The Numerical Investigation into the Influence of the Scattering Effect from the Aggregates of Concrete on the Transient-elastic-wave-based NDT Technologies

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Abstract

Recently, the transient-elastic-wave-based nondestructive evaluation technologies are well developed, and then successively applied to monitor the quality of in-situ civil structures. It is worth to note that the principle of present technologies is based on the assumption that concrete is treated as a kind of homogeneous material. It could really simplify the analysis of the inspected results with that assumption when the wavelength of elastic wave is much larger than the dimension of the largest aggregates. However, the scattering of elastic waves by the aggregates does affect the analysis of the received signals while the short-wavelength elastic wave is used to enhance the resolution of inspection. To understand the influence of scattering effect on those methods, a quantitative analysis on concrete material is indispensable. In this paper, the finite difference method was used to simulate the propagation of transient elastic wave inside concrete structure. The force-time function of impact source corresponding to various steel balls was derived from Hertz contact theory. The numerical model made with two materials, the specific size aggregate and the cement paste, was used to simulate the real concrete. And the other model with only one homogeneous material was treated as an ideal concrete. The surface responses of standard impact-and-receive operation were calculated out on these two models. The coherent coefficient of these two received signals was regarded as the quantitative index of signal distortion owing to scattering effect. Relations between that coefficient and possible effective parameters were carefully analyzed and discussed in this paper. The numerical analysis shows that as the ratio of wavelength to aggregate's diameter increases, the scattering effect decreases. When the ratio is larger than 10, the coherent coefficient approaches to 1 and the scattering from aggregate almost vanishes. The concrete could be treated as a kind of homogeneous material and then the analysis assumption of elastic-wave-based NDT principle matches. Besides, the result also shows that the acoustic impedance difference between aggregate and cement paste will seriously affect the coherent coefficient. It would be very useful when NDT is applied on the high-performance concrete structure. In this paper, the result reveals the quantitative analysis of the scattering effect. The achievement of this research could provide very useful information for selecting a proper elastic wave source when performing the NDT inspection on concrete structures. Also, it could be a useful reference for analyzing the received signals regarding the inhomogeneousity of concrete material when developing new elastic-wave-based NDT technologies.

Keywords: NDT, concrete material, inhomogeneous material

1. Introduction

For years, the point-source/ point-receiver based method has become one of the most popular NDT technology for evaluating the integrity of concrete structures. By using a mechanical impact, it can generate high-energy elastic wave propagating in concrete material to overcome the shortcoming in low detectable depth of the traditional ultrasonic method [1]. In these methods, a steel ball impact on the specimen's surface is often used as the elastic wave generator and then a transducer with a small contact surface is adopted to receive the response on the same surface. This can be simplified as an ideal concentration impulse problem for further analysis. In the analysis, concrete is always ideally treated as a homogeneous material. However, it is intrinsic inhomogeneous which is a mix of cement and aggregate. In the real world, to approach the homogeneous-material assumption, it is very important to check if the wavelength of the induced elastic wave is much larger than the dimension of aggregate. For some in-situ applications, we need to use smaller steel ball to generate short-wavelength elastic wave so that the resolution of inspection will improve. But if the steel ball is too small, the scattering effect from aggregate arises. In order to provide the NDT operating staff a guideline to select a proper impact source, it is very important to find out the quantitative description about how the scattering effect from aggregate influences the inspection result. From 1950s, some research results about the scattering of the elastic wave by the spherical inclusions have been published one after another [2-6]. However, for the elastic-wave-based NDT technologies performed on the concrete material, the quantitative analysis about the scattering effect is still invalid. In this paper, the normalized coherent coefficient of two received signals, unscattered and scattered response, was introduced as the quantitative index of signal distortion owing to scattering effect. Relations between that coefficient and possible effective parameters were carefully analyzed and discussed. Finally, the result of a serial of experiments carried out on the real concrete specimens will be used to verify the numerical results.

2. Evalustion of scattering effect

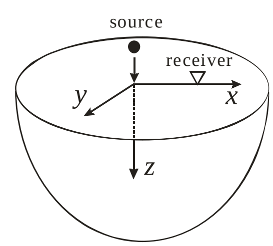

Fig. 1 Coordinates of a half-space with a point source applied at the origin.

For present elastic-wave-based civil NDT technology which adopts point-source/ point-receiver setup, the surface time-domain response is the most important signal for further analysis to find the inclusion inside the concrete structures. In these methods, concrete is always treated as a kind of homogeneous material. If the wave source is not selected properly, however, the homogeneous assumption will be invalid and the scattering from aggregate will arise. The distortion of the received signal will ser iously influence the inspection. To evaluate the scattering effect, the coherent coefficient was introduced to define the distortion quantitatively. The coherent function $R_{xy}(\tau)$ is defined as follows:

$$R_{xy}(\tau) = \frac{\sum_{n=-\infty}^{+\infty} x_n y_{n-\tau}}{\sqrt{\sum_{n=-\infty}^{+\infty} x_n^2 \sum_{n=-\infty}^{+\infty} y_n^2}} \tag{1}$$

where x_n, y_n represent the surface responses induced by the elastic wave propagating in the homogeneous material and the inhomogeneous material respectively. These two responses are received at the same condition excepting the media for wave propagation. The maximum value of coherent function, at $\tau=\tau_0$, is defined as the coherent coefficient which is regarded as the quantitative index about how the received signal is affected by the scattering owing to the inhomogeneous nature of the concrete material. In other words, when the coherent coefficient is 1, it means these two responses are totally the same and no scattering effect arises; when the value is 0, they are totally different signals.

Consider a point impact exerting on the surface of a half-space, the response is recorded on the surface by a point receiver, as shown in Fig. 1. Shown in Fig. 2 are the numerical examples of trace distortion in different coherent coefficients. In each pair, the upper signal is the x-directional displacement response while the elastic wave is propagating in homogeneous material; the lower signal is the response affected by the scattering from inhomogeneous material. A half $\sin^{3/2} t$ function is used to model the force-time function of a steel ball impacting elastically on an elastic material. The value of time axis is normalized by the contact time T_c and the dash line on Fig. 2 represents the arrival time of Rayleigh wave.

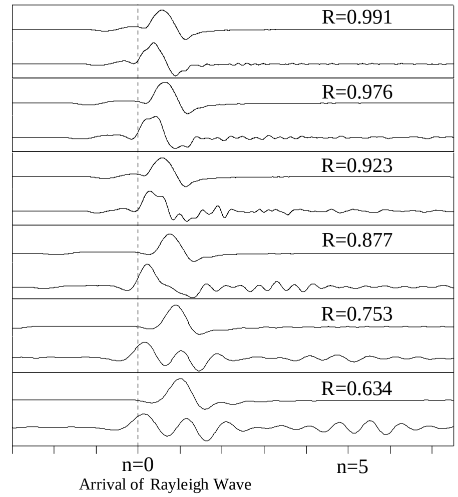

Fig. 2 Examples of trace distortion in different coherent coefficients.

As shown in Fig. 2, it is very easy to find the relation between the scattering effect and the coherent coefficient. The scattering effect almost disappears while the coherent coefficient approaches 1; otherwise the distortion is severer as the coherent coefficient getting smaller.

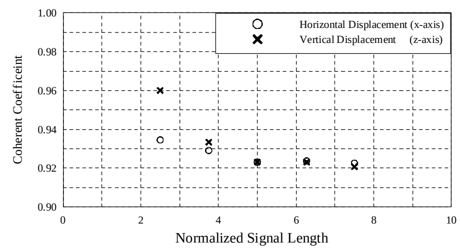

Fig. 3 Relation between normalized signal length and coherent coefficients.

The key of this research is finding how the scattering effect influences the result of NDT inspection. In these methods, the transient response of time-domain signal is the most important data for analysis. Therefore, when evaluating the coherent coefficient, the length of signal captured for calculation will affect the result. In Fig.3, it shows the relation between normalized signal length and coherent coefficients. The horizontal axis is defined the same as that in Fig. 2.As the normalized signal length is larger than 5, the coherent coefficient will become stable.

3. Numerical analysis

To simulate the elastic wave propagating in concrete, the numerical analysis is performed with the finite difference program. As shown in Fig. 4, the numerical model made with two materials, the specific size aggregate and the cement paste, was used to simulate the real concrete. And the other model with only one homogeneous material was treated as an ideal concrete. A half $\sin^{3/2} t$ function is used to model the force-time function of a steel ball impacting elastically on an elastic material.

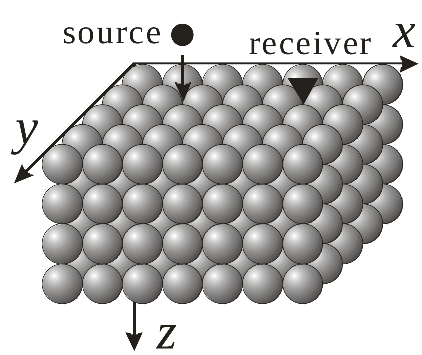

Fig. 4 Configuration of numerical simulation.

In Fig. 5, it shows the relation between λ/D (wavelength to diameter) ratio and coherent coefficient while the wavelength of elastic wave is fixed and the diameter of aggregate changes in each case. The acoustic impedance ratio of cement paste to aggregate is fixed 0.54. From the result, it is easy to find that the larger the λ/D ratio is, the closer the coherent coefficient is approaching the value 1 which means the scattering effect vanishes and therefore it is reasonable to treat concrete as a kind of homogeneous material. One may notice that there is a substantially jump of coherent coefficient around the λ/D ratio of 5. While the wavelength is about 6 times larger than the diameter of the aggregate, the coherent coefficient is

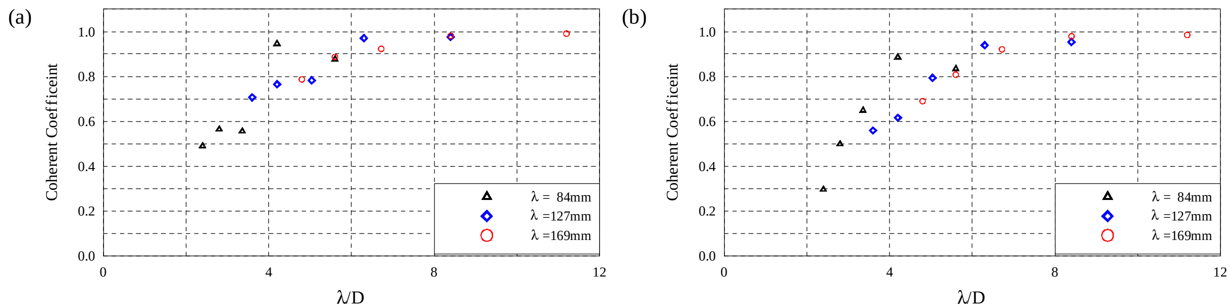

Fig. 5 Relation between λ/D ratio and coherent coefficient while wavelength fixed. (a) x-direction displacement (b) z-direction displacement.

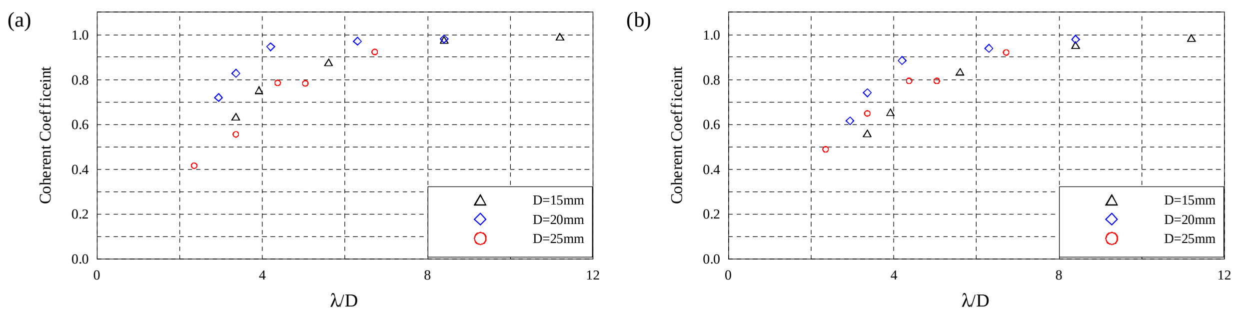

Fig. 6 Relation between λ/D ratio and coherent coefficient while aggregate diameter fixed. (a) x-direction displacement (b) z-direction displacement.

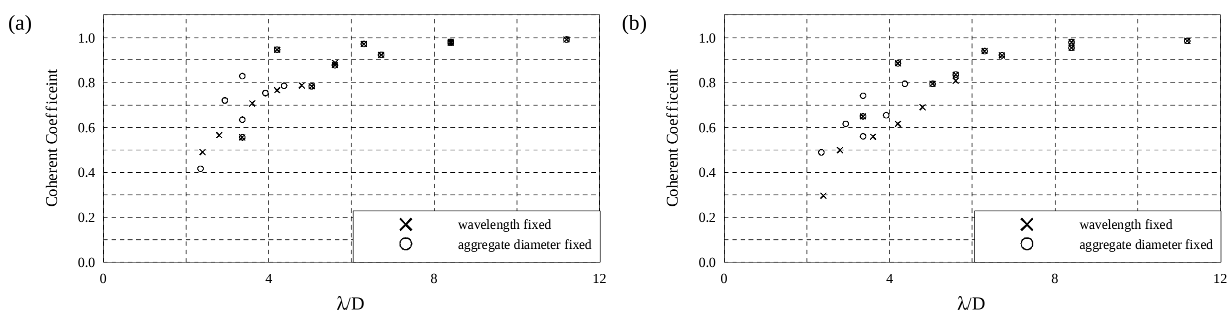

Fig. 7 Relation between λ/D ratio and coherent coefficient. (a) x-direction displacement (b) z-direction displacement.

more than 0.9 which means the scattering effect is very slight. In some in-situ NDT applications, it could be a trade-off point when the inspection parameters of resolution and S/N ratio are taken into consideration.

For present transient-elastic-wave-based NDT technologies, it is often adopted as the elastic wave generating method by shooting a steel ball on the surface of specimen. The advantage of this mechanism is that it can generate high-energy and narrow-band elastic wave. The wavelength corresponding to the central frequency can be estimated easily from Hertz contact theory [7]. In other words, the wavelength of elastic wave can be controlled just by selecting a proper-sized steel ball. In Fig. 6, it shows the relation between λ/D ratio and coherent coefficient while the diameter of aggregate is fixed and the wavelength of elastic wave changes in each case. Putting the result from Fig. 5 and Fig. 6 together, it shows consistent trend of the coherent coefficient varied with the change of λ/D ratio no matter whether the wavelength or the aggregate diameter keeps fixed, as shown in Fig. 7.

From the theory of elastic wave, the energy ratio of reflection and refraction on the interface is determined by the acoustic impedance of these two media. In concrete material, it will form a discontinuous interface when the cement paste meets the aggregate. In Fig. 8, it shows the relation between acoustic impedance ratio and coherent coefficient in different λ/D ratio. The impedance ratio of the cement paste meets the aggregate does affect the coherent coefficient evidently while λ/D ratio keeps fixed. The more the difference of the acoustical properties between two media, the more evident the scattering effect from aggregate it is. One may notice that the λ/D ratio will not be

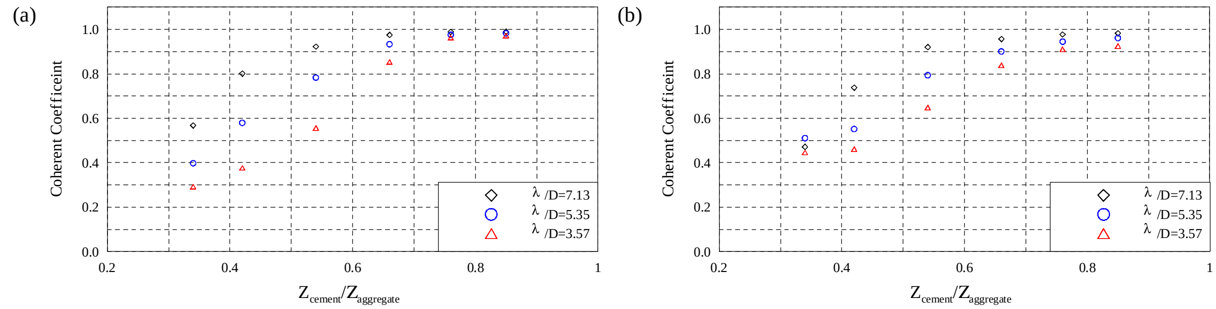

Fig. 8 Relation between impedance ratio and coherent coefficient. (a) x-direction displacement (b) z-direction displacement.

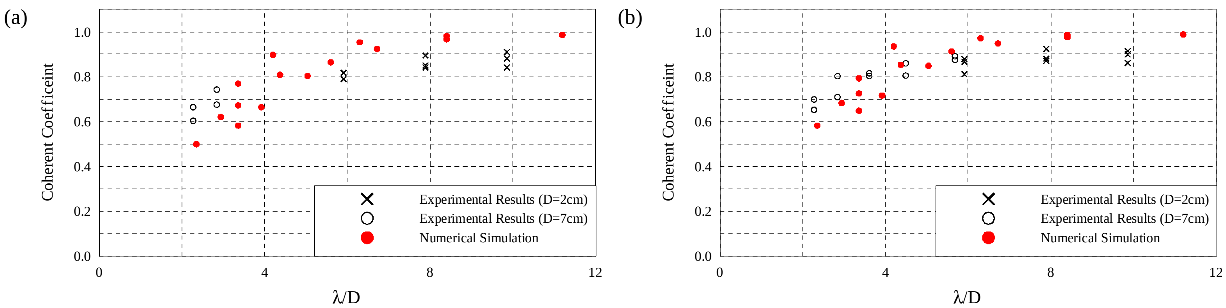

Fig. 9 Experimental results of relation between λ/D ratio and coherent coefficient. (a) n=5.5 (b) n=3.

a critical parameter to the scattering effect when the acoustic impedances of the cement and the aggregate are almost the same; the coherent coefficient approaches 1 while the impedance ratio is very close to 1. In other words, it is very suitable to treat the high-strength concrete as a kind of homogeneous material when performing the transient-elastic-wave-based NDT inspection on it.

4. Experimental result

To verify the numerical analyzing results, two concrete blocks with different size aggregate, 2cm and 7cm in diameter, were fabricated for experiment. The dimension of these specimen are the same, 1m×1m×0.5m. A series of impact-and-receive experiments are performed on these two specimens with steel balls in different diameter. The surface response of vertical displacement (z-direction) was carefully recorded for further processing. To match the assumption of half-space impact response, the portion of the received signal after the arrival time of boundary reflection was cut off. Besides, the coherent function is revised as follows to prevent the error from the DC offset of the experimental signals.

$$R_{xy}(\tau)=\frac{\frac{1}{N}\sum_{n=-\infty}^{+\infty}(x_n-\bar{x})(y_{n-\tau}-\bar{y})}{\sqrt{\frac{1}{N}\sum_{n=-\infty}^{+\infty}(x_n-\bar{x})^2\,\frac{1}{N}\sum_{n=-\infty}^{+\infty}(y_n-\bar{y})^2}}\quad ,\bar{x}=\frac{1}{N}\sum_{n=-\infty}^{+\infty}x_n\ ,\ \bar{y}=\frac{1}{N}\sum_{n=-\infty}^{+\infty}y_n \qquad (2)$$

Where N is the number of data point and x_n, y_n represent the surface responses induced by the elastic wave propagating in the homogeneous material and the inhomogeneous material respectively. In the experimental results, the response of the homogeneous specimen is obtained from the numerical simulation; and the response of the inhomogeneous specimen is obtained from the experiment. All the material constants for numerical simulation are measured on the real concrete specimens.

Shown in Fig. 9 are the relation between λ/D ratio and coherent coefficient obtained from numerical and experimental result. The experimental result shows good agreement with the numerical result. The coherent coefficient arises as the λ/D ratio increases. But there is a little bit different that the coherent coefficient doesn't go very close to the value 1 in the experimental result while the λ/D ratio is over the value of 6. The reason could be that all the parameters of the experiment could not be obtained without error so the numerical simulating response for idea homogeneous modal will be a little different from the response of real condition. The most possible error could be from the uncertainty of the force-time function in real experiment. It will affect the shape of received signal severely. Nevertheless, the trend of the relation between λ/D ratio and coherent coefficient in experimental result is the same as that in numerical result.

5. Conclusion

For present transient-elastic-wave-based NDT technologies on civil structures, it is very important to assume concrete is a kind of homogeneous material when analyzing the received signals. To prevent unwanted scattering caused by aggregate, the selection of wave source is very critical for getting a correct result. In this paper, the coherent coefficient was introduced as a quantitative index of signal distortion owing to scattering effect. Numerical simulation and experimental result both show that as the λ/D ratio increases, the coherent coefficient is closer to 1. In other words, the scattering effect is not more obvious and then concrete could be treated as a kind of homogeneous material when the wavelength is much larger than the diameter of aggregate. One critical value should be point out here, the coherent coefficient approaches 0.9 or above when the λ/D ratio is larger than 6 for general concrete material. Besides, result also shows that the acoustic impedance ratio of cement paste to aggregate is another important parameter of scattering effect. When it approaches 1, the coherent coefficient will be very close to 1 no matter how large the λ/D ratio is. That is to say it may be reasonable to treat the high strength concrete as a kind of homogeneous material when applying the transient-elastic-wave-based NDT inspection on it. All the results obtained in this paper could provide useful information to civil NDT operators for a guideline selecting a proper wave source that could prevent the received signals from affecting by the scattering effect.

6. Reference

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