysis software as presented in Fig. 5. The procedure consists of converting the high-resolution processed radargram into grey scale (Fig. 5a) and then marking the region to be measured with the help of editing tools (Fig. 5b). The number of black square pixels are measured after filling the marked region using fill command (Fig. 5c). Similarly, the total number of square pixels covering the entire image is also measured (Fig. 5d). The procedure is repeated for several times to check for the repeatability of the technic and found to be accurate with a COV of about 0.025. Now, the area of distress is calculated in mm^2 from the number of square pixels measured, based on the known dots per inch (dpi) information of the image, using a conversion formula given by Jones (internet content, 2016). Although, the area (length and depth) of the distress can be calculated from this method, the volume of distress is calculated by determining the settlements along the width of the pavement through multiple GPR surveys as shown in Fig. 2). Table 1 gives the volume of deformed soil and the volume of voids calculated in the stretch 100m-78.5m. Similarly, the deformed soil zones and potential voids on the west side of the bridge stretch between 16m to 18m were also observed in the radargram of test stretch 21.5m to 0m (east-west) and the data is presented in Table 1.

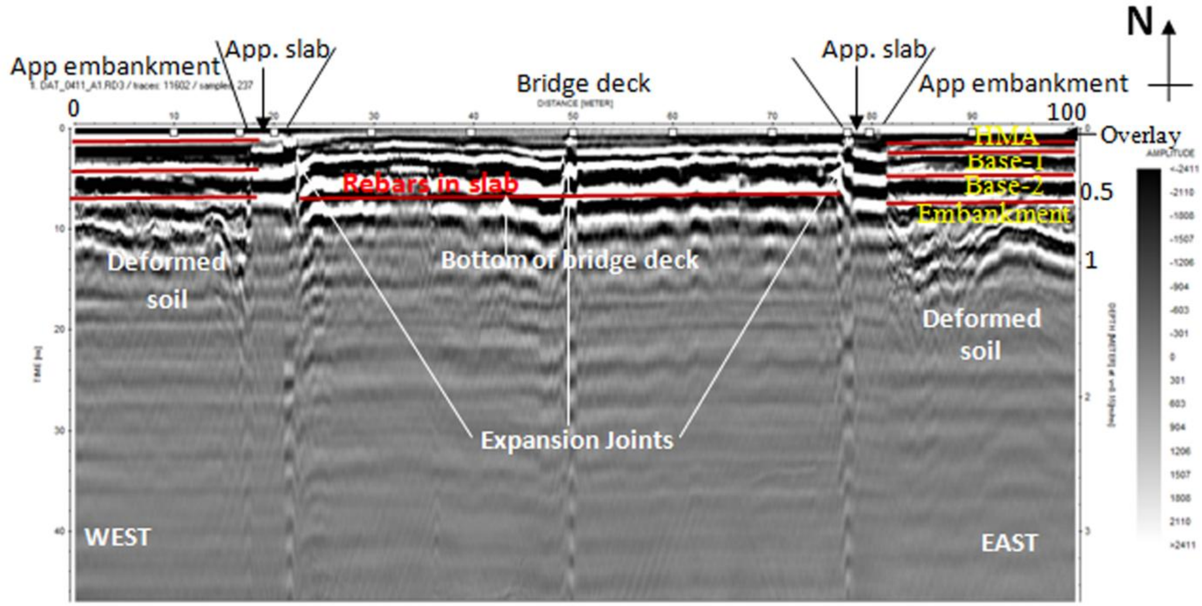

Figure 3. Processed radargram of the complete test stretch (West-East)

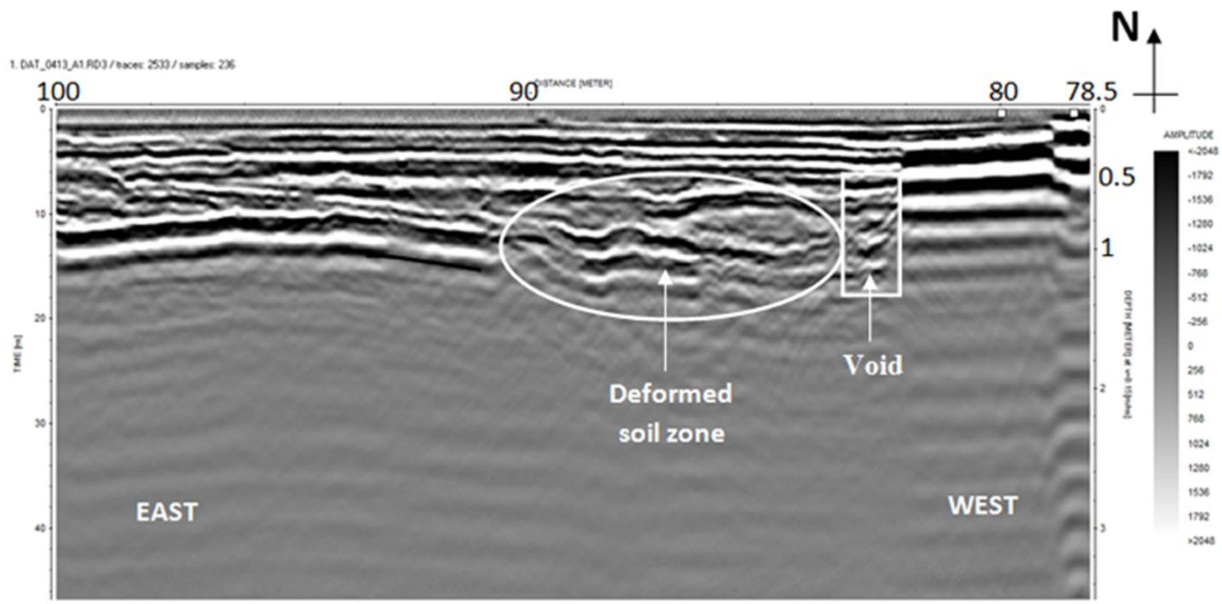

Figure 4. Processed radar gram of the test stretch from 100m to 78.5m (East- West)

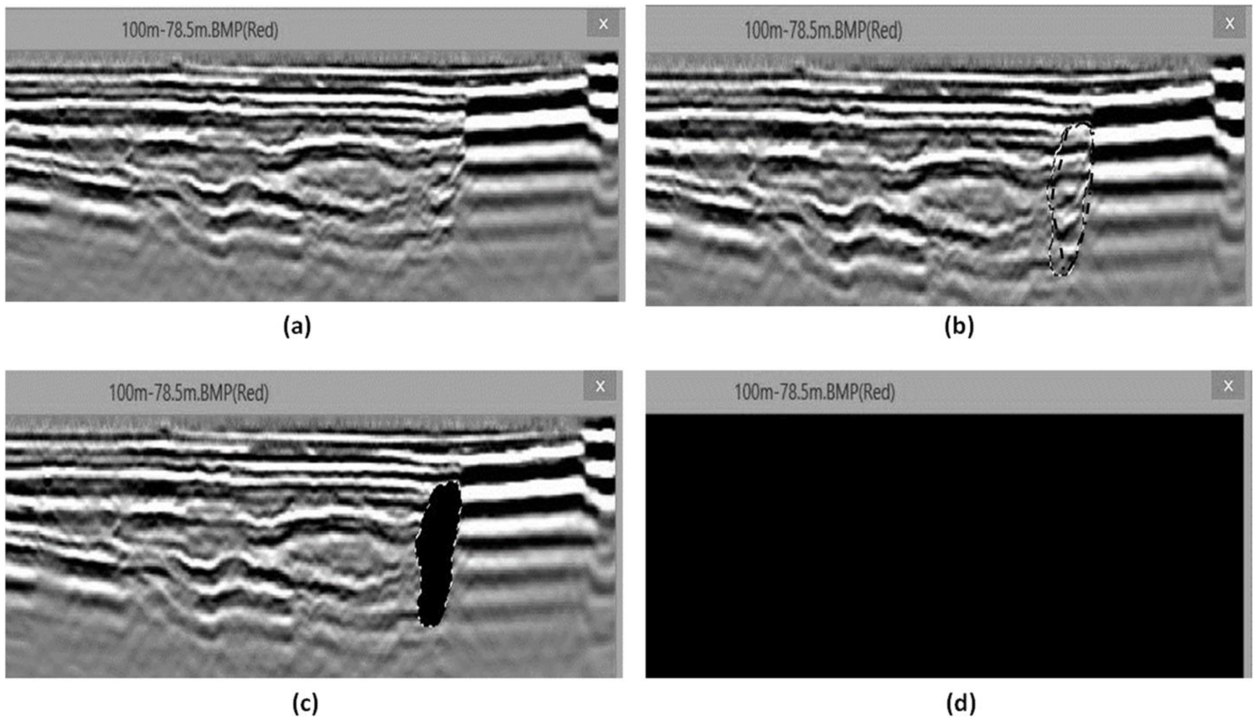

Figure 5. (a) Original image, (b) area of distress is marked using editing tool, (c) darkened distress area, and (d) fully darkened image.

Table 1**:** Summary of distress locations in the test stretch

S/l No.	Total Image area (m^2)	Total Image area in sq. pixels	Distress Area in sq. pixels	Distress area (m^2)	Distress Volume (m^3)	Remarks
1	75.25	306400	2913	0.72	7.56	Void (100m-78.5m)
2	75.25	306400	22950	5.64	59.22	Settlement (100m-78.5m)
3	75.25	306400	3883	0.95	4.98	Void (21.5m-0m)

In continuation in analyzing the distresses, LWD testing has been performed on the pavement test stretch at chainages 0m, 15m, 25m, 75m, 85m, 100m along the west to east directions and vice-versa. The chainages were selected such that the LWD test is conducted on the approach embankment section, settled approach slab and the bridge deck on both west and east directions. The deflection and deformation modulus values along the test stretch are presented in Table 2. It was observed that the deformation modulus values were about 271.08 MPa and 284.81 MPa at 0m and 100m, respectively where there were no soil deformations were identified in the GPR radargrams. Adjacent to the approach slab, where severe deformations were identified in the radargrams, very low deformation Moduli of 135.5 MPa and 132.4 MPa were recorded at 15m and 85m, respectively. The deformation Moduli of the bridge deck were recorded as 218.45 MPa and 220.35 MPa at 25m and 75m respectively. It is very clear that the

LWD test results correlate well with the radargrams obtained by the GPR surveys, thus validating the GPR analysis.

Table 2**:** LWD test results

Location	Chainage (m)	D_{Avg} (mm)	Deformation Modulus (MN/m^2)
Pavement	0	0.083	271.08
	100	0.079	284.81
Approach pavement	15	0.166	135.54
	85	0.17	132.35
Bridge deck	25	0.103	218.45
	75	0.105	220.35

CONCLUSION

Non-destructive testing methods can be effectively used to identify the distress locations in the approach embankments, pavements and other concrete infrastructure very quickly without causing any inconvenience to the traffic. A series of non-destructive tests viz., ground penetrating radar (GPR) and lightweight deflectometer (LWD) were adopted to identify and quantify the anomalies and distresses of a bridge approach embankment on a national highway near Hyderabad city. The following conclusions are drawn from the study:

A series of ground penetrating radar surveys using a 500 MHz mid frequency antenna was adopted to determine the thickness of various bound and unbound layers of the flexible pavement structure. It can also be used to determine the thickness of concrete structures in pavements like cement concrete pavements and bridge decks to the nearest possible extent.

The radargrams were analyzed to quantify the distresses such as voids beneath the approach slabs and soil deformations. The voids were identified using the change in dielctrics of the compacted soil. With the assistance of image processing software, the total volume of the soil involved in the approach embankment settlement was quantified, which amounts to about 72 m^3. In addition, LWD tests were used to determine the approach embankment and pavement condition through deformation modulus. The LWD test results seem to correlate well with the GPR results obtained in the current study.

Overall, the NDT test methods along with advanced image processing technics assist in estimating the anomalies accurately to adopt appropriate maintenance operations, hence, these methods can be adopted in forensic investigations.

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