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Sonic Tomography Analysis of Concrete Structures

Analyse des structures de béton par tomographie sonique

Sonisch-tomographische Analyse von Betonbauwerken

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SUMMARY

This paper discusses theoretical as well as practical aspects of a relatively new process in civil engineering that can be used to visualize the internal condition of a concrete structure using non-intrusive data acquisition techniques. This process combines computer tomography of sonic data with scientific visualisation techniques. The resulting output is a representation of the structure showing the spatial distribution of stress wave velocity within the structure.

RÉSUMÉ

Cet article discute l'aspect théorique aussi bien que l'aspect pratique d'un nouveau procédé en génie civil qui permet la visualisation des conditions internes des structures en béton à partir de données collectées d'une manière non destructive. Ce procédé combine le calcul tomographique de données d'essais soniques aux techniques de visualisation scientifiques récentes. Le résultat est une représentation graphique indiquant la distribution spatiale de la vitesse sonique au sein de la structure.

ZUSAMMENFASSUNG

Diskutiert werden in diesem Artikel die theoretischen sowie die praktischen Aspekte eines neuen Verfahrens im Bauwesen, wodurch eine Visualisierung der inneren Bedingungen eines Betonbauwerkes möglich ist, ohne das Bauwerk zu zerstören. Dieses Verfahren ist eine Kombination von sonisch-tomographischen Berechnungen und der neuesten Kenntnisse in wissenschaftlicher Visualisierungstechnik. Das Ergebnis ist eine graphische Darstellung der Raumverteilung von sonischer Geschwindigkeit innerhalb eines Bauwerkes.

1. INTRODUCTION

Currently, the inspection of concrete structures relies on the visual examination of the exposed concrete surface, occasionally supported by a number of nondestructive tests and by the removal of core samples for laboratory testing. Such an approach is clearly limited if more detailed analysis of the concrete is required for service life predictions, safety assessement, rehabilitation programs or determination of the extent of deterioration throughout the structure.

This paper discusses theoretical and practical aspects of a relatively new process in civil engineering that can be used to visualize the internal condition of a concrete structure using non-intrusive data acquisition techniques. This process combines computer tomography of sonic data with scientific visualisation techniques. The resulting output is a representation of the structure showing the spatial distribution of stress wave velocity within the structure.

2. THEORETICAL ASPECT OF SONIC TOMOGRAPHY

As any other nondestructive technique, sonic tomography includes three steps: (1) the collection of data, (2) processing of the collected data, and (3) the analysis of the results.

The collection of data consists on propagating acoustical waves through the medium from the sources (hammer, air gun, explosive) to the receiver (piezoelectric sensors, accelerometers, geophones or hydrophones). The location of both the source and receiver must vary such so that waves can widely cover the surveyed section, uniformly and in a large number of directions [1]. In this way, it is possible to get a sufficient group of data (N) from the records of impulse waves to describe adequally the internal condition of the medium. For instance, travel times of longitudinal waves are the most information used to reconstruct the cross sectional velocity distribution. This choice is justified by the fact that velocity is related to the modulus and density, and hence indirectly to the srenght of concrete.

The next step of data processing consists in dividing the surveyed section into cells; the number of cells (P) that is produced should be fewer than the number of observed travel times data (N). The measured travel times are inverted by solving the equation:

$$G \cdot m = T \qquad (1)$$

T is a vector which each component t_i represents the travel time of the i^{th} ray path $(1 < i < N)$. m is a vector that describes the distribution of the slowness in the medium defined as the inverse of velocity $(m_j,\ 1 < j < P)$ and G is a P x N matrix which each term g_{ij} is equal to the distance travelled by the i^{th} ray path in the j^{th} cell.

In practice, equation (1) is solved by inverting G and multiplying it with measured data given by T. However, the matrix G is often spare, large and singular [2]. Consequently, the system of equation is either undertermined or overdetermined. Many methods have been developed to estimate a matrix H that satisfies the equation:

$$m = H \cdot T \qquad (2)$$

Such methods are the algebric reconstruction technique (ART, [3]) and the simultaneous iterative reconstruction technique (SIRT, [4]).

In practice, an initial slowness model is determined from the known information on the medium. In the absence of any information, a special algorithm built an homogeneous model and the theoretical travel times of all source-receiver pairs are computed using a ray tracing method. The slowness values in the cells are adjusted to optimize the difference between measured and computed times. The slowness model is modified until the residual becomes acceptable and the final solution obtained.

3. EXAMPLES OF APPLICATION

Tomography measurements were conducted by capturing acoustical waves with a set of six accelerometers working in the frequency domain 1 - 15 KHz. The amplified and filtered signals were fed into a 6-channel data acquisition and recording system. In this manner, the medium response is detected at five different locations for a given source location, one sensor being fixed near the source to get the time zero reference.

Travel times measurements for each source-receiver pair were determined manually at a later time. The iterative algorithm was a SIRT type developed at the Laboratoire Central des Ponts et Chaussées (France) [5] and the back projection technique (BPT) was used for determination of the initial slowness model.

3.1 Diagnosis of a pile

The following example is an interesting one that shows both the effect of cracks and the quality of the concrete on the spatial distribution of the velocity.

Tomography measurements were performed on a 1-m diameter and 0.70-m depth cylindrical pile composed of three concentric cement-based mediums of different mechanical properties (Fig. 1). Before the test, several lateral fractures were induced in the pile by submitting the central medium to a hydraulic compressive stress. Figure 1 shows the cracks cartography as observed from the top of the pile.

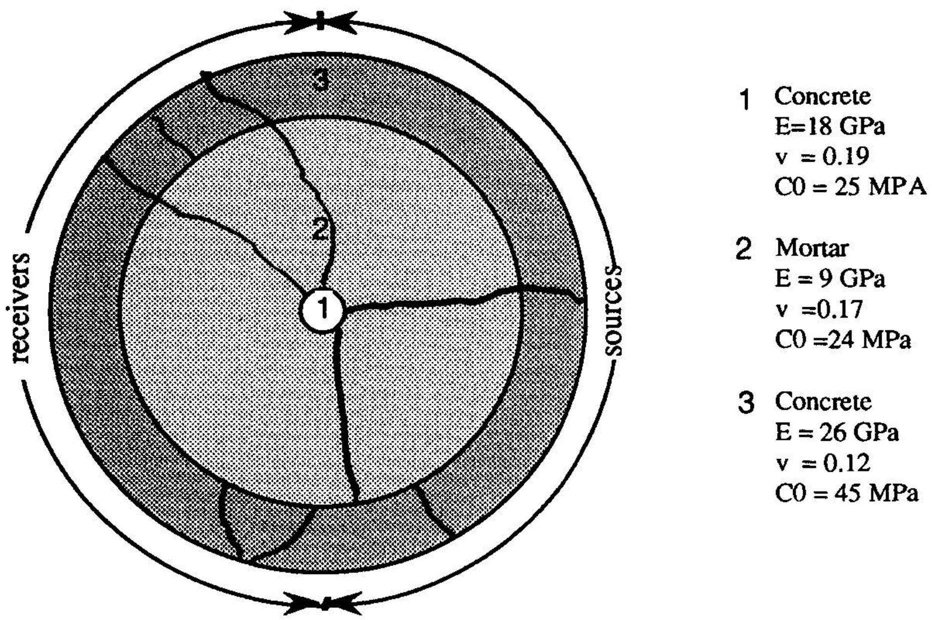

Fig.1 Schematic drawing of the pile with crack cartography and the source-receiver geometry

In the case of this experiment, the best signal to noise ratio was obtained by the impact of a steel ball that has 8 mm diameter. The source-receiver geometry (Fig. 1) was chosen so that ray paths cover uniformly and sufficiently the surveyed section located at 0.30 m from the top of the pile. The distance between two successive emissions and two adjacent receivers were fixed to 0.1 m, resulting in a total of 324 data records (Fig. 2a).

The final velocity distribution indicated on figure 2b globally accounts for the composite nature of the pile:

- the central area is clearly identified and is described by a velocity varying between 4250 and 4 500 m/s,
- the mortar that fills 60% of the surveyed section has a lower velocity (3 750 to 4 000 m/s),
- the peripherical area has a velocity higher than 4 500 m/s.

The mortar - peripherical area boundary is however not regular. In particular, a low velocity (2 500 to 3 000 m/s) exists at the upper left, the middle right and the bottom of the image. Figure 1 shows that these areas are a cracked ones. The cracks are not visible in the image just as they are, but there presence induce a perturbation of the velocity field. Supplementary investigations indicated that the importance of these perturbations are more dependent upon the cracks density, the wave propagation mode (straight or curve) than the the measure density. On the other hand, velocity values at these areas are related to the depth of cracks: deeply is a crack, lower is the velocity value.

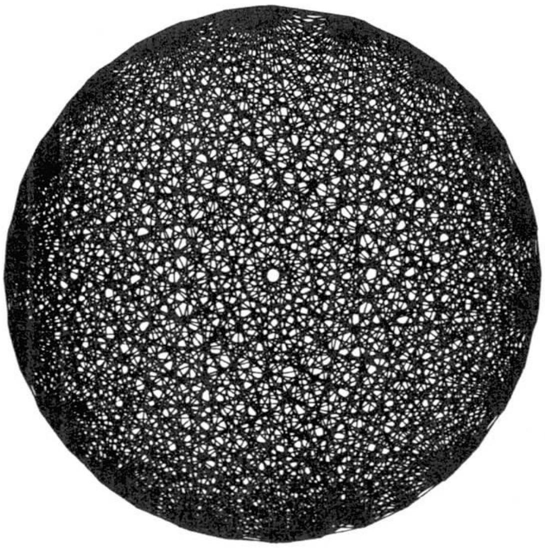

Fig.2a Ray diagram

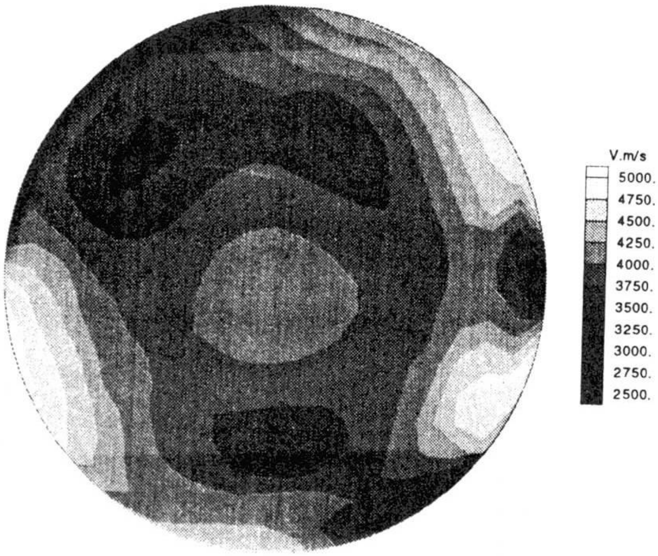

Fig.2b Reconstructed velocity distribution image

3.2 Diagnosis of a pillar

This example illustrate results given by sonic tomography survey recently performed at a pillar of a concrete dam constructed in the 1920's. This pillar has the form of a gravity wall of 20 m in height, 3 m in thickness, and nearly 17 m in width at the bottom. The downstream face of the pillar has been repaired some years ago due to a superficial degradation of the concrete in consequence of the long-term effect of hard climatic condition. Repair consisted of removing the damaged concrete and applying shotcrete. Core samples of 1-m long extracted perpendicularly to this face at four differents elevations (Fig. 3a) indicated that the thickness of shotcrete vary between 0.25 m and 0.40 m, and that the maximum aggregate size of new and old concrete are 20 mm and 50 mm respectively. The cores also indicate the presence of steel reinforcement of 20 mm in diameter.

A vertical section of the pillar was choosen to perform sonic measurements (figure 3a). Acoustical waves were generated by explosive. An existant filled water borehole along the upstream face was used to lower the source which we moved at 1-m intervals along the depth of concrete. The group of five receivers were placed along the downstream side for each source position. This procedure was repeated at three differents elevations of receivers; in this way, 225 travel times along crossing path with different inclinaisons were obtained. Figure 3b shows the final velocity model expressed by assigning the velocity values to each cell 1 m on side. Where ray density is low, reliability is probably poor, but tomographic image of the area gives sufficient informations. In particular, the image points out that the concrete is of two distinct qualities: poor-doubtful (2000 < V < 3600 m/s) and good-excellent (3600 < V < 4500 m/s), and that the concrete quality increases with depth.

The low velocity area on the top of downstream face reveals the extent of a damaged concrete visible from the outside, while the one on the upstream face coincides with the tidal zone. The interface between old and new concrete is however not visible on the image. This is probably due to a lack of data records on the downstream face (source and receivers on the donwstream face). Neverthless, laboratory tests on concrete samples show a good correlation among resistance values, elastic moduli and velocities (Table 1).

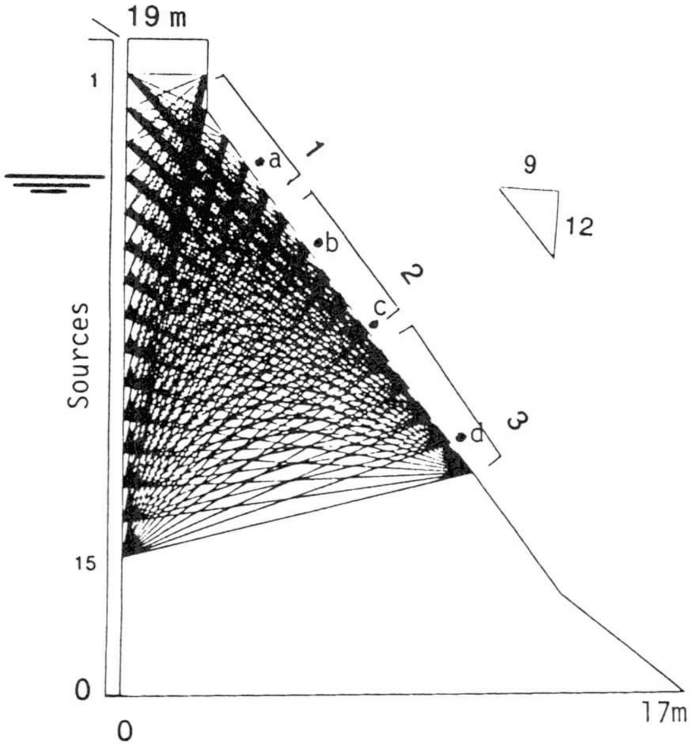

Fig.3a Scheme of measurements (• position of boring)

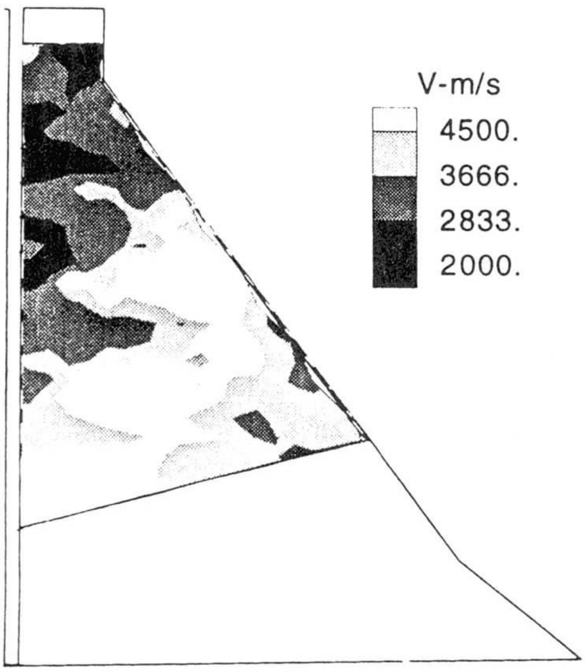

Fig.3b Distribution of sonic velocity.

Drilling N°	a	b	c	d
E (GPa)	14	24	19	21
C_0 (MPa)	18	39	30	26

Table 1 Mean mechanical properties of core samples extracted from the downstream face

3 CONCLUSION

This paper has covered theoretical and practical aspects of sonic tomography. This nondestructive method is reliable, rapid and not very expensive and seems to be effective in evaluating the elastic dynamic characteristics of concrete and the state of intergrety of civil engineering structures. Recent application on a maconery structure has also shown that this technique can be used as a cheking tool of the effectiveness of grouting work.

Obviously, sonic tomography can be improved. A solution that the authors are exploring is to consider wave attenuation inside the section of the structure examined. This information will permit to better define the concrete quality by a better location of the fractured areas

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