Scale experimental testing of the resolution capabilities of seismic tomography techniques

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Abstract - It is well known that tomographic seismic transmission techniques are being utilized more and more in applied geology and in non destructive tests owing to several advantages they offer over traditional surveys. The main tools described in this paper to carry out the scale experimental tests, were ultrasonic techniques. In order to perform the elaboration step, a software (DOGSTOMO) available on the market, utilizing the ART method (Algebraic Reconstruction Technique - regular grid) was considered. Also a tomography program based on the SIRT method to compare the results carried out by different processing approaches was utilized. Three different kinds of samples were chosen. In our opinion, their mechanical-physical characteristics make them representative of some natural systems. In more detail, samples were made up of different materials with a different homogeneity: plexiglas, concrete and brick. Furthermore, tests were performed in both non "perturbed " conditions and with voids and artificial inclusions inside a brick structure. Experimental results show that discontinuities could be more or less highlighted by a tomographic technique, depending on which kind of material the sample is made up of. In spite of the good results obtained for homogeneous material (plexiglas) and for uniform porous material (concrete), the resolution carried out with both tomographic techniques applied to heterogeneous and fractured porous systems (brick), in which voids are localized in the regions where the sample is distinguished by a low propagation velocity, is very poor.

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1. Introduction

The surface geophysical techniques, applied to the upper meters, soil exploration, sometimes show a poor resolution, especially in connection with complex stratigraphic situations (heterogeneous materials, anthropic levels, fractures, perched acquifers, etc.). Seismic transmission tomographic techniques, besides other hole techniques (cross-hole, down-hole, etc.), have been strongly developed over the last years because of their capability to lower indetermination as much as possible.

The aim of the research, already carried out and described in this paper, was to check, experimentally, the resolution grade of the tomographic methodology adopted with well known and representative situations.

2. Experimental tests

Tomographic surveys have been carried out by ultrasonic techniques, in particular by PUNDIT tools equipped with attenuation unity and piezoelectric sensors whose resonance frequency was 150 kHz. Non punctual piezoelectric sensors (about 1 cm of coupling surface) have been used because of coupling problems. Signals have been sampled by a PC with a 400 kHz ARIEL card.

Experimental tests concerned three different kinds of samples: a thick plexiglas layer, a reinforced concrete cylinder and a brick.

The plexiglas sample was representative of an almost homogeneous and isotropic natural material. In the middle of the sample (33 cm high, 21 cm long and 8 cm thick) a hole, five centimeters in diameter, was made (Fig. 1). Twenty-eight transmission points and as many receiver points were put along the four sides.

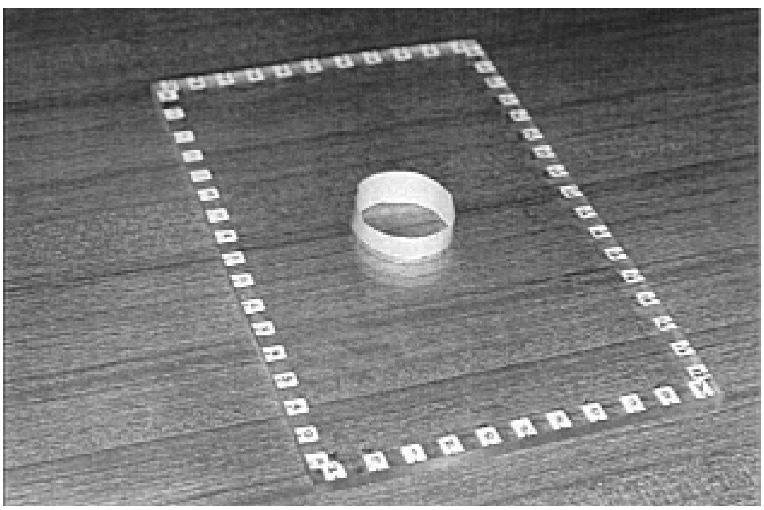

Fig. 1 - Plexiglas sample.

The reinforced concrete sample considered was a cylinder 104 cm high cylinder with a diameter of cm 12 (Fig. 2). The reinforcement was necessary to guarantee structural integrity; furthermore, a gravel nest of about 10 cm was put inside it at a distance of about 15 cm from the top of the cylinder in order to verify the capability of the methodology to correctly detect this kind of anomaly.

Tomographic analyses were carried out on the lateral surface of the cylinder by 12 transmission points spaced 9 cm apart and, by as many receivers on the opposite side (generatrix).

The purpose of studying this kind of concrete sample was to simulate the behavior of a natural material with fairly good isotropic and homogeneity characteristics affected by anomaly (gravel nest).

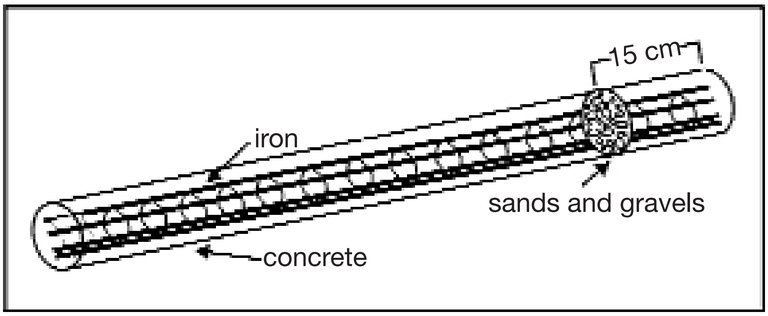

Fig. 2 - Reinforced concrete sample.

The third sample analyzed was a clay brick: 26 cm high, 12.5 cm long and 6 cm thick (Fig. 3). The particular kind of clay mixing, the non-uniform baking causing a different work hardening marked out by micro fractures, different porosity and different mixture content of each part of the sample were particularly suitable to make the brick as representative of low isotropic and low homogeneous natural material. Eleven transmission points spaced 2.1 cm apart and as many receiver points on the opposite side were put on the sample surface to carry out two

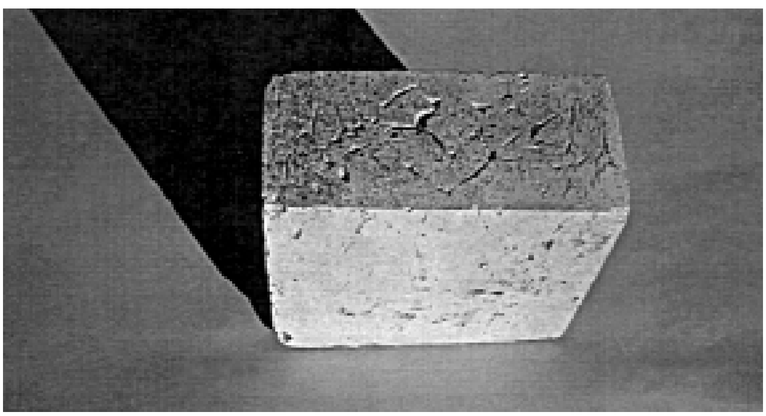

Fig. 3 - Clay brick sample.

different tomographic analyses: the first one with the sample without holes inside, the other one, with cross-holes through the brick's zones characterized by different physical properties (i.e. density) as displayed in Fig. 4.

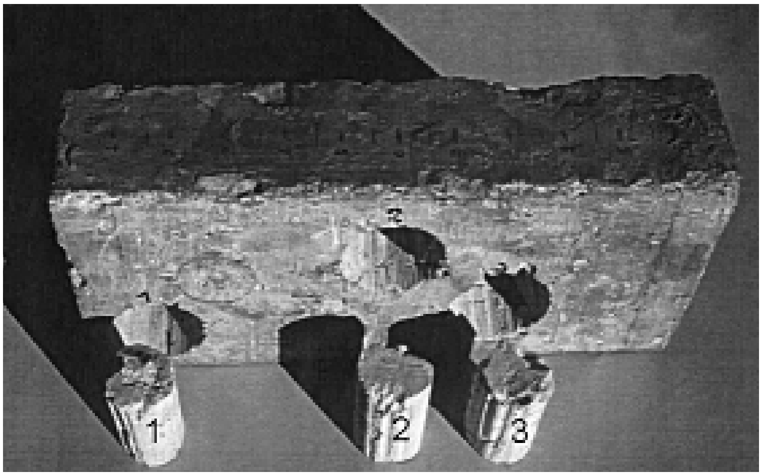

Fig. 4 - Drilled clay brick sample.

3. Brief overview on the tomographic technique adopted

To perform experimental tests described in this paper, a similar cross-hole tomography equipments have been employed. In particular, in order to develop a two dimensional model, sources and receivers have been placed only in two opposite sides of the sample considered for each tests.

Further, the monitoring was concerned with only transmission waves (first travel time). The samples have been discretised into tomographic cells (25 × 16 the plexiglas sample, 25 × 25 the reinforced concrete sample, 25 × 25 the clay brick) by a regular grid. Each area was supposed to be characterized by physical properties constant in space.

Then the resolution of the whole sample was obtained measuring travel time of the "first break signals" detected by each receiver-point and emitted by each transmitter-point (both the source and the receiver being in movement). First break picking has been improved by increasing the S/N ratio using the stacking operation as shown in Fig. 5. If strong velocity gradients were not detected among transmitter-receiver points, the ray path of the travelling wave could be considered straight. Otherwise, it would have been necessary to consider a curvilinear ray path, in which case, in spite of a better general interpretation, there would have been many more problems to solve. In particular, the consequent attenuation coefficient selection and refractive phenomena could produce artificial distortion in velocities around cells through which the slowness was higher. So, we considered different attenuation coefficient depending on the cell slowness.

Once experimental tests have been carried out, the vector t of the measured travel times of the waves was related to the vector u of the unknown slowness by a linear function:

$$t = A\,u \tag{1}$$

where the tomographic matrix A depends on the ray path of the considered waves.

Because the cell number was, in general, less than the ray number (410 rays for the plexiglas sample, 144 rays for the reinforced concrete sample, 121 rays for the clay brick), the system (1) was lacking rank: we could obtain only a set of solutions instead of just one. Thus, we had to choose some of them satisfying further requirements. A very effective choice was to require the energy of the unknown u vector to be minimum (Carrion, 1991). In this way, the solution was unique and not contaminated by the null-space.

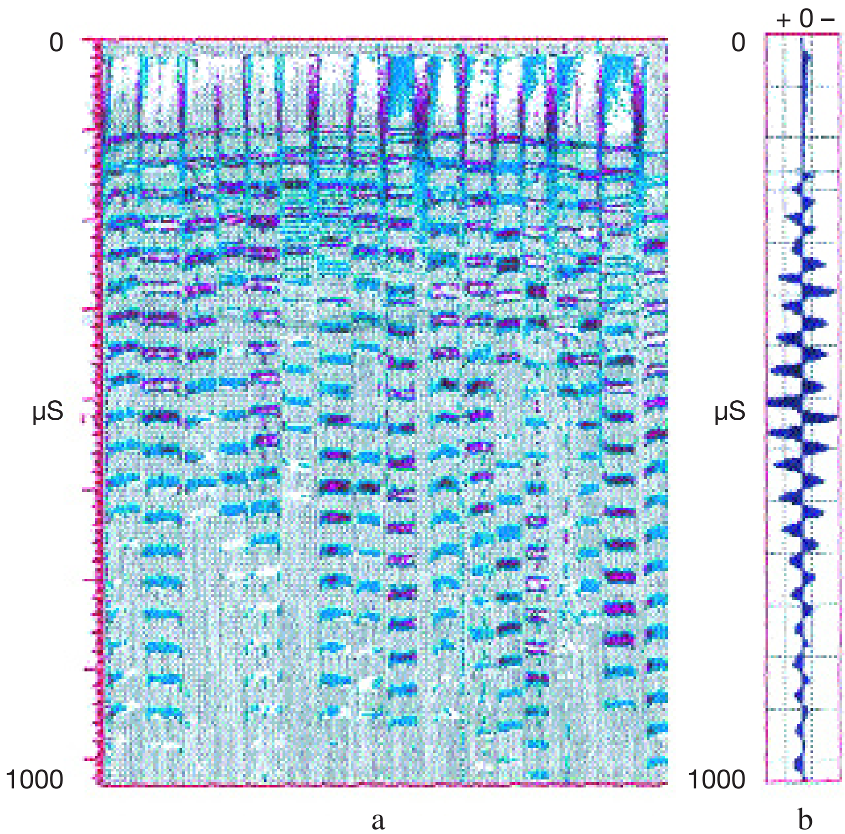

Fig. 5 - Increasing S/N ratio by stacking traces to improve first break picking: a) stacked traces; b) single trace.

A homogeneous input velocity model characterized by a velocity a little higher than the real one of the sample has been used: in fact, we found that this would have improved the output of the velocity model.

We inverted system (1) by ART model (Dines and Lytle, 1979; Tarantola and Valette, 1982a, 1982b; Tarantola, 1987). This kind of algorithm consists in a recursive approach starting from a guessed slowness vector. Then, the differences between the calculated wave travel time and the measured ones were optimized by the least-square method. One of the major drawbacks of this approach, however, is the diffusion of the slowness indetermination along the path of each ray. In this way, the resolution could be lowered.

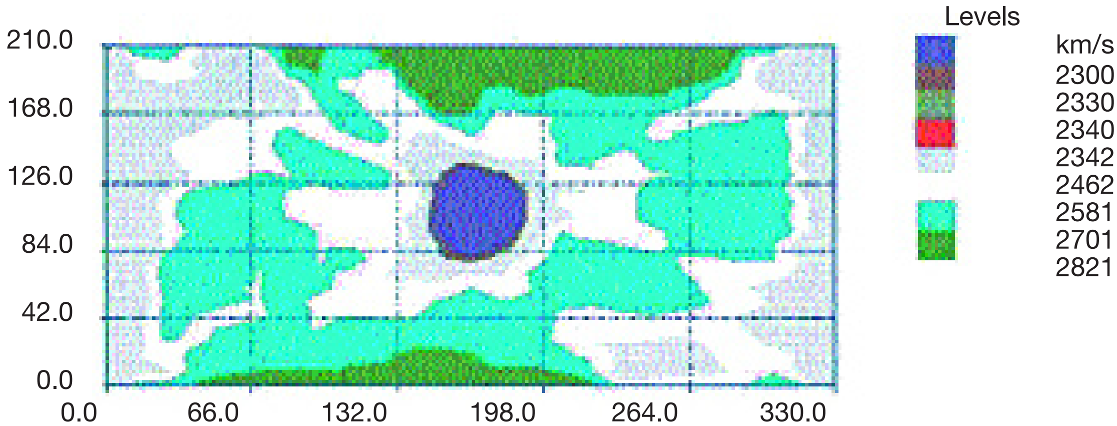

Fig. 6 - Plexiglas test result.

In the last section of this paper, some images obtained applying the inversion algorithm SIRT and an adaptive irregular regridding model are reported.

The SIRT inversion method, based on the Kaczmarz' algorithm (Kaczmarz, 1937; van der Sluis and van der Vorst, 1987), is a bit slower than the ART approach. Tomographic images carried out by the SIRT method do not depend on the equation order in system (1) as happens with ART. Furthermore, the SIRT method is more stable and robust: it could be applied even when the picked travel times are affected by experimental errors (Dobroka et al., 1991). The adaptive irregular regridding approach, based on a grid refinement in those zones where the ray density was higher, was applied to construct the tomographic images reported at the end of this paper.

4. Results description

The analysis of tomographic experimental tests allow us to make the following comments:

1. plexiglas test (Fig. 6) clearly shows the anomaly produced by the hole and how, of course , it was characterized by the lowest signal speed through the whole sample. Displayed

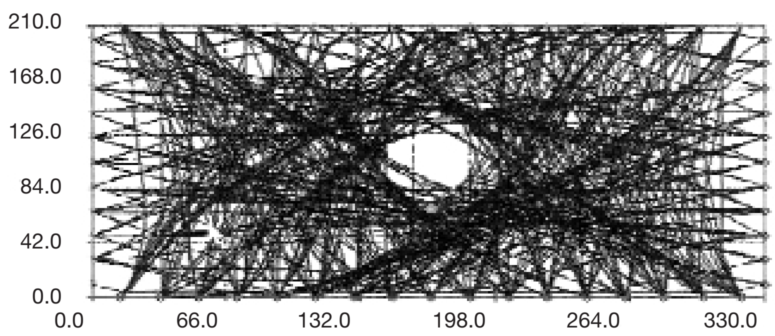

Fig. 7 - Plexiglas test rays path.

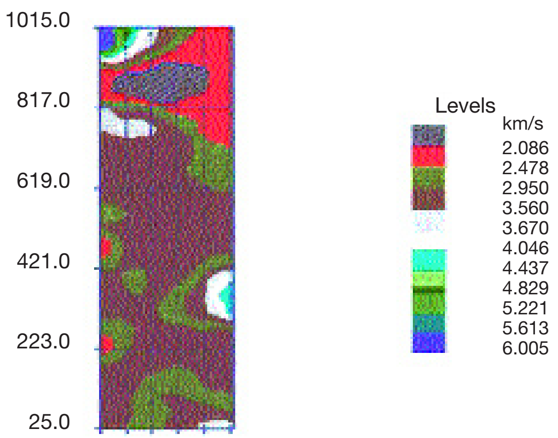

Fig. 8 - Reinforced concrete test result.

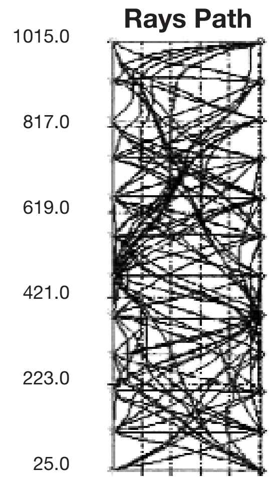

Fig. 9 - Reinforced concrete rays path.

disuniformity of velocities is due to their knowledge indetermination all around the hole (an element through which the speed indetermination is maximum) and to the consequent error "distribution" over the entire sample. This limitation is due to the particular technique applied, and not to sample characteristics. As for the plexiglas, we already know the exact value for the velocity of the entire sample (2625 ± 5 m/s, determined by the measurements on the above-said sample); on the other hand, emptiness should have the velocity (340 m/s) of air. In this case, we noted that while the sample's geometry was quite respected, the same could not be said for the minimum velocity, as this was strongly over-estimated (Fig. 6). Fig. 7 shows ray path related to Fig. 6;

2. gravel nest inside the concrete sample was well highlighted (Fig. 8). On the contrary small anomalies were ambiguously detectable as actual or as just a methodology limitation. Fig. 9 displays ray paths related to Fig. 8;

3. tomography of the intact brick shows the importance of the manufacturing technique and the consequent introduction of symmetries inside the sample (Fig. 10). The detection of the "first break" of the transmitted wave involved some difficulties due to fractures, porosity and high work frequency (150 kHz) signals. In order to improve the detection, it was necessary to adopt a stacking processing of the signals and the introduction of sections concerning signals coming from and going to each pair of transmitter-receiver points (Fig. 5). To make a further results' check, the transmitters' position was exchanged with the receivers' position and a new tomography (we called "reverse tomography") was carried out (Figs. 12 and 13). It is possible to see that the difference between Figs. 10 and 12, and Figs. 11 and 13 is very small. This confirms the good quality of the collected data and the resolution power of the tomographic method. Figs. 14 and 15 show the results of these "direct" and "reverse" tomographies of the intact brick after a second iteration. It is possible to note the greater difference between "direct" and "reverse" tomographies in the result of the second iteration.

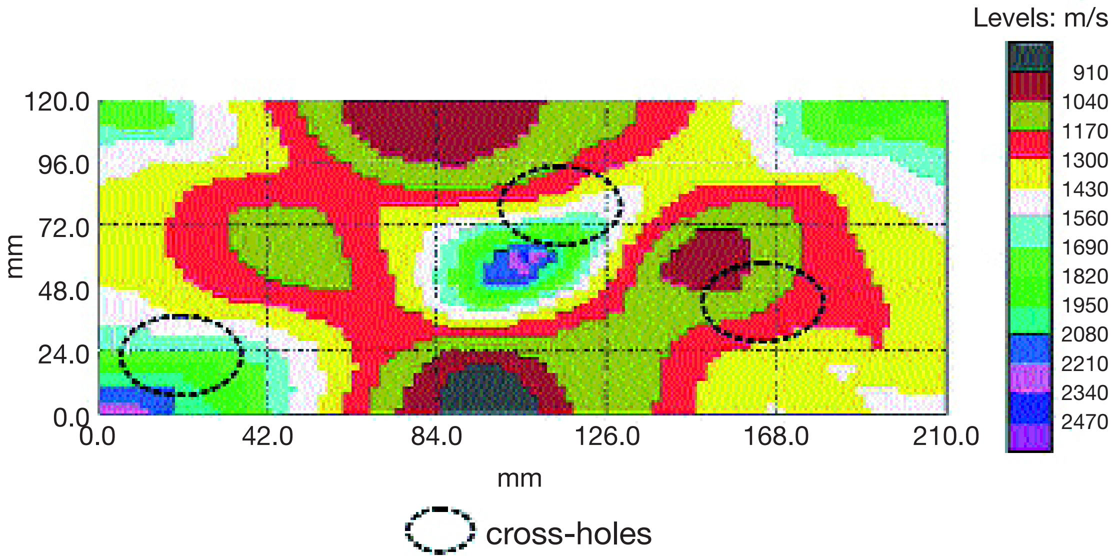

Fig. 10 - Intact brick test result.

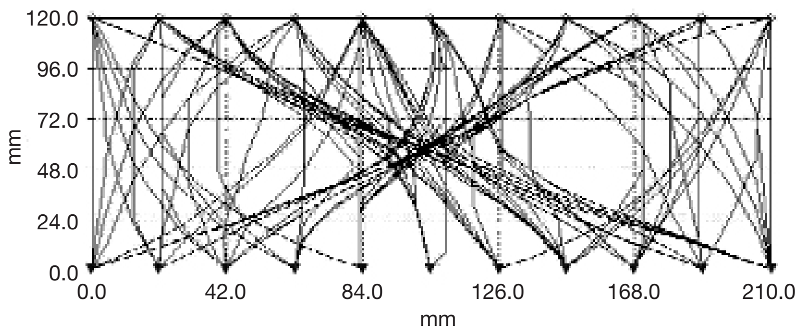

Fig. 11 - Intact brick rays path.

In our opinion, these divergences of results in refined models are linked to the attempt of the software to resolve the model with the ray's path obtained from the first iteration (Figs. 11 and 13);

4. the last test showed an internal structure similar to the former, with the consequence of good quality measurements. Brick tomography reported in this paper shows three zones with a different velocity field: low, medium and high. Thus, a cross hole has been made through each zone, and the three cores have been analyzed. Actually, core densities were different to each others as Table 1 shows. Different relative density areas are well highlighted by the different relative velocity distribution detected by the tomography;

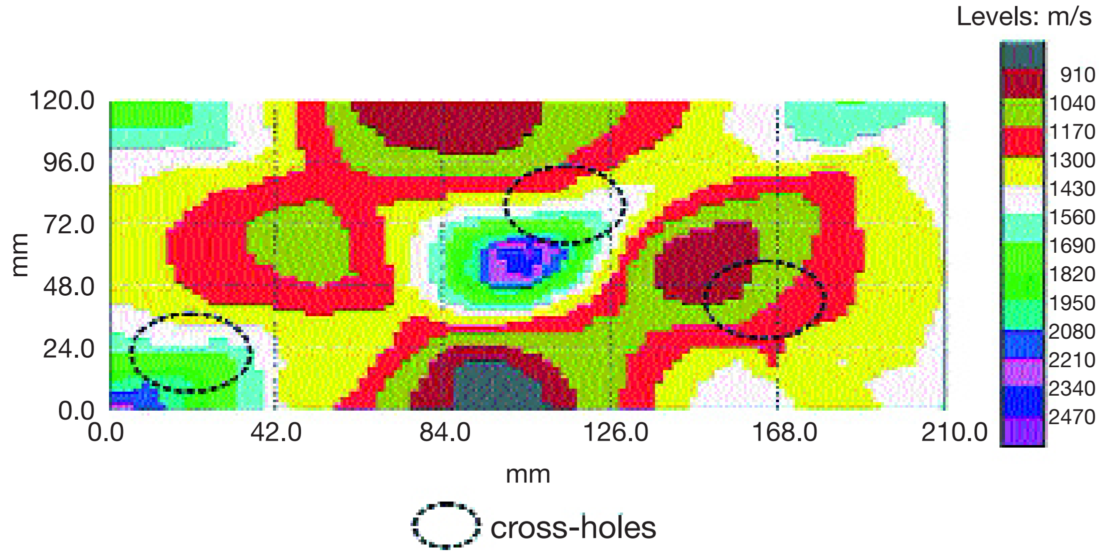

Fig. 12 - Reverse tomography of the intact brick test.

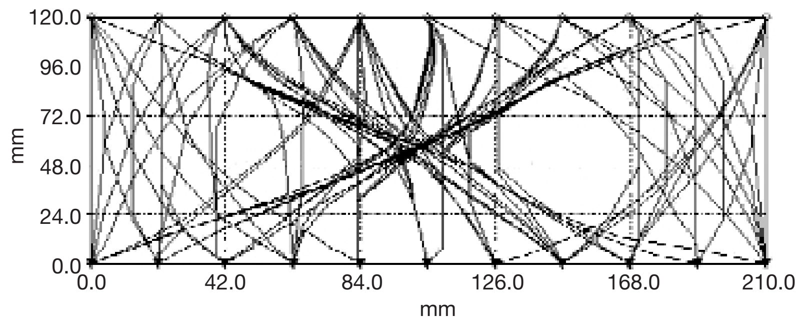

Fig. 13 - Rays path of the “reverse” tomography of the intact brick.

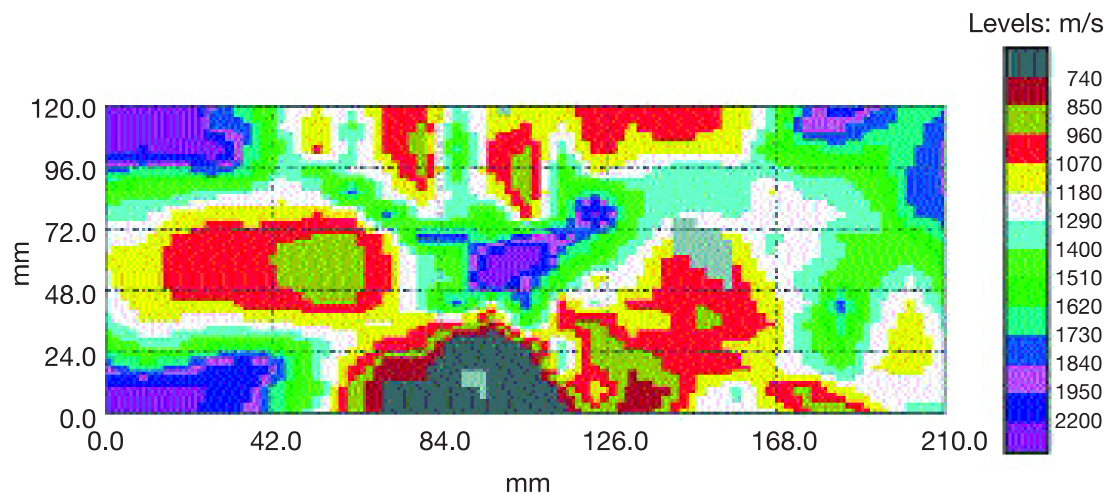

Fig. 14 - Intact brick test result after the second iteration.

Table 1 - Samples densities.

Carrot N°	Density (gr/cm^3)
1	1.72
2	1.67
3	1.64

5. it is easy to observe in Figs.16 and 17 that the presence of the cross holes made in high and middle velocity zones is well highlighted by the tomographic method. In spite of this we do not have appreciable results when the hole is located in the lower velocity zones;

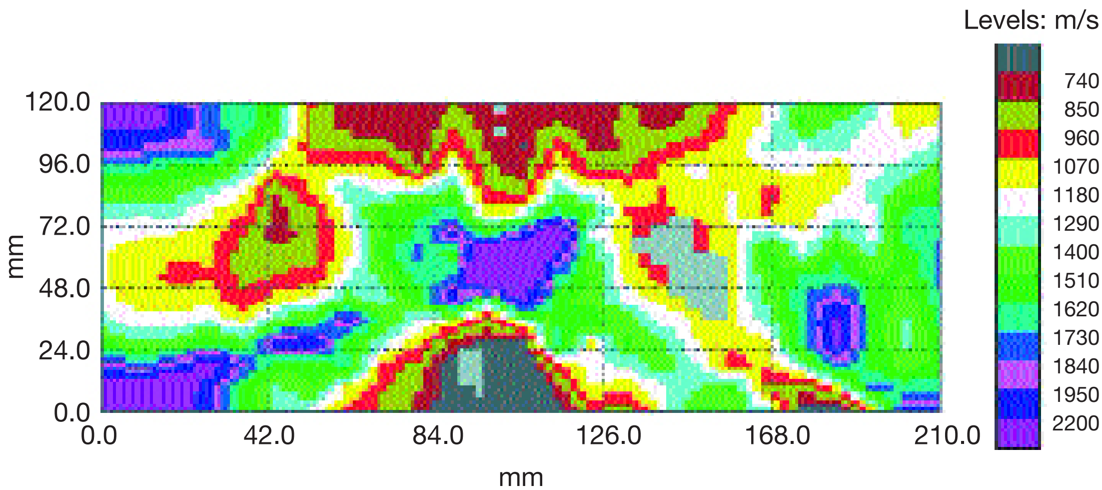

Fig. 15 - "Reverse" tomography of the intact brick test after the second iteration.

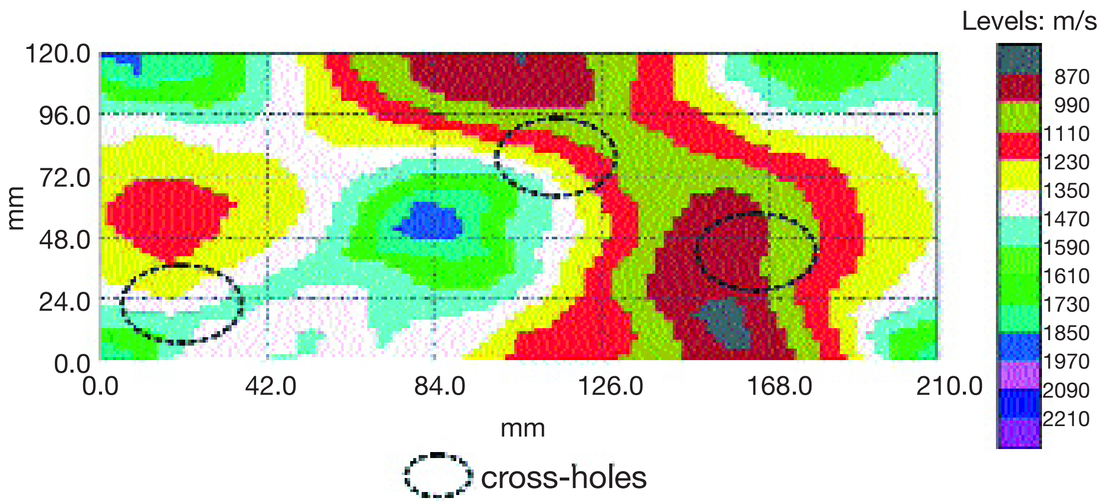

Fig. 16 - Drilled brick test result.

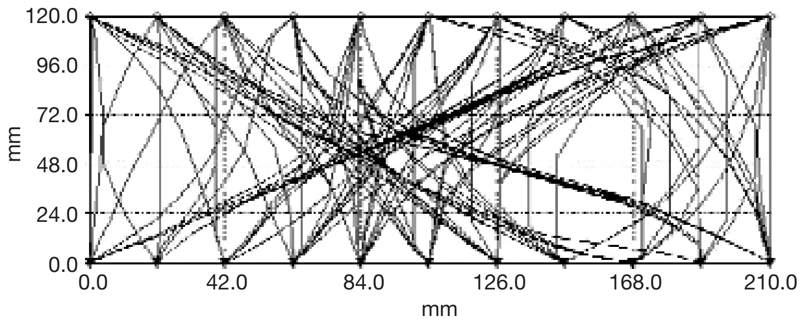

Fig. 17 - Rays path of the drilled brick.

6. to verify that the lack of results for the low velocity zones was due to the kind of algorithm used (ART) or to the methodology limits of the tomography, we carried out the same calculations with both intact and drilled brick data, but, this time, using a different mathematical tool based on the SIRT algorithm described in Bohm et al. (1997).

Figs.18 and 19 show, respectively, "direct" and "reverse" (exchanged transmitter and receiver positions) intact brick tomographies. Furthermore, Fig. 18 shows the adopted grid and

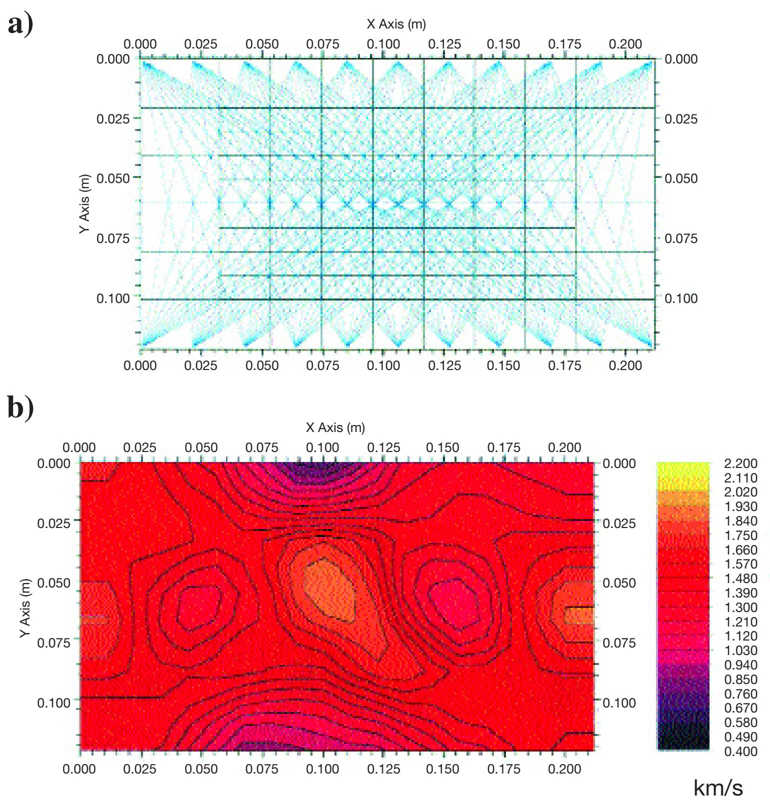

Fig. 18 - "Direct" intact brick test performed by a regridding method: a) rays path; b) test result.

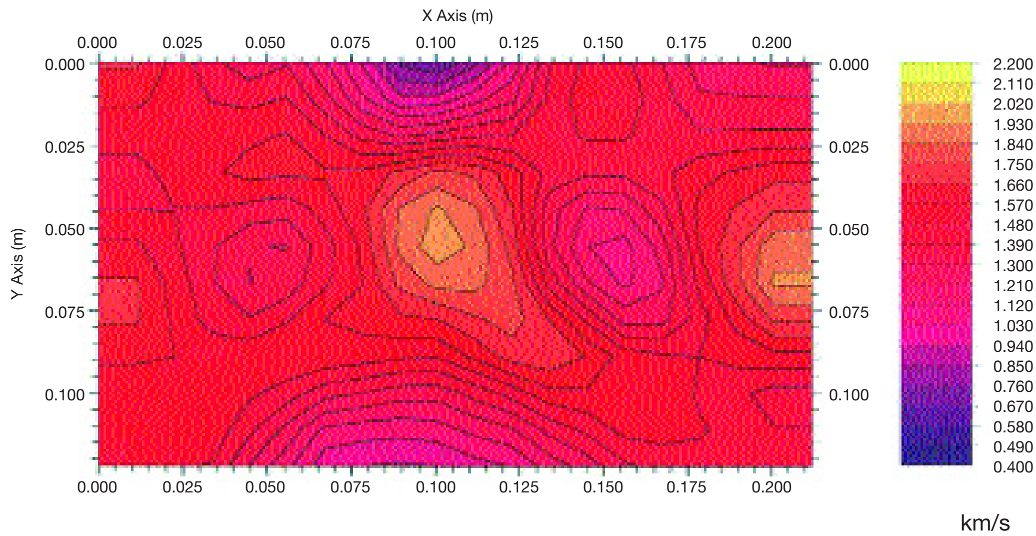

Fig. 19 - “Reverse” intact brick test performed by a regridding method.

the acquisition geometry for these kind of calculations. Fig. 20 shows “direct” drilled brick tomographies.

The last calculations, performed by regridding with a finer meshing, do not seem to improve the information we were able to obtain about the internal structure of the anisotropic brick.

Finally, in order to check how much the tomography resolution was influenced by the number of transmitter and receiver units, we performed a new experimental test on drilled bricks, with 22 transmitters and 22 receivers.

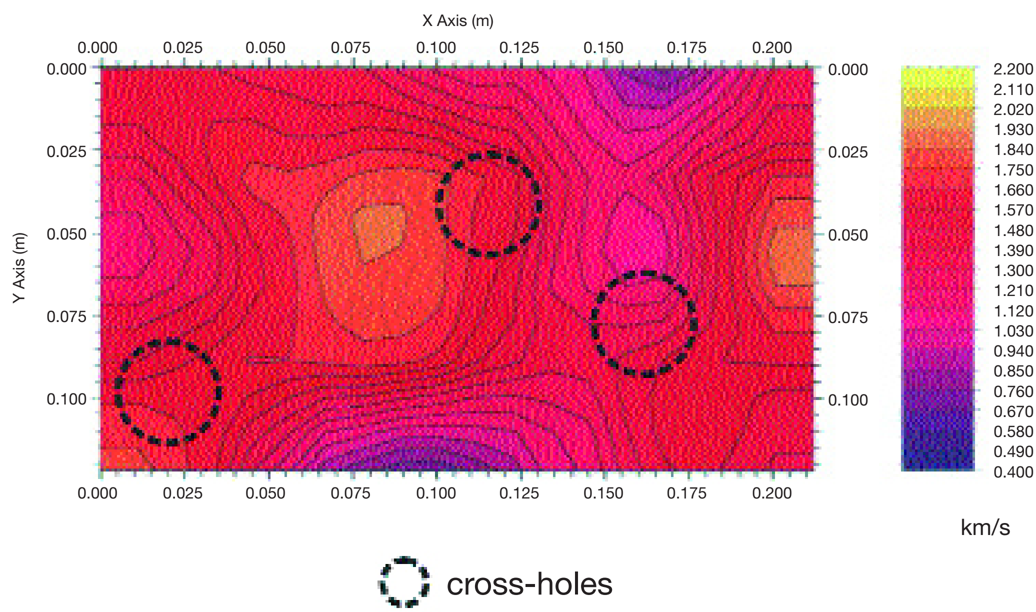

Fig. 20 - “Direct” drilled brick test performed by a regridding method.

The results are shown in Figs. 21 and 22. It is possible to see (Fig. 16 and 21) that the increase in the number of rays does not improve the resolution. We can observe by comparising Figs. 21 and 22 that also the iteration process does not seem to increase the quality of the results.

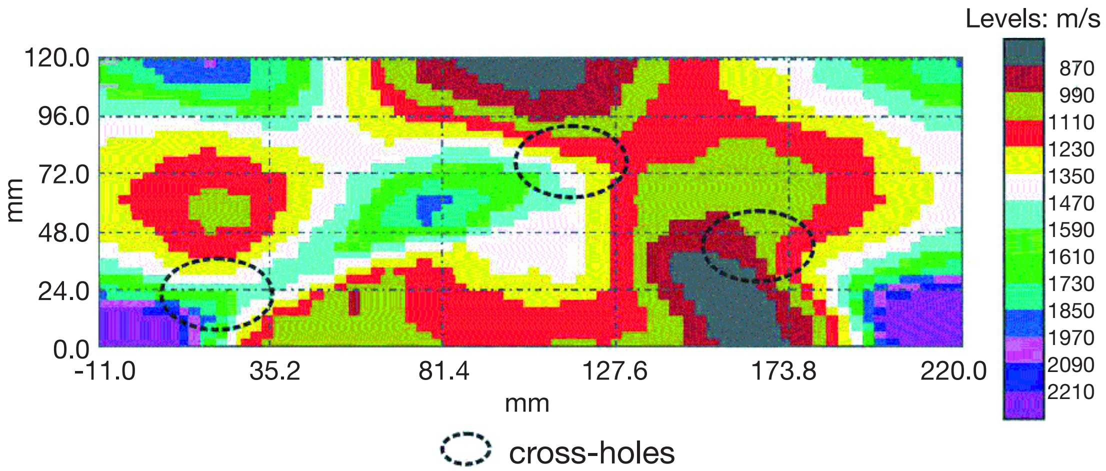

Fig. 21 - Drilled brick tomography performed through 22 transmitters and 22 receivers.

a)

b)

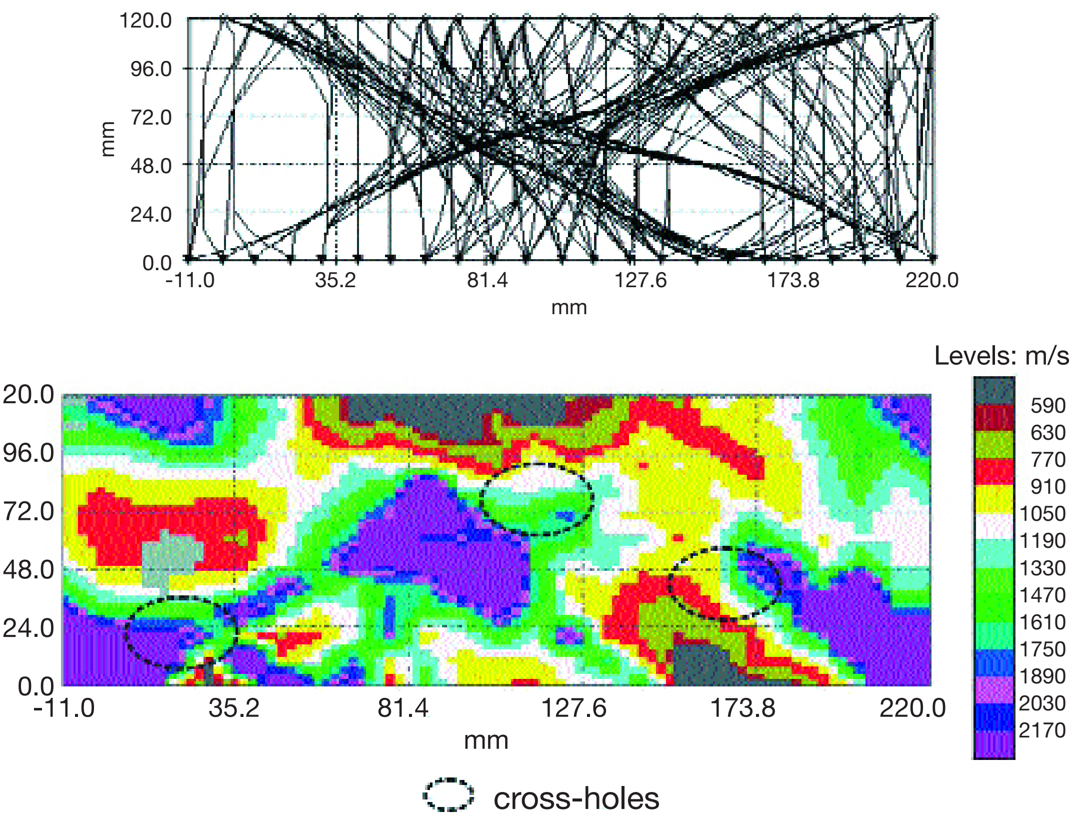

Fig. 22 - "Reverse" drilled brick tomography performed through 22 transmitters and 22 receivers after the second iteration: a) rays path; b) test result.

5. Conclusions

Experimental tomography tests, described just above, identified intrinsic limits due to the method utilized.

Notwithstanding, we carried out more calculations using an adaptive regridding method and we performed more analyses by doubling transmitter and receiver units, the results do not seem to be sensibly improved.

The methology's most evident limits were mainly related to the heterogeneous samples and seem to be due to the limits of the tomography itself. The text carried out on the homogeneous sample (plexiglas) shows, anyhow, the most reliable results in terms of images and velocity. This proves to be also the case of the other two situations examined.

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