Assessment of the dynamic properties of highly saturated concrete using one-sided acoustic tomography. Application in the Marathon Dam

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Abstract

Within the frames of a geophysical project aimed at assessing the Marathon Dam and its surrounding area, it was decided to implement the one-sided acoustic refraction tomography method in the main interior tunnel of this concrete dam, in order to get a picture about the dynamic properties of the concrete. This method was chosen since the implementation of the acoustic crosshole tomography method with the sources and the receivers at different sides of the dam, was not feasible due to the existence of an ornamental marble pavement. This marble pavement could not accept any physical destruction, but additionally it was of higher seismic velocity than the interior material, resulting in problems on the correct application of this method. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The monitoring of old large construction works such as dams, bridges etc., has been intensified in recent years worldwide. Many of these works have long ago passed their scheduled operational lifetime and the need for quality control becomes imperative, especially when these constructions have suffered from strong seismic shocks.

The Marathon dam, having completed 70 years of its lifetime, was tested by the strong earthquake of Athens in September of 1999. A geophysical survey program was conducted afterwards, aiming to the detection of leakages and the investigation of the geological conditions of its basement and surrounding area, and during its course it was decided to extend the work into the body of the dam, particularly at its main tunnel, using the methods of acoustic and electrical tomography. In view of the fact that very little information was available, regarding the dynamic properties and strength characteristics of the concrete, it was agreed to conduct surveys within the body of the dam, in order to have a general evaluation of its mechanical characteristics. The method, in combination with the electrical tomography, aimed to detect potential points that may enable water infiltration within the structure. The acoustic and electric tomography methods, having been developed and established in the field of Applied Geophysics, have been recently introduced in the area of Non-Destructive Testing investigations (NDT) for dams and other large construction works [1–4].

The traditional destructive investigation methods included the drilling of two to four boreholes, sited at the top of the dam and reaching its basement, in order to extract large diameter core samples (250–300 mm) for laboratory testing. These samples were destructively tested, to determine their strength and elasticity module. The problem with the destructive methods is that despite their high cost, they examine only a small fraction of the volume, usually not larger than 0.1% [3]. Additionally, these techniques are not capable of determining anomalies to the construction of the dam.

The acoustic tomography besides the evaluation, by non-destructive means, of the strength and elasticity modulus, can also describe the characteristics of the internal structure of the construction material of the dam...
and to determine its significant defects. In combination with electrical tomography, it can also detect points of leakage in the dam.

2. The method

The mapping of the acoustic wave velocity within a medium, at various sections known as acoustic travel-time tomography (or sonic tomography), may give important information with regard to the structure and condition of the medium. The velocity determination is accomplished by measuring the time intervals taken by acoustic waves to travel from various sources to receivers placed on the surface of the medium (geophones or accelerometers). An acoustic ray is defined by each pair of source-geophone and its calculated velocity is just an average of the particular velocities along its trajectory path, without containing information about points of acceleration or retardation. So we have a group of velocities \( v_1, v_2, \ldots, v_n \) at the relative distance intervals \( x_1, x_2, \ldots, x_m \), yielding a total time \( t_x \) (an equation with many unknown parameters). To determine exactly these points we need to combine a large number of sources and receivers (matrix of equations). The set of measurements is processed by specialized inversion software solving the particular problem.

Instead of the velocity, tomography (attenuation tomography) can also describe the attenuation factor. In this kind of tomography, the measurements are related to the amplitudes of the acoustic waves.

The sources and the receivers can be located either in faced positions (crosshole tomography) or at the same surface (one-sided acoustic tomography). The term ‘one-sided’ has preferentially been used in Engineering literature and terminology [5] than in geophysical research, where the method of traveltime tomography has been originated. In Geophysics the one-sided traveltime tomography is usually specified as refraction or reflection seismic tomography depending upon the nature of the wave arrivals used. Considering that the source and the receivers are set on the ground surface, the waves generated by the source can travel to the receivers either directly or after critical refraction or reflection on subsurface interfaces. The seismic waves have scarcely straight ray-paths since mostly the earth layers present a gradient of velocity, which increases with depth. The term ‘seismic’ is mainly attributed to the passing of waves through the earth.

The traveltime tomography usually uses a regular grid of cells but it is also possible to use an irregular grid [6,7]. The algorithm used in the present study, Rayinvr [7], is a simultaneous refraction and reflection tomography program for 2-D velocity and interface structure using an irregular grid. In particular, it is a ray-tracing algorithm accompanied by a least-square inversion routine that uses a layered model consisted of trapezoids cells. The number and shape of the trapezoid cells are defined by the user. In this procedure, velocity values are assigned to the cell corners. The velocity values within the trapezoids come from a linear interpolation between the four defined corner velocities. The Rayinvr has been mostly used in crustal studies such as those reported in refs. [8–10], but recently also in surface scale problems [11].

In non-destructive testing, engineers basically use acoustic tomography for scanning walls [12–14]. In most applications the sources and the receivers have been set on opposite sides of the investigated body in order to succeed the best ray coverage. When both sources and receivers are at the same side of a uniform body, the investigation depth of the acoustic tomography is limited near to the surface. However, the one-sided acoustic tomography can be effectively applied on a body if a reflecting or refracting interface with higher wave velocity exists in a lower part of the body, or in case that there is a positive gradient of velocity change with depth. In the case of a continuous positive gradient of velocity change, the rays of the direct waves are arc-shaped bended due to their successive refraction, resulting in an increase of investigation depth. The algorithm Rayinvr can manage such models, with gradual increase of the velocity, and takes into account the bending of the ray-paths; therefore, it can be used in such cases.

3. Data acquisition

The instrumentation used was based on the 24-channel seismograph of the Institute of Geodynamics, EG&G Geometrics StrataView R, which was able to record in the domain of acoustic frequencies. The seismograph uses 24 bits A/D converters with a 32 kHz oversampling and dynamic range of 135 dB. It is capable of sampling at 32 \( \mu s \) (31.25 kHz), which records frequencies in the range of 16 kHz with no aliasing.

The acoustic source used was a seismic hammer, and the receivers used had a flat response throughout the recorded frequency spectrum. The 24 receivers were placed at 2-m intervals along the tunnel, covering a total distance of 46 m (Fig. 1a,b). Nine sources were used. The locations of the sources and the receivers are shown in Fig. 1b. The measurements were taken twice with and without a coupler at the acoustic source. When the coupler was used, stacking of the signal was used by using three stacks. The two stacking ways were tested in order to have a clear and certainly identified signal.

In order to minimize the delay time of the start of the recording, we did not implement the usual triggering system of the seismograph, that was a piezoelectric hammer switch, but instead we preferred to use a short-circuit between the hammer and plate. The one cable of the triggering system was connected on the metallic head of the hammer and the other one on the metallic
coupler, giving so an instantaneous start of the recording by the action of the hammer on the coupler. In recording without the coupler, we could not use the above procedure so we led to the following method: we short-circuited the triggering cables and by the hammer action on the concrete, we cut the circuit to initiate the recording.

4. Data processing and results

The processing was done at a UNIX, Sun Ultra 10 workstation, by using the programs SU 34 [15] and the inverse modeling algorithm Rayinvr [7]. SU was chosen against certain commercial packages, due to its enhanced capabilities regarding the available amplification modes,
a very crucial issue when dealing with high frequency data. The spectral analysis that was implemented via the Gabor transform (Fig. 2), in order to examine separately the frequency content of each phase of wave arrival, showed that the dominant frequencies were in the order of 1.5 kHz.

Fig. 3 shows a record processed in such a way to enhance the P-wave (compressional wave) arrivals, which come first.

The section of Fig. 4 was the result of the data processing by the refraction tomography inversion algorithm. The tomography showed a very good fitting

Fig. 2. A time-frequency representation of instantaneous amplitude of acoustic data via the Gabor transform. The dominant frequency of the acoustic waves in the order of 1.5 kHz.

Fig. 3. Examples of seismic records taken within the tunnel. Record (a) is specially processed to highlight the first arrivals corresponding to the compressional waves, where in recording (b) the surface waves are enhanced. The first trace is at 2 m and the last one at 48 m. The vertical axis is the recording time.
Fig. 4. P-wave tomography within the tunnel. All values are higher than 4.55 km/s and higher than 4.8 km/s at its largest part. The line bearing is SN.

between the observed times and the model calculated times ($\chi^2 = 1$), with an RMS error equal to 0.000072 s. This error is exceptionally small, indicating the high reliability of the model to depths of 2 m. Very high velocity values (>4500 m/s) are observed along the length of the section, indicating an excellent quality concrete (Table 1) [16].

The small variations in velocity values are due to the varying degree of water saturation of the concrete. The compressional wave velocity is increased slightly at the presence of interstitial water. The relation between the velocity and the porosity of the filling material is governed by the formula of Wyllie et al. [17]:

$$V = \frac{\phi}{V_f} + \frac{1 - \phi}{V_m}$$  \hspace{1cm} (1)

Where $\phi$ is the porosity, $V$ the acoustic velocity of the porous medium, $V_f$ the velocity of the filling fluid, and $V_m$ the relevant velocity of the non-porous medium.

When the filling material of porous is water, $V_f$ is equal to 1500 m/s, whereas for air $V_f$ is 330 m/s. Good quality concrete may have $V_m$ equal to 6 km/s and porosity in the order of 2%. If we consider the extreme case of all porous being filled up by water, then the velocity of the material would equal to 5.66 km/s. In the case of completely dry concrete, its velocity would

Table 1
Classification of concrete according to compressional wave velocity

<table>
<thead>
<tr>
<th>Velocity $P$ (m/s)</th>
<th>&gt;4500</th>
<th>3500–4500</th>
<th>3000–3500</th>
<th>2000–3000</th>
<th>&lt;2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete quality</td>
<td>Excellent</td>
<td>Good</td>
<td>Doubtful</td>
<td>Poor</td>
<td>Very poor</td>
</tr>
</tbody>
</table>

Velocity variation with moisture

Fig. 5. Experiment conducted by Popovic et al. [5] showed that the P-wave and Rayleigh wave velocity is increased by the moisture.
Fig. 6. Electrical tomography section at the interior of the tunnel. Values are in Ohm-m.

fall to 4.5 km/s. If we consider a 50% filling of porous with water, its velocity would be in the order of 5 km/s.

A 100% filling with water cannot be achieved in practice. Experiments by Popovics et al. [5] showed the variation of P-wave velocity as a function of moisture content of the concrete. They used a saturated concrete sample of 39.7 kg, and measured the P-wave acoustic velocity and the Rayleigh wave velocity during the drying process in an oven and the environment. Fig. 5 shows the variation of the acoustic wave velocity in relation to the reducing weight of the sample due to desiccation. From our calculations using the data of Popovics et al. [5], we found that the concrete they used had porosity in the order of 2%, \( V_a \), was equal to 5.5 km/s and as a result, the maximum porosity level of their sample did not reach higher than 50%.

Variations of the velocity in the order of up to 400 m/s can be fully justified by the moisture content variations. Thus, in the acoustic profile of Fig. 4 these small variations, observed in the velocity field, could be possibly attributed to the moisture.

The determination of moisture was also attempted by the use of electrical tomography within the tunnel.

Since the electrical resistivity of concrete depends on porosity, moisture content, chloride penetration and transportation mechanism [4], electrical methods are used to assess the moisture and erosion hazard, in order to take protective measures for the concrete.

The resistivity values of concrete may vary between 10 and 10^5 Ohm-m, according to the moisture content and its nature [18,19]. The dominant mechanism of electrical current passage through the concrete is via the transportation of ions in the filling fluid of the porous part of concrete.

Fig. 6 shows the tomography interpreted model that resulted from a dipole–dipole array at a 2-m electrode interval. The resistivity values are in the order of 50–200 Ohm-m, which correspond to ‘very wet, submerged, splash zone’ concrete, according to the final report of

Fig. 7. Variation of elasticity module and velocity of concrete (after Bond et al. [2]).
It is observed at the section that the resistivity values down to a depth of 2 m are at relatively higher levels compared to those at larger depths. The high resistivity values can be attributed to low moisture content. The increase of the values near surface is explained by the evaporation of moisture.

The area characterized by high resistivity values, at the left part of the electrical section, coincides with the low P-wave velocity area, found at the acoustic tomography section. This observation supports the following hypothesis: The variations found in the velocity values are not due to some structural change of the material, but due to variations of the retained moisture. At larger depths resistivity values are in the order of 40 Ohm·m, clearly indicating the presence of moisture and saturation of the concrete by water.

There are additional areas along the line with very low resistivity (at depth of 3.5–4 m, at stations 13, 26 and 34 m), at approximately 20 Ohm·m. These values probably imply the presence of slow water seepage, if the occurrence of a metallic element is excluded.

The velocity variations can be attributed either to moisture or to the presence of fractures, since both result to a drop of P-wave velocity. Hence, it may be wise to check all these points where the velocity drop is observed.

Despite the fact that the observed P-wave velocity values of the concrete are slightly overestimated due to its porous saturation, we may certainly argue that its high values are characteristic of the quality of the material, since according to the experiment referred previously, the velocity increase that is induced by saturation is not more than 8% at its extreme values.

Therefore, we may conclude by saying that the concrete of the Marathon Dam remains of excellent quality to date.

From the P-wave velocity measurements, an elasticity module E tomogram can be produced. A diagram of the empirical relation between the elasticity module E and the P-wave velocity of the concrete is presented in Fig. 7 [2].

The elasticity module tomography section resulting from this empiric relation, is presented in Fig. 8. The elasticity module values may be overestimated at the moist areas, since they have been calculated on the basis of the P-wave velocities. The elasticity module has values of 37–40 GPa, at relatively dry areas. Even these smaller values are considered as very good for concrete.

Another important characteristic observed in Fig. 5 is that the variation of \( V_{Rayleigh} \) to that of \( V_p \) is at approximately 1:2. According to the literature, the Rayleigh velocity value is at 47–56% to that of the P-waves, so the presence of moisture does not have a high influence on the \( V_p/V_R \) ratio. This ratio may be correlated to the Poisson ratio (Fig. 9). Hence, by the determination of \( V_R \), we may have a general evaluation of the Poisson ratio along the tunnel.

The Rayleigh waves were recorded without using coupler and with no stacking. A typical example of such a record is shown at Fig. 3b. The surface waves’ arrivals look similar to the first arrivals, since the P-wave arrivals have been degraded after applying suitable gains. The P-waves can be vaguely recognized before the Rayleigh waves’ arrival, not influencing the picking of them.

The main wavelength (\( \lambda \)) of the Rayleigh waves was measured less than 2 m and as a result, the effective penetration depth was at approximately 0.5–0.7 m.
Nevertheless, the effect of the waves to the material could be as deep as 3 m.

The Rayleigh wave velocity can be calculated by these measurements along the section. The measured values are mainly representative to a depth of 0.5–0.7 m (Fig. 10).

After taking into account the results regarding the surface and compressional waves, we produced a diagram of the lateral variation of the respective velocities ratio and the Poisson ratio $\sigma$ (dependent on the velocity ratio) (Fig. 11). The determined values are typical for concrete. In highly moist areas, though the calculated Poisson ratio is less reliable, in view of a probable divergence of the $V_{\text{Rayleigh}}/V_p$ ratio from its real value. At dry areas, low values of the Poisson ratio were observed, in the order of 0.20–0.25.

It may have been interesting to acquire and process data with shear waves within the tunnel. This was proved unfeasible due to the large size of the source, which involved a long beam positioned across the line direction. We may comment at this point that the Poisson ratio would differ significantly from the determined values, since the shear waves are not influenced by the concrete saturation to the same degree as the compressional waves.

5. Conclusions

The application of the one-sided acoustic traveltime tomography, in combination with geoelectrical measurements within the central tunnel of the dam was highly informative regarding the present condition of the dam. The body of the dam is composed of high quality concrete. This was witnessed by the high values of acoustic waves velocity. The high quality is reflected on the high values of elasticity module. Normal values of the Poisson ratio were recorded. A large amount of moisture is retained in the concrete pores, at the interior of the dam. This has the effect of small variations on the velocities of acoustic waves and in particular, it significantly lowers the values of electrical resistivity. Three probable sources of slow water infiltration were detected.

The experiment also resulted in some general conclusions about the study of concrete in highly saturated environment, when the one-sided acoustic tomography is implemented. In such an environment, the effect of the presence of water on the increase in compressional wave velocity measurements must be taken into account. The lack of homogeneity in water filling of the porosity in a body can result in small variations in measured and
calculated quantities, such as the velocity of the compressional waves, the velocity of the surface waves and the modulus of elasticity. When acoustic measurements are conducted in a saturated environment, the combined use of electrical measurements is strongly recommended. Electrical measurements can determine whether the possible variations in the acoustic velocity can be attributed to differences in water saturation or if these are related to structural anomalies. Finally, it is possible for the one-sided acoustic tomography to estimate Poisson ratio by taking into account the $V_p/V_{\text{Rayleigh}}$ (compressional wave velocity to surface wave velocity ratio) instead of $V_p/V_s$ (compressional wave velocity to shear wave velocity ratio). It is worth noting that the estimation with the former method is less affected by the presence of water in the investigated body than the latter one.

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