Full wavefield imaging detection method and its application on defect investigation of highway embankment

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ABSTRACT

A full-wavefield imaging detection method is developed and then applied to reveal the defects in the highway embankment. This testing system integrates the point- source/point-receiver scheme with the multi-directional imaging technique to achieve the effect like scanning. It is equipped with an impacting hammer, a series of three-component velocity transducers and a signal capturing unit. To evaluate the feasibility of this system for detecting defect of highway embankment, a full-scaled highway embankment model test with pre-setting defection is conducted. And a 3-D numerical simulation using FEM are performed for comparison and mechanism study. It is paid special attention on the propagation characteristics of full wave field in the model. The characteristics of spectral characteristics derived from Fourier transform are analyzed. Experimental results show agreement with the numerical ones on the processed scanning images. It is concluded that the full-wavefield imaging detection method exhibits high potential in inspecting the defects of highway embankment by imaging.

Keywords: detecting defect, full-wavefield imaging detection method, highway embankment, 3-D numerical simulation

1 INTRODUCTION

In China, there were 96200 km highways (end of 2012), ranking first in the world. Subgrade is required to be stable enough to provide a reliable bearing capacity during operation time. Defect of subgrade usually leads to pavement damages, especially for high subgrades, soft soil subgrades, and seasonal frozen soil subgrades. The type of defects were non-homogenous settlement, crack, hollow under pavement, subgrade cavities and so on. It may even cause serious safety problem, so a fast and effective detection and evaluation method to defect investigation is very important. Now real-time monitoring and GPR is considered as a significant method in detecting unequal settlement defects, including soil freezing, soil loosing, and soil disengaging (Malhotra & Carino, 1991; Shaw, et al. 2005).

Recently the elastic-wave based techniques are paid great attentions in nondestructive testing (NDT) technologies for civil engineering. In 1991, the impact-echo method, which transforms the time-domain signal into the frequency domain, then searches for the resonance frequency, to detect the defects inside a specimen (Malhotra, & Carino, 1991). In detection of concrete, elastic-wave-based imaging method is used to display the tip of surface-breaking cracks (Chang, et al. 2001; Tong, et al. 2007). The

point-source/ point-receiver scheme is especially suitable for the inspection of on-site civil infrastructures. In 2008, Che et al., Feng et al. (Che, et al. 2011, Feng, et al. 2013) and Liu et al. (Liu, et al. 2013) proposed an elastic-wave imaging method to investigate the grouting construction of the immersed tube tunnel. It could be a practical and effective NDT method for defect inspection on civil infrastructures. However, these studies also focus the one-direction. The image quality can be affected by reflection of boundaries as the boundaries of inspection structure belong to a limited inspection. Therefore, more signals are captured by multi-direction and used to obtain more information under the structures. In this paper, a 3D model is build and finite element method is employed to analysis the propagation characteristic of elastic wave in the numerical model. And in the field test a full scale model that has been built with the materials and construction in accord with the real highway. The results from the finite element analyses are compared with actual measurements in predominant frequency could be used as the basis for detection.

2 PRINCIPLE OF FULL WAVE-FIELD IMAGING METHOD

To match the present NDT measuring scheme in civil engineering, the measurement of full-wavefield

imaging detection method is completed with a point-source/point-receiver set with certain space. As shown in Figure 1, a series of impact-and-receive operations is performed on the free surface of the model. Let S_i and R_i represent the locations of a set of the source and receiver for the i -th measurement. Furthermore let $T_i(t)$ be the response signal recorded at R_i for this measurement. The domain of $T_i(t)$ is then divided into three directions. And then the spectrum characteristic of $T_i(t)$ can be obtained by FFT analysis in three directions.

Fig. 1. Schematic showing the implementation of impact-and-receive operations.

As we know, in semi-infinite space a localized disturbance on the surface of elastic medium should occur oscillation (Miller & Pursey, 1955). Loading from any surface point, the type of wavefield, displacement mode, propagation direction and amplitude can be described as Figure 2. Longitudinal waves (P) and shear waves ($S=SH+SV$) propagate radially outward along the radial direction of hemispherical centered the exciting point. And the wave surface of the Rayleigh wave (R) is a cylindrical surface centered the exciting point as column center. Rayleigh wave (R) consists of horizontal and vertical components, which composited an elliptical trajectory. Its amplitude is rapidly decreased with depth both of the vertical and horizontal components. When the medium is layered structure, another surface waves will produce in the media surface, called Love wave (L). The propagation direction of the Love wave is perpendicular to the wave propagation and parallel to the surface of the medium. When the materials of the medium are different, there will be occurred reflection and refraction. The response is rather complicated due to consist of P-wave, S-wave and surface waves as well as converted waves, as shown in Figure 2.

3 NUMERICAL SIMULATION OF THE FULL-WAVEFIELD PROPAGATION IN 3D HIGHWAY EMBANKMENT MODEL

3.1 Numerical model and parameters

To clarify the full-wavefield propagation, a three-dimensional finite element model of highway embankment model with defection is simulated, as

shown in Figure 3. The model consists of three parts, pavement in the top of the model with 0.25 m depth and concrete material and below the pavement there is embankment of the highway with compacting soil. The defect area measures $0.5 \times 0.5 \times 0.15 \text{ m}^3$ and is filled by some other soft material. This area is in the middle of the embankment just blow the pavement. The model is divided by hexahedron elements whose minimum size is 0.1m in both width and height, as shown in Figure 3(a). It consists of 125,168 elements and 141,948 nodes. The bottom boundary of model is connected with infinite regions in order to absorb P-wave and S-waves.

Fig. 2. Propagation of elastic wave in semi-infinite space.

Fig. 3. 3D FEM model and layout of survey lines.

The material parameters are chosen from the conditions related to reality. All of the material parameters are listed in Table 1, where ρ is the density of material, E is the modulus and μ is the Poisson's

ratio. Figure 4 shows the wave form and spectral characteristic of the source. The excitation of elastic wave is conducted by continuous dynamic loads containing the time of 0.024 seconds. The frequency of source is in range from 0 kHz to 10 kHz and the predominant frequency is about 1500 Hz.

Table 1. Material parameters.

Layer	$\rho(\text{kg/m}^3)$	$E(\text{GPa})$	μ
Pavement	2400	34.5	0.2
Local defect area	1100	0.001	0.45
Subgrade	2300	25	0.25

Fig. 4. Waveform and spectral characteristic of the source.

3.2 Full-wavefield propagation characteristics

A series of impact-and-receive operations are performed on the top surface of the model as shown in Figure 3(b). The response signals of the velocity recorded by the nearby receiver on the surface are obtained for further process. Inputting the vibration source on the surface in the center of the model, and the dynamic response can be obtained. Figure 5 shows distribution of horizontal and vertical velocity of the model at the time 0.00077 s, where the color changed by amplitude. It shows the propagation path change with the different directions. The spectrum characteristics are obtained by FFT analysis, as shown in Figure 6. The spectrum is predominant at 1600 Hz in the three directions, and the corresponding predominant amplitude is different, which is largest in the z direction, and the next is in the y direction. The spectrum characteristic is shown predominant at defect location in the three directions. It can be considered that the SH wave and the Rayleigh waves reflect from the boundaries between the defect and the concrete.

Fig. 5. Distributions of horizontal and vertical velocity.

Fig. 6 Spectrum characteristic of Line-1.

To discuss the influence of epicenter location, the predominant amplitude of the spectrum of Line-1 and Line-4 is placed in upward order along the measurement lines, as shown in Figure 7, where the input of Line-1 locate at defect area, and input of Line-4 without defect. It can be observed that the amplification of predominant spectrum increases around the defect area in the three directions. The increasing magnification and area are largest in x direction. In y direction, the increasing area is smallest. Anyway, it can be concluded that the sensitivity of defect from impact is great larger than the receiver.

Fig. 7. Distribution of predominant amplitude of spectrum.

Using the predominant amplitude of the spectrum and image processing technique, a scan-like image can be obtained as shown in Figure 8. In these figures, a red bright area in the center indicates that there exists a defect in x , y and z directions. From the figures, the location of the defect can be observed. It can be seen that in y direction the defect may be presented in a more evident and accurate way.

Fig. 8. Distribution of predominant amplitude of spectrum.

4 MODEL TEST OF HIGHWAY EMBANKMENT

4.1 Test introduction and Data acquisition

To evaluate the feasibility of the observation system, we carried out a model experiment located at Zhengzhou University, China. The model is built with the materials and method according to the real highway as shown in Figure 9. It consists of three parts, the first layer is pavement with 0.25 m depth and concrete, and

the second layer is embankment of the highway with compacting soil. Among them, a defect area, which measures $0.5 \times 0.5 \times 0.15 \text{ m}^3$ with saturated soil, is set up. There is a coupling layer between the pavement and embankment, which made of clay with 2 cm depth.

Fig. 9. Field test model and its structure

This testing system is equipped with an impacting hammer, a series of three-component velocity transducers and a signal capturing unit. Digital seismograph (Geode) with 24-channel (Ch) and 24-bit A/D conversion is used as the data acquisition system. The 3-component geophones with 2-horizontal and 1-vertical direction on the pavement together with a suit of coupling device are used for receiving the ground response excited by a 0.454 kg rubber hammer. Figure 10 shows the details of the layout of survey line on the pavement. The distance between the impacting source and the receiver is always set to be 20 cm and the distance to move from the current impacting point to the next one is 30 cm. The first measurement is made at 30 cm from the side surface of the plate. Each line is arranged by a total of 8 survey points.

4.2 Data acquisition and analysis

The experiment is then carried out with a series of impact-and-receive operations on the top surface of the concrete plate. The diagram of the velocity waves recorded when the concrete plate is impacted by a hammer. The spectrum characteristics are obtained by FFT analysis, as shown in Figure 11. The spectrum

characteristic is shown predominant at defect location in the three directions. It can be considered that the SH wave and the Rayleigh waves reflect from the boundaries between the defect and the concrete.

Fig. 10. Layout of survey lines.

Fig.11. Spectrum characteristic of Line-4.

Using the predominant amplitude of the spectrum and image processing technique, a scan-like image can be obtained as shown in Figure 12. It can be seen that a red bright zone appears at the place of the defect in x , y and z directions. It can be considered that this method

can provide good results to identify the number of the defects and their locations, sizes. The experimental result shows good agreement with numerical simulation result presented previously.

Fig. 12. Distribution of predominant amplitude of spectrum.

5 CONCLUSIONS

A well-developed instrument is essential for a new NDT method when it is applied to in-situ highway

embankment. The integrating point-source / point-receiver scheme with full-wavefield for defects imaging is developed. The image can expose the defect location in the highway embankment immediately after a series of impact-and-receive operations. The experimental result inspected by this system shows very good agreement with the result simulated by FEM method. The location and size of the defect can be clearly identified from the image. It shows great potential of this full-wavefield imaging detection method on detecting the defects in in-situ highway embankment.

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