

Developing Corrosion Maps of RC bridge elements based on automated visual image analysis

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ABSTRACT

Reinforced Concrete (RC) bridge elements scanned by Ground Penetrating Radar (GPR) are widely analyzed by utilizing numerical analysis approach. Typically, this involves picking amplitude values at rebar location manually or automatically after applying depth correction and subsequently, utilizing these values to develop corrosion maps. However, the results obtained from this approach have proven to be unreliable when it is compared with actual bridge element condition at the construction or destruction phase. Based on another new visual image analysis approach, accurate condition maps can be developed with less noise as this approach involves an expert analyst to scan through each GPR profile of bridge element while considering all surface and structural anomalies. The current visual image method is highly subjective because it involves manual condition zoning of each profile and it is also prone to human error. The authors of this paper aim to automate this approach through image processing tools in MATLAB® and develop corrosion maps which will be unique and more objective in nature. Image filtering will be utilized to detect hyperbolic regions in a GPR profile and furthermore, corrosion maps will be developed based on intensity of pixels present in the detected hyperbolic regions. The developed maps are expected to be reliable and will be useful in conditional assessment of bridge elements.

Keywords: Ground Penetrating Radar (GPR), Visual Image Analysis, Automating analysis, RC Bridge Elements, Condition Assessment, Corrosion Maps, Numerical Analysis, image processing, MATLAB, image segmentation

INTRODUCTION

Condition assessment and maintenance of reinforced bridge deck element is critical for long term sustainability of bridges. Visual inspection is the widely utilized approach by bridge agencies wherein experienced bridge inspectors visually observe the surface defects and based on his/her knowledge rate the bridge deck according to its condition (1). Even though this method is simple and effective, it does not detect internal defects such as corrosion, voids and delamination and thus, does not provide accurate information about bridge decks which might lead to detrimental decision making. Due to such limitations, various destructive and non-destructive techniques have been adopted which can assist in determining wholesome health of a bridge deck. Due to obvious benefit of not having to damage bridge deck using non-destructive measures, these techniques are preferred and some of them include half-cell potential, infrared thermography, impact echo and ground-penetrating radar (GPR) (2). Based on the report on nondestructive testing (NDT) to identify bridge deck deterioration (3), GPR is the recommended technique for overall condition assessment at network level due to its ability to identify major subsurface defects within a short span of time. The method involves scanning a signal emitting GPR equipment across the bridge deck and recording these emitted signals. The recorded signals are analyzed through various methods found in the literature which could yield the concrete deterioration maps of a bridge deck for condition assessment. The commonly utilized method for analysis adopted by federal agencies is the numerical approach and is based on employing amplitude values at rebar reflections which are indicators of corrosions at these levels. However, utilizing this approach itself has major limitations as the deterioration map obtained from this approach has been proved to vary from the actual ground condition when compared during destruction phase (4) and therefore, making this method not completely reliable. Tarussov et al. (4) introduced a different approach for analyzing profiles obtained from GPR scans based on visual interpretation which overcomes major limitations of numerical analysis method. The visual interpretation approach involves an expert scanning through each GPR profile scanned and zoning it based on appropriate deterioration level accordingly while considering all structural and subsurface anomalies to yield reliable deterioration maps. However, since this approach needs an experienced analyst each time for interpretation, it is highly subjective and time consuming. The authors of this paper have developed a method utilizing digital image processing techniques with the aim of automating the visual interpretation method by Tarussov et al. (4) and subsequently, developed corrosion map for an actual bridge in Iowa for results validation.

Objectives of Research

The primary objective as stated before is to develop an automated method for visual image based interpretation of profiles obtained through scanning of bridge deck scanned using GPR equipment and develop corrosion maps. The following include the sub-objectives achieved while developing this approach:

- a) Review the numerical analysis approach of analysis and its limitations.
- b) Introduce the visual interpretation approach and discuss its advantages over other methods.
- c) Review image processing techniques employed in previous literature for analyzing GPR profiles
- d) Propose the newly developed automated visual image based method and validate it by applying it over an actual bridge deck.

RESEARCH BACKGROUND

Numerical Analysis

GPR equipment have an antenna which emits electromagnetic (radio) waves into the bridge deck to record reflections within the subsurface and this technique is based on “radio detection and ranging” (radar) technique to detect hidden objects. The recorded reflections are prominent at various interfaces present in the deck like at the asphalt-concrete or concrete-rebar layers and properties such as thickness of concrete, cover depth of asphalt, voids and rebar corrosion can be determined using these reflected data. Although there are various approaches proposed in the literature to interpret this signal data, the widely utilized approach is called the “numerical analysis” approach and it considers the amplitude values at the rebar locations to assess the condition of the deck. The emitted signal recorded at a certain point or location is called an A-Scan and can be drawn as an amplitude vs. time graph as shown in figure 1. When such A-scan are combined across the whole swab of a section of the bridge and recorded at regular intervals, it can be represented as B-scan wherein, the X-axis represents the distance along the direction of scan and Y-axis represents amplitude values.

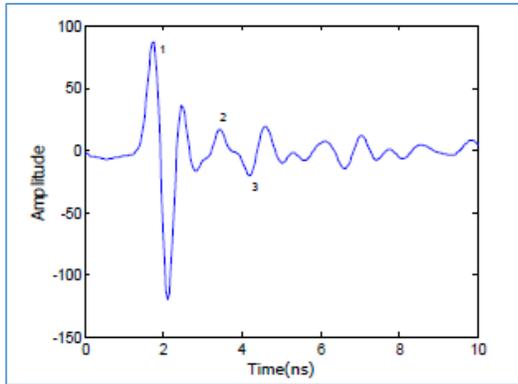


Figure 1 A- Scan (5)

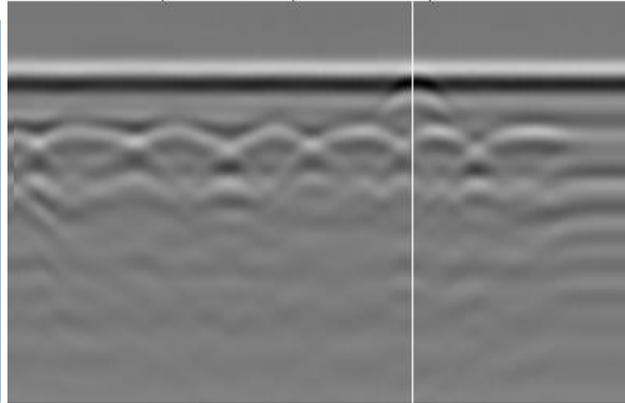


Figure 2 B-Scan (marked vertical white line represents extracted trace in Fig 1) (5)

The reflections at the interface of concrete and rebar form a characteristic hyperbolic signature and the peak of these hyperbolas correspond to the rebar location in the bridge deck (6). Hence, these peak points are picked as shown in Figure 3 in a given GPR Profile for numerical amplitude analysis. ASTM D6087 enlists a standard procedure to develop deterioration maps based on the amplitude values (4) and it is based on the simple concept that higher the peak value of amplitude obtained at the peak of the hyperbola, better is the condition of the concrete and vice versa. The amplitude can be measured at top layer, bottom or top reinforcement of papers. There are number of methods developed based on numerical analysis which include (7), (8), (9), (10), (11), (12) and (13). A method developed also determines chloride content present in the bridge deck using amplitude analysis and the results obtained were considerably good.(14). To detect corrosion and delamination at early stages, a new approach detects moisture content based on amplitude values and can be used as a prevention measure (15). Although numerical approach is a commonly adopted approach for GPR profile analysis (16), it has various limitations as discussed in next section.

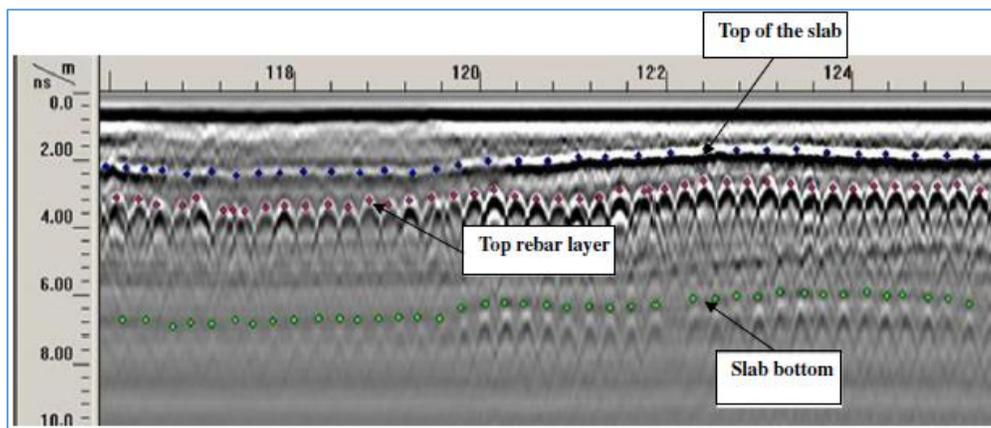


Figure 3 Picking of points in a GPR profile for amplitude analysis

The results obtained from numerical approach do not yield completely reliable results as by considering only the amplitude values contained within the profile, it neglects 90% of the data contained within it (4). As such, the deterioration maps generated from such an analysis contains noise leading to deceptive results due to various factors amplitude like reinforcement bar spacing, depth, surface anomalies and others (4). Therefore, when the resultant deterioration map is compared at construction/demolition phase of the bridge deck, it fails to show proper correlation. In order to overcome these limitations, a better alternative approach has been proposed by Tarussov et al. (4) which is based on visual analysis of GPR profiles.

Alternative Approach – Visual Analysis

Tarussov et al. (4) approach involves interpreting the visual data contained in a GPR data profile by considering it as an image rather an amplitude measuring tool. In this procedure, an experience analyst visually scans through a GPR data profile and marks areas of corrosion in it manually. Areas of severe corrosion are marked as red while the areas of moderate corrosion are marked as yellow as shown in Figure 5. The areas which are unmarked are green zones having no or minimum corrosion. While marking these areas, the analyst considers all structural and surface anomalies like presence of beams or tightly spaced reinforced bars or others. In doing so, the deterioration maps generated through this approach has better correlation with the actual ground condition and thus, contains less noise with areas of corrosion clearly distinguished from each other.

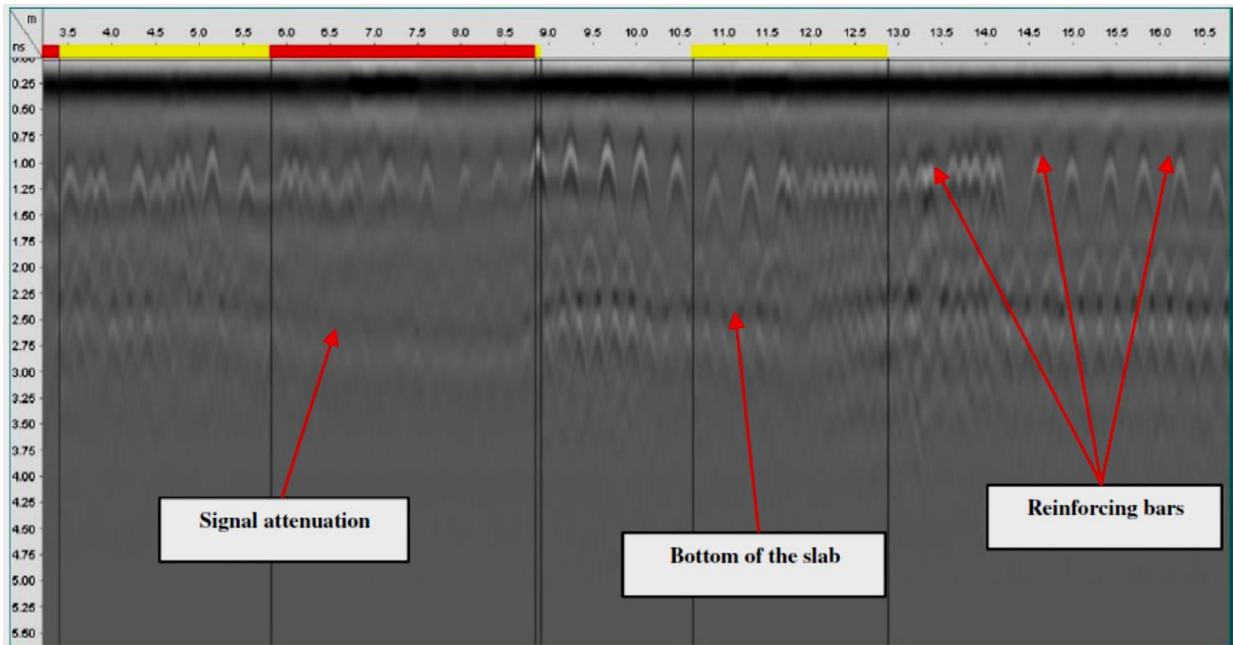


FIGURE 5 Marking attenuated areas using Visual Approach (4)

By considering even small variations or anomalies, the visual approach is clearly advantageous over numerical analysis, which only considers amplitude value. This can be illustrated with an

example shown in Figure 6, the amplitude analysis does not consider the presence of anomaly (beam) as the amplitude values will correspond to corrosion. However, the analyst in visual approach can clearly identify that there is no corrosion present in the zone of beam and will mark the region appropriately to yield a precise and noise free corrosion map. Similarly, visual method consider all such anomalies and other factors while marking attenuated areas.

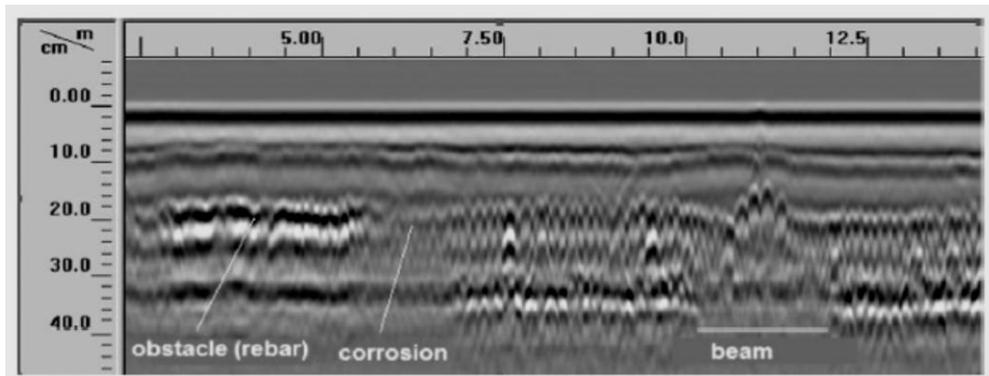


FIGURE 6 Zone of corrosion and anomaly easily distinguished by visual approach (4)

The deterioration maps generated from visual approach closely represent the real-time actual bridge deck condition which proves the superiority of this approach over numerical or other approaches. However, since an expert is always required to process this approach, it is highly subjective and prone to human error. To overcome these limitations, the authors of this papers have automated this approach by applying image processing techniques on GPR data profiles and the results from developed model is later compared with expert-based manual visual approach for validation.

Previous Efforts of Image Processing

There are numerous efforts found in literature which have implemented image processing techniques of GPR profiles. However, all of these approaches have focused on detecting hyperbolic signatures in a profile and further processing them based on numerical analysis or its variations. None of the techniques developed are focused on visual image analysis. The previous methods developed can be broadly classified into two major regions (17): a) Edge detection or thresholding an image based on local extrema of intensity and b) template matching i.e., to identify hyperbolic regions based on predefined templates stored in a library using suitable algorithm. The first approach of edge detection has major limitations which include noise and image blurring while thresholding generally requires manually selected parameters which does not automate the approach and consequently, cannot be applied uniformly across all GPR bridge scans. Template matching approach has also significant limitations which include difficulty in sound matching of templates with a given GPR profile as there is huge variation in the appearance of hyperbolas in different bridge scans due to type of concrete, rebar depth and noise. Furthermore, this approach may also lead to many missing and false detections of hyperbolas.

The automated rebar detection in GPR profiles has been majorly done in literature by applying neural networks as in (18), (19), (20), (21) and (22). However, these methods use edge detection as the preselected criteria to distinguish hyperbolas and thus, have the same limitations as discussed before. There is also an alternative approach utilized by (23) for automated rebar detections using support vector machines (SVM). But, it has the limitation of utilizing a thresholding algorithm to binarize an image based on manual selection of parameters. A new approach has been developed by (17) utilizes SVM without the need of a thresholding step for hyperbolic region detection and Random sample consensus (RANSAC) curve fitting for identifying peak points of whose amplitudes values are taken to generated deterioration maps based on numerical approach. All the previous efforts found in literature indicate that image processing techniques have been employed previously to pick rebar locations in a GPR profile. However, as stated before, these methods have applied numerical analysis method or its variations to develop condition maps while the authors of this paper have developed a unique model based on image processing techniques based on visual approach.

RESEARCH METHDOLOGY

The premier step for condition assessment of bridge is to scan the bridge deck using a GPR equipment from manufacturers such as Geophysical Survey Systems, Inc. (GSSI) or Ingegneria Dei Sistemi (IDS). The typical frequency range of GPR antenna for scanning bridge deck varies from 1 to 5 GHz and lower the frequency, higher the depth an antenna can penetrate (24). The developed model using image processing for generating deterioration map is formulated in the flowchart as shown in Figure 7. After the GPR bridge deck is scanned, the profile data is obtained from respective equipment and it is converted into image files such 'jpeg' or 'png'. These image files are loaded into the MATLAB® software for further processing of image. Each loaded image is composed of small units or square areas called as pixels. The loaded files are converted into greyscale image having intensities ranging from 0 to 256 pixels, wherein lower pixel values indicates darker shades of grey and vice versa. An image containing pixel value of 0 indicates absolute black color and 256 pixel value indicates absolute white color. Any pixel contained within the GPR profile after it is converted to greyscale image has a unique value in the range of 0 to 256 as stated.

The GPR data has profiles of bridge deck in a sequential order depending upon the way and direction it is scanned. Each profile is analyzed one at a time and after generating deterioration scale for one profile, another profile is analyzed and so on. This process is iterated until all profiles are completed and later on, all the individual deterioration scales of each profile are cumulated to form a complete deterioration map for the whole bridge deck.

The next step in the iterative process of analyzing individual profile after converting it into greyscale is to apply a thresholding filter known as 'standard filter'. When the background is highly uniform as in the case of GPR profiles, instead of applying global threshold, utilizing a local threshold is more beneficial (25) and can be useful in distinguishing hyperbolic variations in the image.

In this approach, a threshold is computed at every point or pixel (x, y) in the image depending upon one or more specified properties of the neighborhood pixels of (x, y) . The standard filter finds the local standard deviation of each pixel in its neighborhood in the image. The mean and standard deviation of a point (x, y) in an image can be represented as m_{xy} and σ_{xy} . The local standard deviation of image is calculated using MATLAB function 'stdfilt' having the following syntax:

$$g = \text{stdfilt}(f, \text{nhood}) \quad (1)$$

where 'f' is the input image and nhood is an array of zeros and ones in which the nonzero elements specify the neighbors used in the computation of the local standard deviation' (25). The default value of nhood is ones(3) but in our case nhood of ones(9) is specified to factor in more range of neighborhood pixel to calculated stand deviation. Its size should always be odd when it is defined. The following custom function is used to calculate the mean at each pixel value:

```
function mean = localmean(f, nhood)
%LOCALMEAN Computes an array of local means.
if nargin == 1
nhood ones(9) / 27;
else
nhood nhood / sum(nhood(:));
end
mean = imfilter(tofloat(f), nhood, 'replicate');
```

This function calculates the mean of each pixel by assuming it to be neighbor of nhood of 9 equal ones. The output MEAN is an array the same size as F containing the local mean at each point' (25). The function 'imfilter' filter the multidimensional array of image f with neighborhood filter of ones (9) matrix. The threshold function based on the local mean and local standard deviation for a pixel (x, y) can be defined as follows:

$$T_{xy} = a\sigma_{xy} + bm_{xy} \quad (2)$$

If global mean of the image is used instead of local mean for each pixel, the function is written as, where m_G represents the global mean:

$$T_{xy} = a\sigma_{xy} + bm_G \quad (3)$$

The segmented image is a contrast enhancement techniques and is computed as follows, wherein $f(x, y)$ is the input image and it is calculated for all pixels in the image:

$$g(x, y) = \{1 \text{ if } f(x, y) > T_{xy}; 0 \text{ if } f(x, y) \leq T_{xy}\} \quad (4)$$

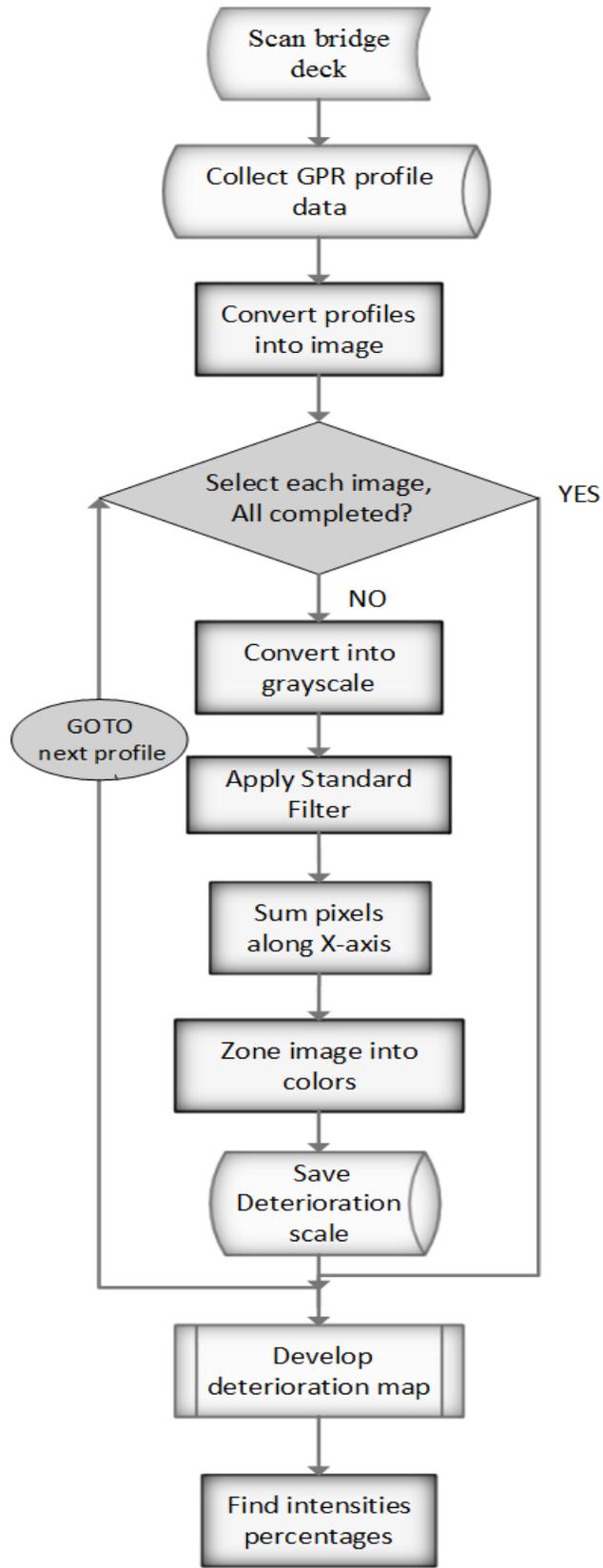


Figure 7 Model Development for developing deterioration map using image processing

Based on the concepts discussed above, all profiles which are converted into image are applied with standard filter. The process of applying this filter and its consequence on the image will be described in the next section. After applying the standard filter, the images look like an 'x-ray' of the original grayscale image and show the hyperbolas distinctly in white color and based on the deterioration level of the rebars, the intensities vary. Higher intensities with distinct hyperbolas indicate areas of good corrosion while lower intensities with distorted or faded hyperbolas indicate areas of corroded regions. This methodology is used to develop a deterioration scale for each image. It is generated by adding all pixel values along horizontal axis at the base and later normalizing the summed values on a scale of zero to 256 pixels to indicate variations of grey shades across the image. By summing up and normalizing the values along the horizontal axis, the image is converted like a frequency one-dimensional signal having peaks and troughs. It is utilized to zone the image into three colors: green, indicating no or low corrosion region; yellow, indicating medium corrosion; and red, indicating areas of high corrosion. The zoning of image yields to a deterioration scale for a particular profiles. Such scales are developed for all profiles and combined to generate deterioration map for the complete bridge deck. From the deterioration map, the areas of green, yellow and red zones are counted and the percentages of each areas are calculated to assess the overall condition of the bridge deck.

MODEL IMPLEMENTATION

In order to illustrate the result of applying the model over an image using a neighborhood of ones (9) matrix, consider the image as shown in Figure 8 (a). The sample image shown is the GPR profile scan of a real case bridge and when the standard filter is applied to find local standard deviation of image based on the above equations described, the result obtained is shown as the black and white image in Figure 8(b). The hyperbolic variations clearly stand out in the output image based on this thresholding and will be useful in zoning the image based on its deterioration level.

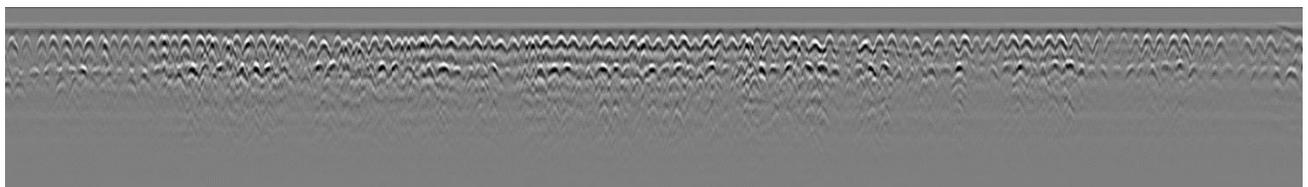


Figure 8 (a) Sample GPR Profile

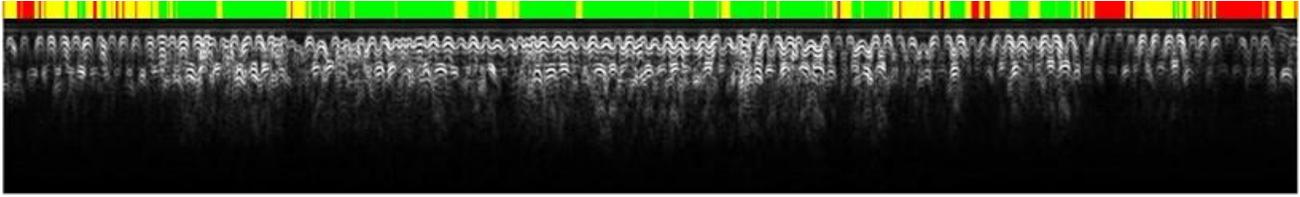


Figure 8(b) Output image with deterioration scale

After the output image is obtained by applying the standard filter, the next step is to zone this profile based on severity of corrosion. This is performed using the following steps: firstly, pixel values are all added vertically across each column across the whole image horizontally and later on the sum of pixel values obtained are normalized on a scale of 0 to 256 indicating the range of grey level a pixel can contain. Once the normalization is performed, each column or stripe of 1 pixel length can be represented by one unique grey level. Based on the grey level contained in each stripe, it is zoned as red, yellow and green based on its value. Red indicates high level of corrosion, yellow indicates moderate while green indicates no or low corrosion level of that stripe or column in the image. If the pixel value lies in the range of 0 to 30, it is zoned as red, if the value lies in the range of 31 to 120, it is zoned as yellow and if the value lies between 121 and 256 it is zoned as green. This zoning is performed for all the stripes or columns in the image and a deterioration scale is developed for the GPR profile as shown by the colored scale on top of the black and white profile in Figure 8(b). Consequently, green areas in this scale represent areas of no or low corrosion, yellow as moderate and red as areas of high corrosion corresponding in the GPR profile as stated before.

The deterioration scale is developed similarity for all GPR profiles of the scanned bridge deck and cumulated to generate the deterioration map for the whole bridge deck. By calculating the total areas of red, yellow and green pixel in the generated map, a bridge inspector can use it an indicator for schedule repair or maintenance of the bridge deck. Additionally, the red zones in the map will indicate zones of concern or repair which could help prioritize the areas of bridge deck which need immediate attention from bridge maintenance authorities.

CASE STUDY

A real case bridge deck is analyzed using the developed model, deterioration map is generated and compared with result obtained from visual image analysis approach performed manually by an expert for validation. The bridge deck inspected is located in Iowa State and was scanned using a GSSI GPR equipment named SIR[®] 3000 with a 1.5 GHz antenna. The ground-couple GPR antenna was dragged across the bridge deck at uniform speed by pulling the cart over the bridge deck. Each trace was performed at 2 feet apart from each other and a total of 24 swabs were needed to complete the scan of the bridge.

The scanned bridge deck data can be seen in the registered trademark propriety software of GSSI called 'RADAN[®]'. The GPR profile data in the RADAN software is converted into image files (.bmp format) using a software utility tool provided by GSSI called 'rad2bmp.exe'. All the 24 GPR profiles are converted to image files and loaded into MATLAB[®] software for image processing using the developed model. Each profile is applied the standard filter and other consecutive steps are performed to create separate deterioration scales for each of the profiles based on the steps described in the model implementation. The developed scales of all profiles are cumulated to generate the deterioration map for the bridge deck as shown in Figure 9. For a visual comparison, the deterioration map generated by an expert using the original visual image interpretation method is shown in Figure 10. If both the figures are compared visually, it can be inferred that the deterioration map using the developed model correspond closely with the manual expert based method. The zones of deterioration or bad concrete as shown in both the figures in yellow and red color are similar and take the priority during bridge deck repair.

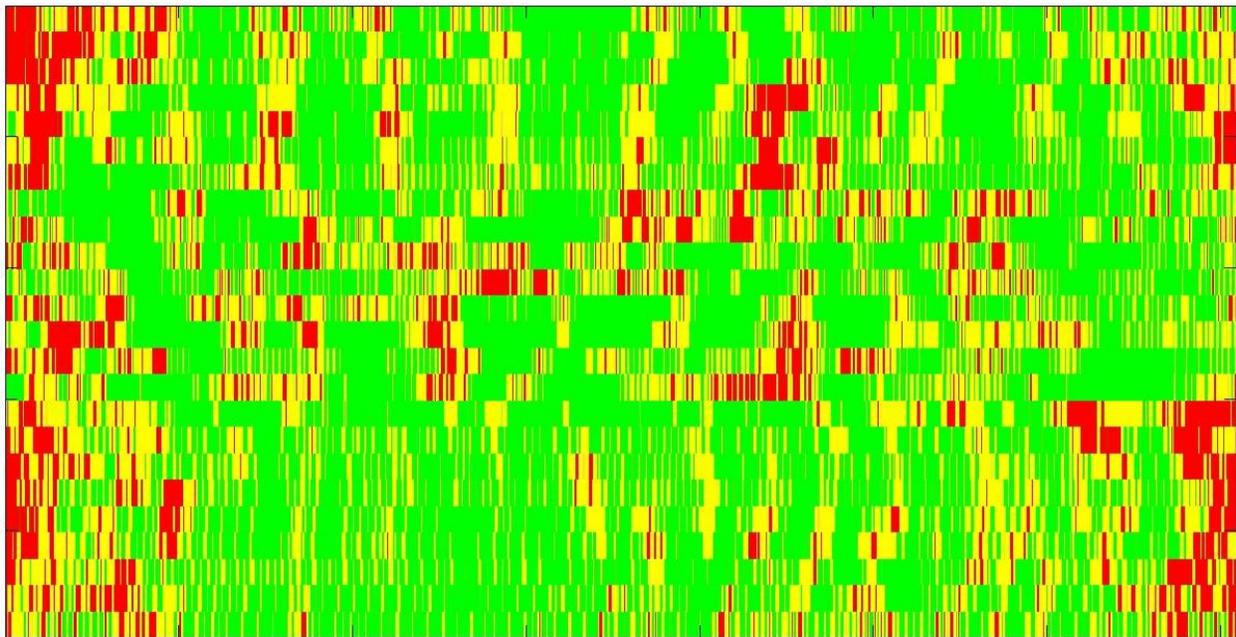


Figure 9 Deterioration map generated using developed scale for Iowa bridge deck

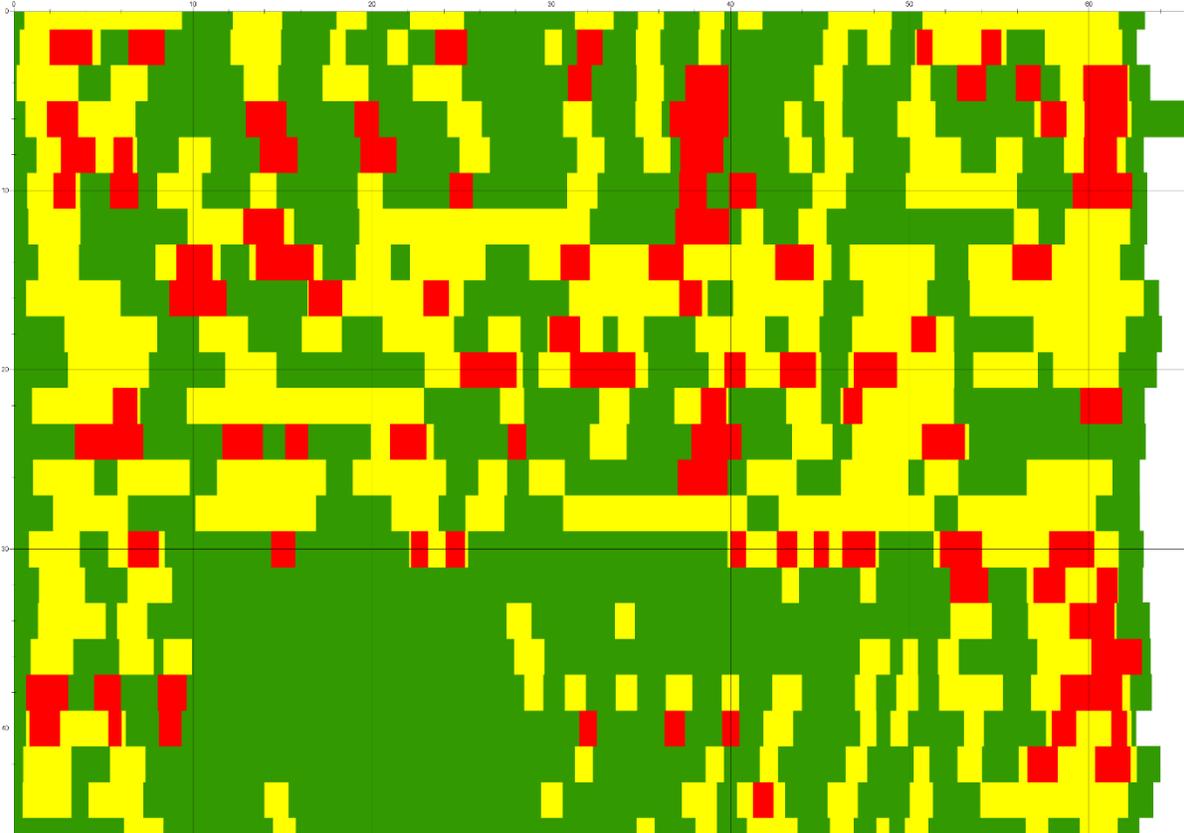


Figure 10 Deterioration map for Iowa bridge deck using expert based visual approach

A quantitative comparison between both the deterioration maps can be done by calculating areas percentages of red, yellow and green pixels. The scale for zoning (0 to 30 for red zone, 21 to 120 for yellow zone and 120 to 256) was developed after multiple iterations and performing sensitivity analysis with various ranges of pixel values. However, the scale utilized is chosen based on its deterioration map generated which shows closest correspondence with the expert based visual approach map as shown in Table 1 and it was also tested on GPR profiles of other bridges. The percentages of green area in developed model map (53.6%) is very close to the percentage of green area in expert based manual map. Similarly other areas are similar and this validates our developed model. Hence, utilizing image processing techniques an automated approach based on visual approach for generating deterioration maps of reinforced concrete bridge deck has been developed.

Table 1 Percentage of Areas of Green, Yellow and Red in Developed Model vs. Manual Expert based visual approach

Deterioration Map Type	% of Area of Green	% of Area of Yellow	% of Area of Red
Expert based manual visual approach	54%	34.5%	11.5%
Automated Model { Zone Scale: Red (0-30); Yellow (31 – 120); Green (121 -256) }	53.6%	35.6%	10.8%

CONCLUSION

GPR is a powerful NDT technique for condition assessment of reinforced concrete bridge decks. However, the interpretation of GPR data has been an issue with the commonly utilized numerical analysis approach. A novel visual approach which utilizes an expert to manually browse through profiles to mark attenuated areas and develop corrosion maps proposed in the literature overcomes various limitations of numerical approach. However, subjectivity is an issue with this approach. The authors of this paper have automated this approach by utilizing image processing tools and have developed a model which generates map having results similar to the subjective approach. Image filtering is utilized along with summation of pixels along an axis to create a one-dimensional signal which can be utilized to develop deterioration scale. The scales are combined for all profile to generate deterioration map for the whole bridge deck and percentage intensities are calculated for assessing the bridge condition which can be utilized for decision making by bridge authorities. The model validated through application over a real case bridge in Iowa and the percentages of areas developed correspond closely with the manual expert-based visual image method. Such an automated model can be very useful for bridge inspectors as the deterioration maps generated through this model can be used to identify and focus on critical zones of corroded areas in a reinforced bridge deck.

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