Journal of Nepal Geological Society, 2000, Vol. 22, pp. 49-54

Effectiveness of *in situ* P-wave measurements in monuments. Examples from Greece

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Abstract:

The P & S waves velocities can be used for both *in situ* and laboratory measurements. These methods are used for studying properties such as the mechanical anisotropy, and the modulus of elasticity of the materials. In this paper, the P-wave velocities were used for the estimation of the depth of weathered or artificially consolidated layers as well as the depth of cracks at the surface of the building stone. This estimation was performed in relation to the lithology and texture of the materials, given that in many cases different lithological data create similar diagrams. All tests were performed on representative monuments in Greece.

1. Introduction

Methods using P & S wave velocities (V, ASTM 597, ASTM D 2845- 83) provide data related to the elasticity, anisotropy and mechanical and weathering resistance of the stones. Porosity, dry density, water absorption and abrasion resistance can also tested on small specimens, providing data related to weathering and the measured velocities. For this purpose a PUNDIT ultrasonic non-destructive digital tester is used.

Figure 1. Location of the studied monuments

Ultrasonic velocity is related to the moduli of elasticity of rocks, such as Young's modulus and Poisson's ratio. Furthermore, it is a very good index for rock quality classification and weathering determination (Topal & Doyuran[6], Clark[2]).

Tests are made using the direct or the indirect method, depending on the case. The direct method is referred to the arrangement of the transducers of the apparatus on the opposite surfaces of the specimen tested. The indirect method, used especially on in-situ measurements, refers to arrangement of the transducers on the same surface of the stone.

The sites of study are given in the map of Figure 1.

3. Surface weathering and cracks

The depth of weathering at a stone surface can be evaluated using the indirect ultrasonic velocity technique (Christaras[1] Zezza[7]). In this case the transmitter is placed on a suitable point of the surface and the receiver is placed on the same surface at successive positions along a specific line. The transit time is plotted in relation to the distance between the centres of the transducers. A change of slope in the plot could indicate that the pulse velocity near the surface is much lower than it is deeper down in the rock (Fig. 2). This layer of inferior quality could arise as a result of weathering.

The thickness of the weathered surface layer is estimated as follows (Fig. 2):

$$D = \frac{Xo}{2}\sqrt{\frac{Vs - Vd}{Vs + Vd}}$$

Where Vs: Pulse velocity in the sound rock (Km/s)
Vd: Pulse velocity in the damaged rock (Km/s)
Xo: Distance at which the change of slope occurs (mm)
D: depth of weathering (in mm)

This application was performed on the walls of the Medieval City of Rhode and some representative results are presented in the diagrams of Figures 3 and 4. These diagrams correspond to measurements on two neighbouring sites at the moat of the Medieval City (Figs. 5, 6).

In this investigation, the above mentioned technique was not only performed for investigating the damage depth at the surface of the weathered building stones but also for evaluating the effectiveness of this method to estimate the consolidation depth at the stones, after treatment. This technique is important to be performed in relation to the other non-destructive methods used in similar cases (Moropoulou & Bacolas[3], Moropoulou et al.[4]).

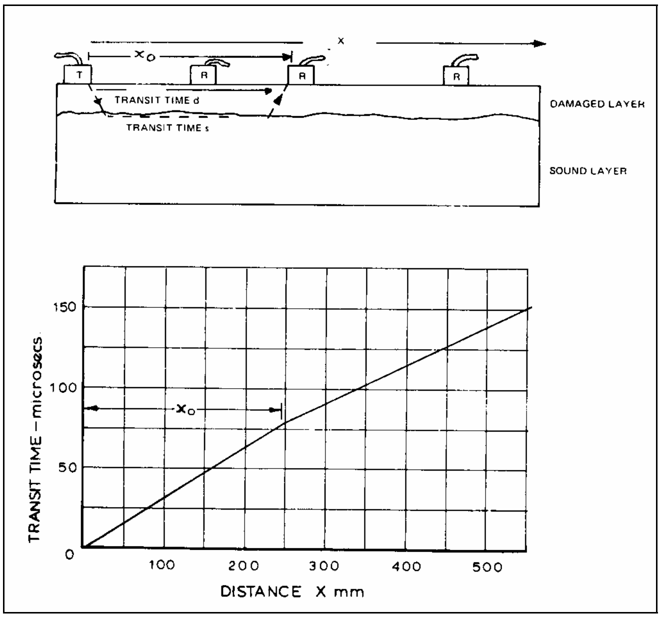

Figure 2. Diagram showing the depth of the damaged layer(PUNDIT Manual[5])

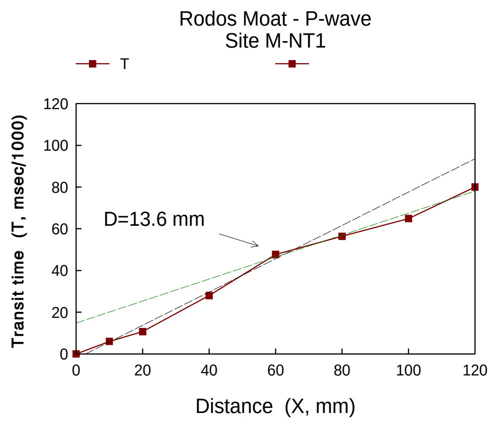

Figure 3. Ultrasonic velocities measured on untreated surface of calcarenitic blocks. The change of the regression slope corresponds to the depth of the weathered zone.

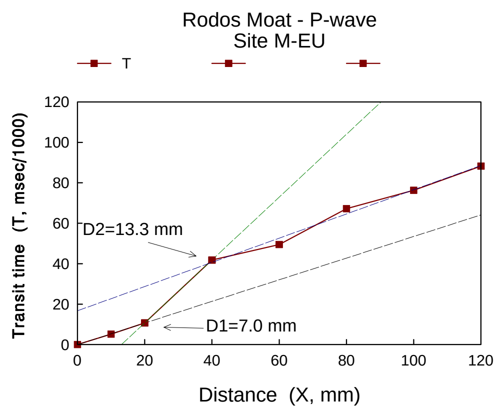

Figure 4. Ultrasonic velocities measured on the surface of calcarenite blocks, treated with consolidation liquid. The change of the regression slope corresponds to both consolidation and weathering depths.

Comparing the diagrams of Figures 3 & 4, a higher velocity is realised at the external layer of the stone, after treatment, corresponding to the consolidated zone. An intermediate, non-treated - damaged zone is also observed. The evaluation of the thickness of this zone depends on the spacing of the successive points of measurement. However, the displacement of the regression line is directly related to the thickness of the non-consolidated – damaged zone.

Consequently, a full consolidation procedure corresponds to a linear (without displacement) diagram (distance / time).

Figure 5. The moat around the medieval city of Rhode, where the tests of Figures 3 & 4 were performed

Figure 6. The calcarenite blocks where the measurements of Figures 3 & 4 were performed

The arrangement of the transducers at the same surface of a stone, but from the opposite sides of a crack can be used for estimating the depth of the crack. In the obtained diagram, a displacement of the regression is occurred, due to the depth of the crack (Fig. 7). This depth is estimated using the following equation:

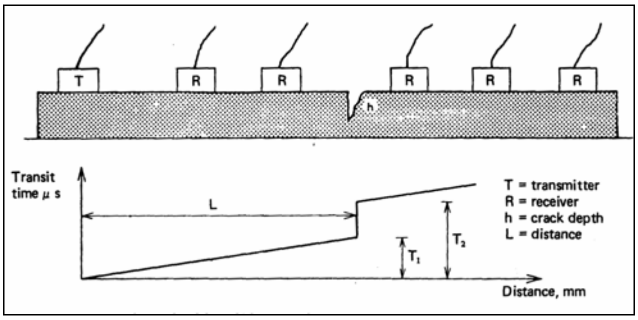

Figure 7. Diagram showing the depth of a crack, on the surface of a stone (PUNDIT Manual[5])

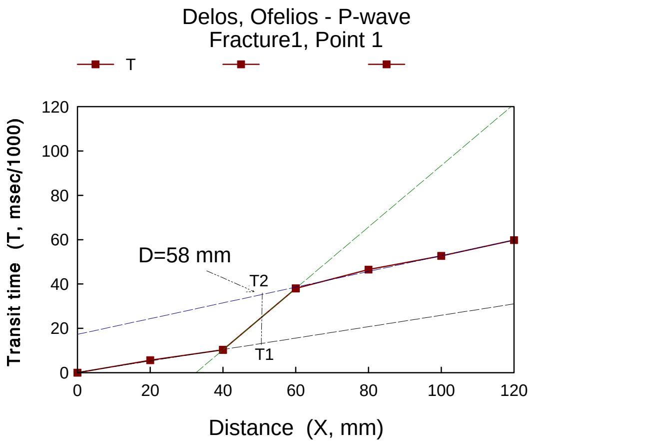

Figure 8. Ultrasonic velocities diagram on the surface of Ophelios marble statue (Delos island, Greece), for estimating the depth of a crack along its left leg.

Figure 9. Gaios Ophelios statue, in Delos island (Greece)

$$h = \frac{L}{2}\left(\frac{T_2}{T_1} - \frac{T_1}{T_2}\right)$$

In the diagram of Figure 8, the depth of a crack was calculated along the leg of the statue of Gaios Ophelios in Delos Island (Fig. 9).

4. Conclusions

The change of the P-wave velocity gives information for the depth of damage, or the quality change, at the external layers of stones. The depth of cracks can also be evaluated.

Furthermore, the infiltration depth of chemicals used for consolidating the external – damaged layer of the stones can also be estimated.

5 Acknowledgement

The measurements in Rhode Island were performed in the framework of a pilot project for the protection of the Medieval City of Rhode. This project was co-ordinated by Prof. A. Moropoulou.

The measurements on the statue of Gaios Ophelios, in Delos Island, were performed in framework of a project funded by the French Archaeological School of Athens and co-ordinated by Prof. B. Christaras.

6. Key words

Non destructive methods, ultrasonic velocity, conservation of monuments.

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