Health Assessment of a Pedestrian Bridge Deck using Ground Penetrating Radar

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ABSTRACT: Scanning concrete structures using ground penetrating radars (GPR) continues to be one of the most efficient methods for defect (i.e. crack, void and delamination) detection within concrete structures as well as detection of reinforcing bars damage due to corrosion. The aim of this study was to assess the structural health of a 45-year old pedestrian bridge deck. To achieve this, a number of experiments using a GPR system were conducted on a strong concrete floor with known construction drawings to detect cover depth and rebar orientations. After validating the GPR results through the experiments, the GPR system was used for non-destructive assessment of the pedestrian bridge deck. From the scanned results, the location and orientation of the reinforcing bar were established. In addition, the diameters of the bars was estimated by measuring the thickness of the hyperbola curves in the B-scans. The scanned output shows no signs of corrosion of reinforcement or damage of concrete in the form of delamination or cracking.

1 INTRODUCTION

With the aging infrastructure, the cost of road maintenance is increasing worldwide. For instance in 2015/16 in Australia, over 6 billion dollars were spent for road maintenance, including over 500 million dollars for bridge maintenance and rehabilitation (Economics, 2017). Health monitoring of reinforced concrete elements is of critical importance as it ensures the safety and serviceability of the structure and its timely maintenance which can potentially reduce the maintenance cost. Concrete structures undergo a number of surface and subsurface changes during the service life due to weathering and cyclic loading. These defects (in the form of cracks, voids, and delaminations) provide an easy access for water and harmful chemicals into concrete leading to corrosion of steel reinforcements. The integrity of the entire structural systems can be compromised if corrosion is left undetected.

There are several non-destructive techniques (NDT) which can be used for defect detection in concrete structures including infrared technology, ultrasound pulse velocity method as well as ground penetrating radar (GPR). The application of GPR as a NDT method to assess concrete structures status has become increasingly popular over the past decades. The GPR has been widely used to determine the reinforced concrete cover depth, the position of reinforcements within the concrete, location of voids, moisture distribution and structural integrity of reinforcements (Parrillo et al., 2006).

GPR uses Electromagnetic Waves (EMW) to image the subsurface region. It comprises of a control unit, transmitter and a receiver antenna and a computer for interpreting and displaying results. The transmitter antenna emits the EMW into the structure. While some part of the waves energy is transmitted through the material, some part is reflected and recorded by the receiver antenna. As the speed of the EMW through any material depends on the dielectric constant of the material, any changes in the speed of propagation of the EMW indicate a change in material composition. (Clem et al., 2015).

The following equation describes the relationship between speed of propagation of the EMW and relative dielectric constant:

$$C_{material} = \frac{c_{air}}{\sqrt{\varepsilon_r}} \qquad (1)$$

where, $C_{material}$ is the speed of EMW in the material through which the EMW passes, C_{air} is speed of EMW in air = 300 mm/ns and ε_r is the relative dielectric constant. The relative dielectric constant of concrete is between 6 and 11 and the speed of propagation varies between 9 to 12 cm/ns (Lachowicz and Rucka, 2015, Clem et al., 2015).

The EMW have frequencies ranging from 500MHz to 3000 MHz (Clem et al., 2015). The GPR

EMW with a higher frequency gives a better resolution image, but cannot penetrate deeply in the material, whereas GPR EMW with lower frequencies penetrate deeper but produces a lower resolution image (Srinivasan et al., 2012).

The GPR measurement results are presented in the form of scans, as shown in Figure 1. A-scan

obtained. (Lachowicz and Rucka, 2015, Srinivasan et al., 2012).

The main aim of this research was to assess the structural health of a pedestrian bridge and to use GPR system to detect any damages in the concrete structure (such as corrosion related voids and delamination). To achieve this, a number of experiments
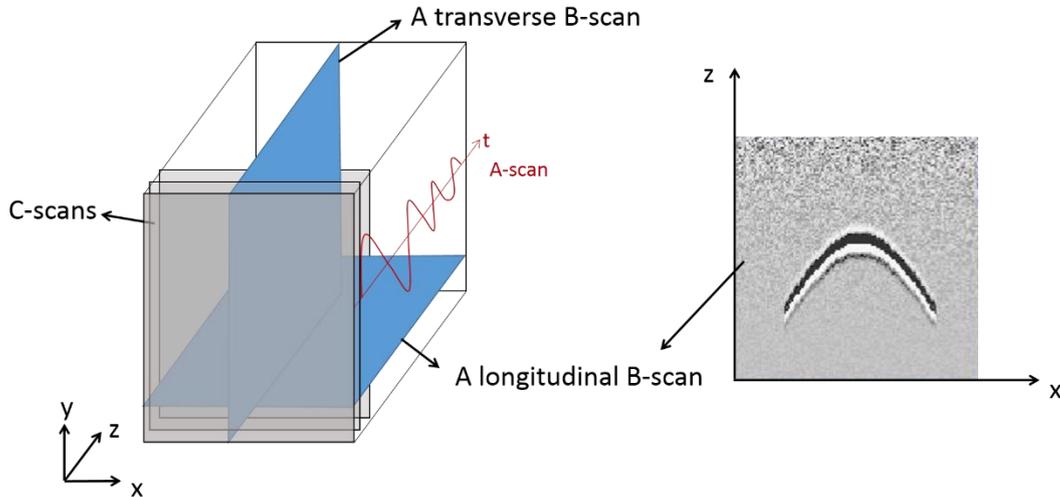
Figure 1 GPR data collection and scans

plots the amplitude of a reflected wavelet versus time at a specific point. By processing many A-scans obtained over a path, a grayscale image (radargram) known as B-scan is generated which plots the waves reflection magnitudes over the scanned path using different gray intensities. The vertical axis of a B-scan corresponds to the depth of wave penetration and the horizontal axis corresponds to length of the path that has been scanned. Through side-by side scanning of the object in two orthogonal directions (i.e. longitudinal and transverse directions), a 3D display of GPR radiogram, known as C-scan, can be

using a GPR system were conducted on a strong concrete floor (in a structural engineering laboratory) with known construction drawings to detect cover depth and rebar orientations. After validating the GPR results through the experiments, the GPR system was used for non-destructive assessment of the pedestrian bridge.

2 METHODS
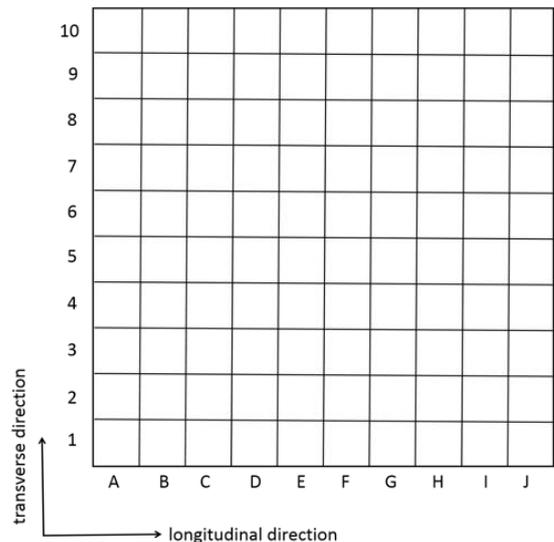
Figure 2. (a) The pedestrian arch bridge selected for GPR scanning in this study, (b) The grid lines used for data acquisition from the strong concrete floor

In this study, an Aladdin GPR survey kit (IDS GeoRadar) for data acquisition was used and the scanned results were processed and analysed using FastWave software. Aladdin GPR is equipped with 2GHz frequency dual polarized antenna comprising of 2 transmitters and 2 receivers. The dual polarized antennas in Aladdin GPR are perpendicular to each other which enable deeper penetration of the waves and provide higher resolution of scans.

The data acquisition software of Aladdin GPR (i.e. K2 Fastwave software) provides a tomographic view of the subsurface of the scanned area. The GPR data acquisition parameters such as sampling size, frequency and number of antennas are adjusted by user in software to calibrate the data of any acquisition channels. The data processed in K2 FastWave software can be imported to GRED HD software for the 3D image reconstruction of structure subsurface using the GPR scanning results.

2.1 Data acquisitions from a floor slab

A grid sheet of 1 m × 1 m with 0.1 m spacing between the grid lines was prepared to facilitate data acquisition. The data acquisition parameters were defined in K2 FastWave software with coordinate step of 0.1m in both longitudinal and transverse directions along with position marker step of 1m. The grid sheet was placed over the floor slab and data was acquired by scanning the GPR over each individual grid lines in both longitudinal and transverse direction. The GPR data acquired from scanning the concrete floor was converted to tomographic images using K2 Fastwave software and then the data was post-processed by using GRED HD software for 3D image reconstruction of the concrete floor. The processed data was then compared with the structural drawing of the slab for validating the simulation results.

2.2 Data acquisition from a bridge deck

After validating the GPR results obtained in section 2.1, the system was used to check the structural integrity of a pedestrian bridge (located at the intersection of Swanston and Elgin Street, Parkville, Victoria, Australia). The location of bridge is shown in Figure 2.a A grid of 500mm × 500mm with 100 mm spacing in longitudinal and transverse directions was used for data acquisition for the bridge deck. The data acquisition parameters were redefined in K2Fastwave software for the newly established grid and the data was collected by GPR scanning on the central part of the bridge deck as indicated in Figure 2.a.

3 RESULTS AND DISCUSSIONS

3.1 Data acquisition result for the floor slab

Figure 2.b illustrates the schematic of the grid lines used for data acquisition from the slab floor. The GPR B-scans in longitudinal direction (grid 1-10) and transverse direction (grid A-J) of concrete floor slab are shown in Figure 3.a. and 3.b respectively. It is worth mentioning that as the GPR used in this study was bipolar, it generated two set of scan images for each grid line. One set of images represents the scan by antenna oriented in direction parallel to scan direction, while the other set (for same grid line) captures by antenna oriented in perpendicular direction to scan path. It was observed that the perpendicular antenna (orientation perpendicular to scan direction) detects the location of cross targets (reinforcements/objects) better than the alternate antenna.

The hyperbolas in the B-scans show the reinforcement bars inside the concrete that are perpendicular to the scan direction. The location of the reinforcement bars is at the peak amplitude of the hyperbolas. It can be seen that, the hyperbolas are repeated in the adjacent grid scans as shown in Figure 3.a,b. This shows that the reinforcement bars are exactly perpendicular to the scan direction. It can be observed from Figure 3.a that, there are 5 superficial transverse bars at 0.1 m depth of the floor surface (see the hyperbola peaks), while there are additional transverse bars below the superficial bars as indicated by lighter hyperbolas.

It can be seen that the spacing of bars increased as we moved from bar 4 to 5 on grid line 1 (Figure 3.a). The 4th and 5th transverse bar are represented by respective upper 4th and 5th hyperbolas (from left) on Grid 1, Scan 1 in Figure 3.a. As it can be seen in the scan, the relative distance between the 4th and 5th hyperbolas has increased as compared to relative distance between 2nd, 3rd and other adjacent hyperbolas. The distance between adjacent hyperbolas was measured in GRED HD and the distance between 4th and 5th hyperbola was found to be 300mm which was larger compared to the distance between other adjacent hyperbolas (i.e. 250mm) in Figure 3.a, Grid 1 Scan 1.

The collected GPR data can be further processed using GRED HD software to detect the location and diameter of reinforcement bars and any defects within the slab. In order to estimate the diameter of bars, the thickness of hyperbolic curve was measured in the software. By analyzing the B-scans in longitudinal direction, the locations of the bars that are oriented along the transverse direction in superficial and deep layers were identified. Figure 4.a and 4.b show cross-section and elevation views of transverse bars within the scanned slab respectively and the

bars diameter was estimated to be 25mm. The adjacent longitudinal
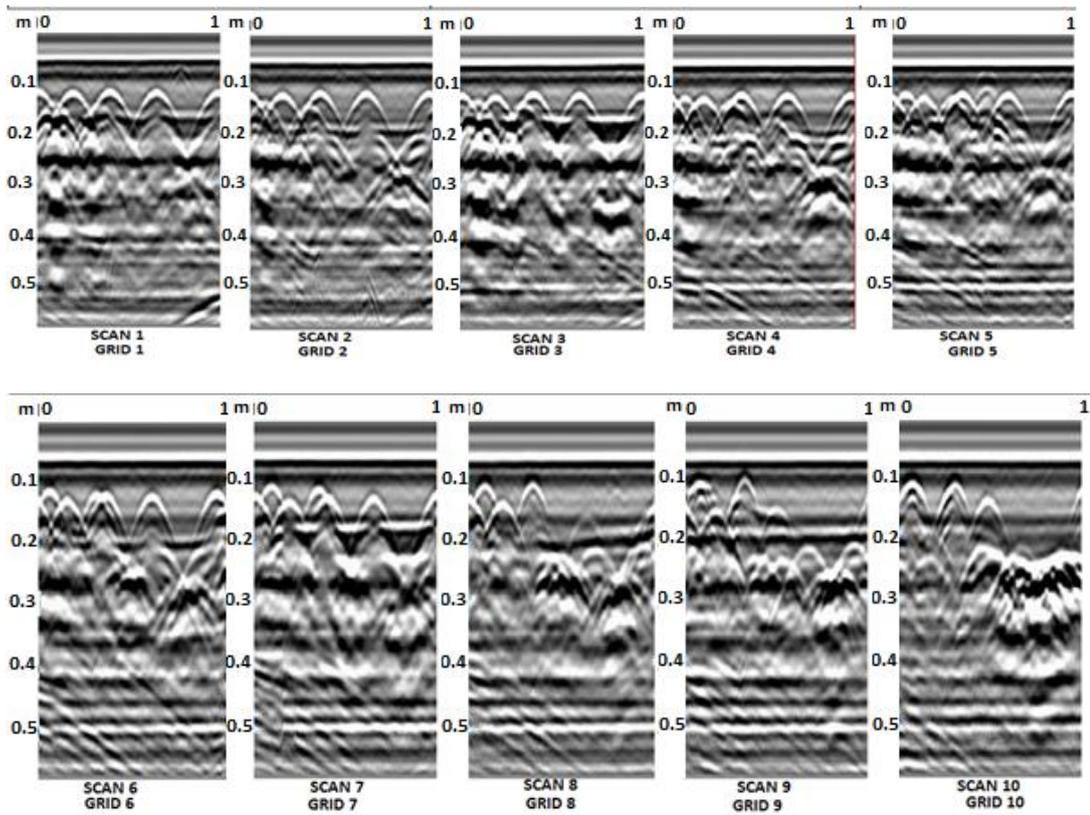
a) The GPR B-scans in longitudinal direction of concrete floor slab (grids 1-10)
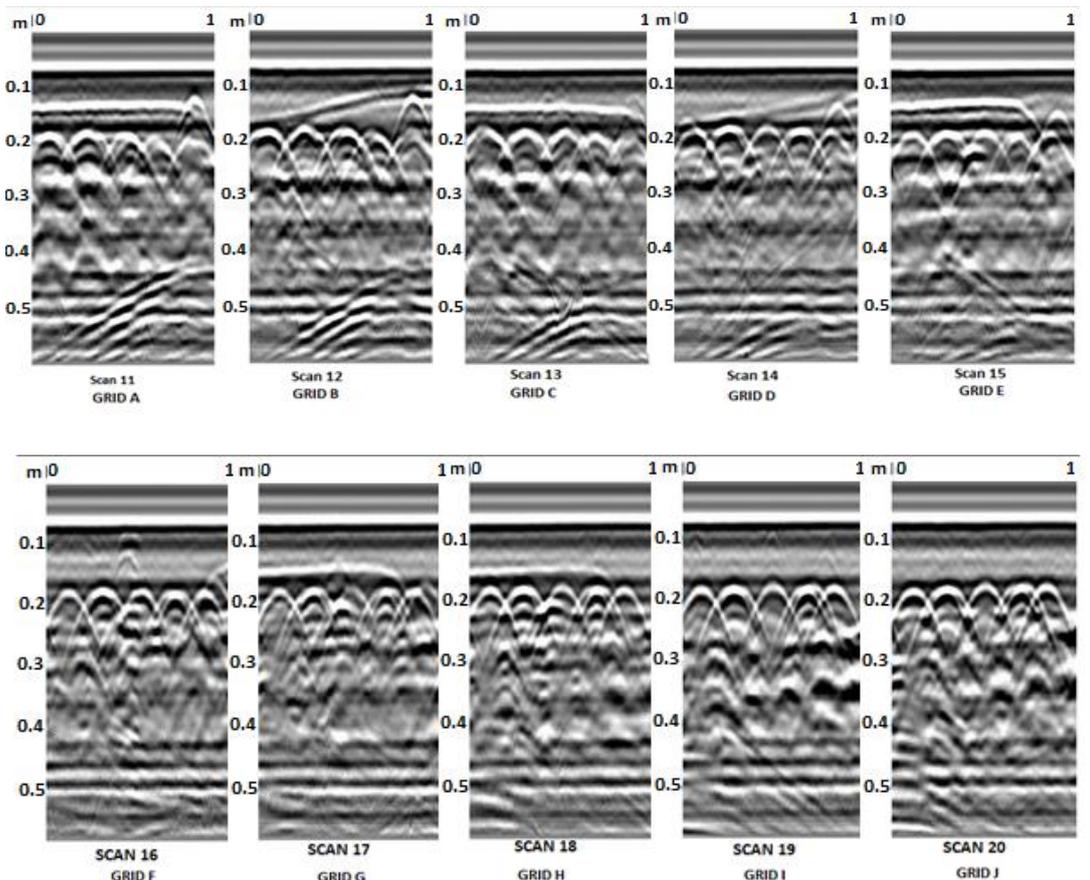
b) The GPR B-scans in transverse direction of concrete floor slab (grids A-J)

Figure 3 The GPR B-scan results for the concrete floor slab

a)   Cross section of the transverse bars

b)   Elevation of the transverse bars
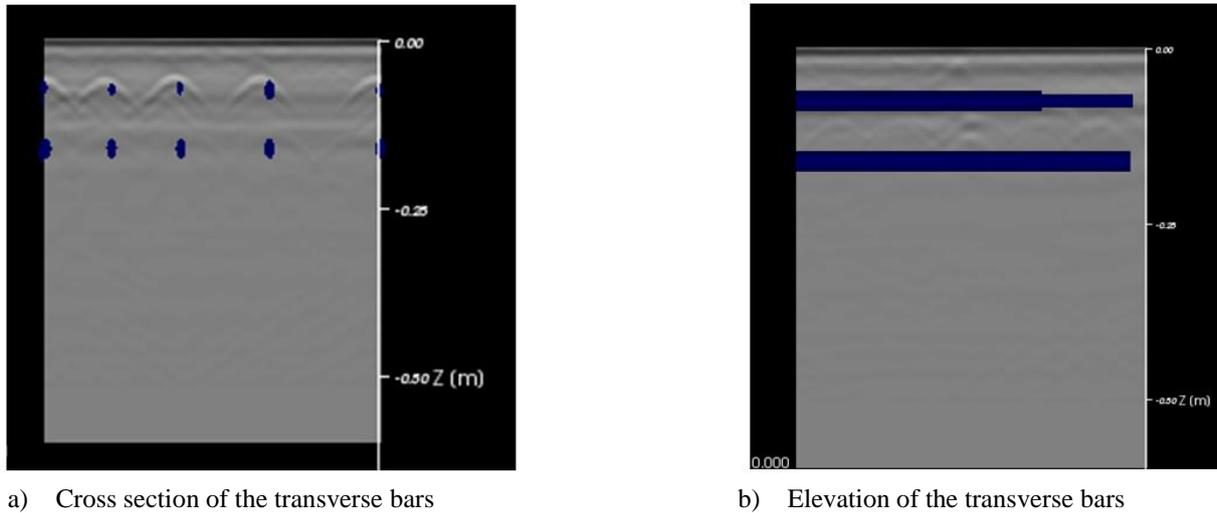
Figure 4. Scanned results showing rebar details

bars are hidden behind the darker transverse bar in Figure 4.b.

Figure 5 shows the B-scan data in gridline A in transverse direction. The red arrows in Figure 5 shows the location of reinforcement bars that are positioned along the longitudinal direction. It is seen that these longitudinal bars lie approximately at 125mm below from slab surface. They are located under the main transverse bars, which are highlighted by blue box in the figure.

3.1.2 *Comparison of the GPR results with structural drawings*

The structural drawings of concrete lab floor (Figure 7) were compared against the GPR scanning results for validation. The slab had a total depth of 48 inches (1,219.2mm). It should be mentioned that the GPR EMW used in this study could only penetrate down to depth of 300mm due to high transmitted frequency (i.e. 2GHz). The structural drawing

Figure 5. Scan result interpretation in transverse direction

3.1.1 *Concrete floor 3D model*

Using the B-scans in longitudinal and transverse direction, the 3D model of the floor slab was reconstructed and shown in Figure 6. By reconstructing the 3D model of steel reinforcements in concrete, the rebar profiles can be observed and inspected. This enables detection of any possible excessive deformation in steel rebars.

shows two layers of longitudinal reinforcement (horizontal direction of cross-section) and one layer of transverse reinforcements (direction into the page of cross-section). These reinforcement bars are of 32mm diameter and are spaced at 250mm. The GPR scanning results estimated bar diameter to be 25mm with the bars spacing of 250 mm on average, showing a good agreement with the structural drawing data. The above difference in diameter can be reduced if a more refined method is adopted. While configuring acquisition parameters in this test, propagation

XYZ: 1.223m; 1.816m; -0.174m
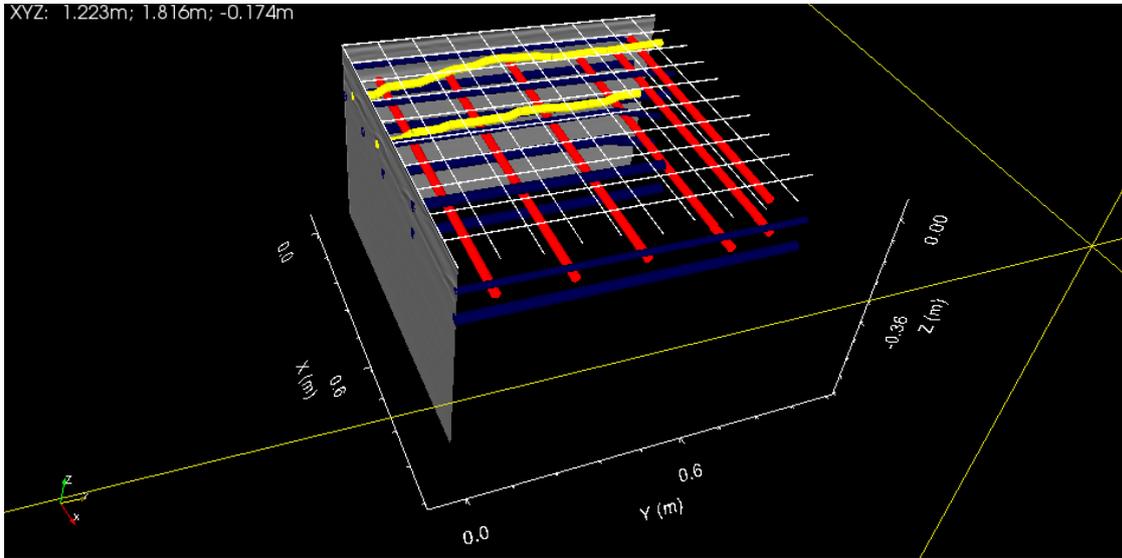
Figure 6. 3D Model of Floor Slab reconstructed using the B-scans
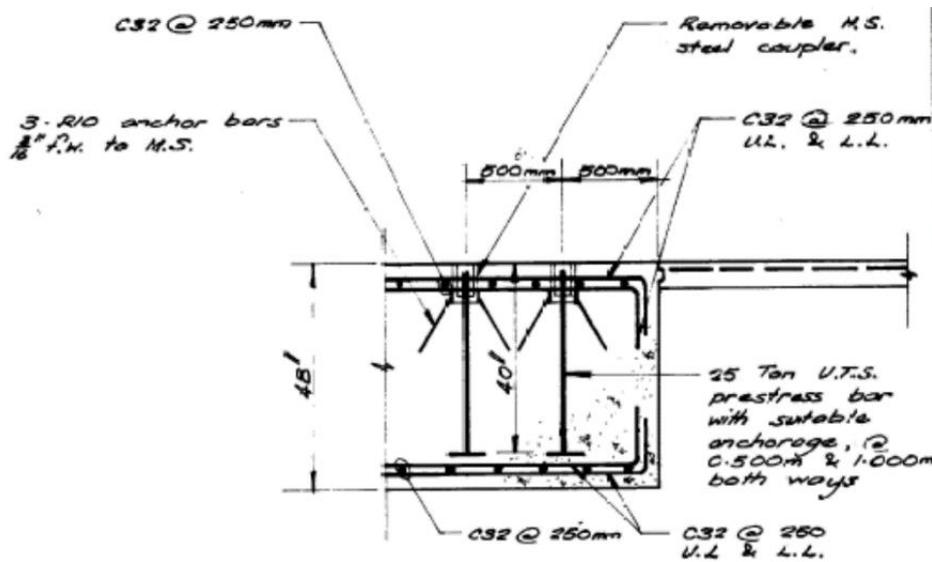
Figure 7. Structural drawing showing cross-section of floor Slab

speed of EMW was set to be 10 cm/sec which is the average speed through normal concrete. However, the EMW propagation speed depends on number of factors which includes life of concrete, moisture content, voids, temperature, etc. If these corrections are further considered, the difference between the results could be reduced. After confirming the GPR scanning results against structural drawing data, the system was used for health assessment of the pedestrian bridge (as described in section 2.2).

3.2 Data acquisition result for the bridge deck

Figure 8.a and 8.b show the GPR scanning results of the bridge deck in transverse and longitudinal directions respectively. It can be seen that there are 8 bars along longitudinal direction and 4 bars along transverse direction.

The 3D model for bridge reinforcement was reconstructed in GRED HD as shown in Figure 9. Longitudinal reinforcements are shown in orange color while the transverse rebars are shown in red.

The longitudinal bar diameter was measured in GRED HD using hyperbola peak width and was found to be 30mm. The horizontal spacing, measured by finding the adjacent distance between hyperbolas, was found to be 125mm. However, the spacing between 6th and 7th longitudinal bar was increased up to 150mm while it was reduced down to 100mm between 7th and 8th bar. Similarly, GPR scans predicted the cover reduction of 6th and 7th bar to 55mm from 65mm for remaining longitudinal bars. The transverse bars were found to be of same 30mm diameter with 250 mm spacing along with cover of 30mm. No significant change was detected in the pattern for the transverse bars. It is worth mentioning that longitudinal bars were detected to have irregularities at some locations.
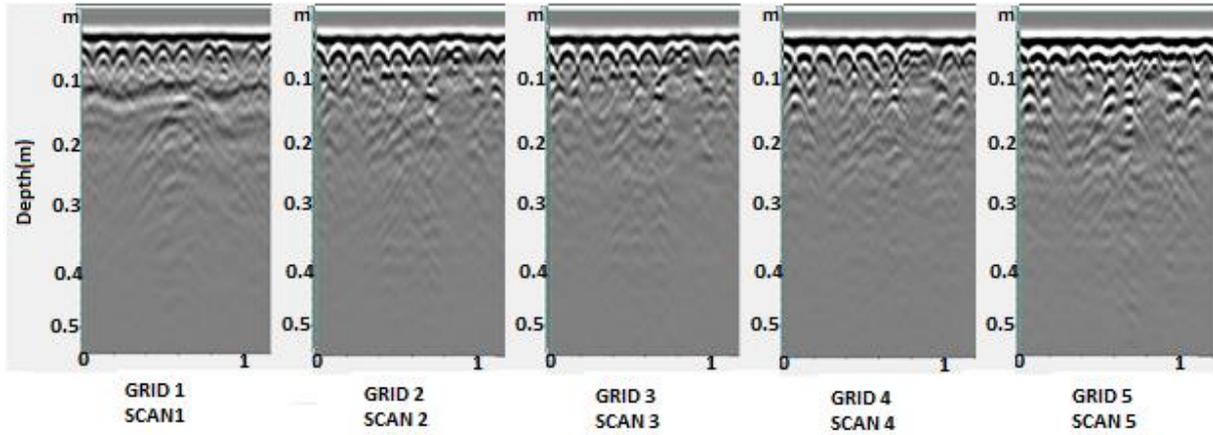
a) Results of the scans transverse direction (The hyperbolas show the reinforcement bars in longitudinal direction)
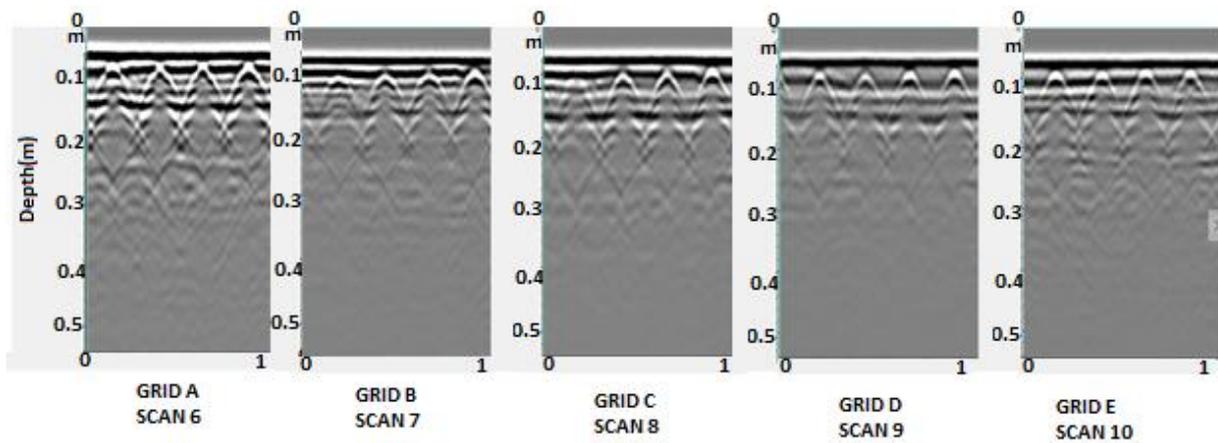
b) Results of the scans longitudinal direction (The hyperbolas show the reinforcement bars in transverse direction)

Figure 8 GPR scanning results of the bridge deck
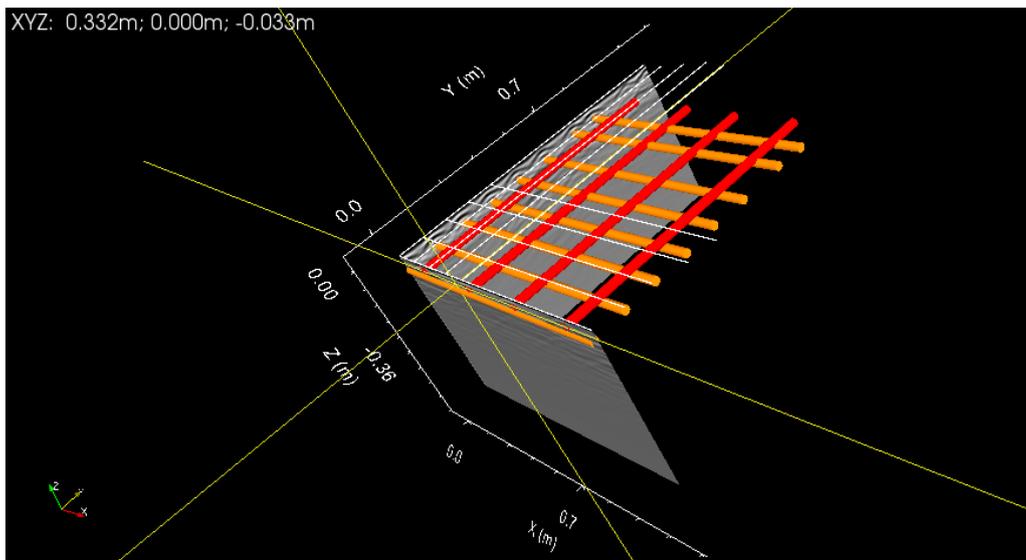
Figure 9. 3D Model of the bridge deck

4 CONCLUSION

The result of the experiments conducted in this study shows that GPR can be used as a reliable tool to determine the position and condition of the reinforcement bars inside the concrete. The 3D modelling of the results helps in better visualization for interpretation of the results and enables detection of any irregularities or deformations of steel reinforcements.

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