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Effectiveness of in situ P-wave measurements in monuments: examples from Greece

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ABSTRACT

P and S wave velocities can be used for both in situ and laboratory measurements of stones. These methods are used for studying such properties as mechanical anisotropy and modulus of elasticity. 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 developed at the surface of the building stone. This estimation was made in relation to the lithology and texture of the materials, given that in many cases different lithological data create similar diagrams. All tests were carried out on representative monuments in Greece.

INTRODUCTION

P and S wave velocity measurements (V, ASTM 597, ASTM D 2845–83) can be useful for estimating elasticity, anisotropy, and mechanical and weathering resistance of stones. Porosity, dry density, water absorption, and abrasion resistance of small specimens can also be helpful for obtaining the data related to weathering and mechanical resistance. However, for this purpose, an ultrasonic non-destructive digital tester named PUNDIT was found to be most suitable. The study was carried out in the medieval city of Rhode and on the island of Delos, Greece (Fig. 1).

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 estimating rock quality and depth of weathering (Topal and Doyuran 1995; Clark 1966).

Tests are made using direct or 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 for in situ measurements, refers to the arrangement of the transducers on the same surface of the stone.

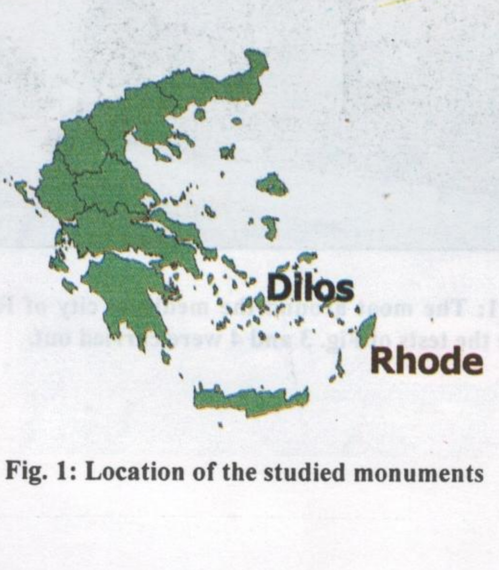

Fig. 1: Location of the studied monuments

SURFACE WEATHERING AND CRACKS

The depth of weathering at a stone surface can be evaluated using the indirect ultrasonic velocity technique (Christaras 1997; Zezza 1993). 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 indicates 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):

$$D = \frac{X_0}{2}\sqrt{\frac{V_s - V_d}{V_s + V_d}}$$

where, D is the depth of weathering (mm); X_o is the distance at which the change of slope occurs (mm); V_s is the pulse velocity in the sound rock (km/s); and V_d is the pulse velocity in the damaged rock (km/s).

The study was carried out on the walls of the medieval city of Rhode and some representative results are presented in Fig. 3 and 4. These diagrams correspond to measurements on two neighbouring sites at the moat of the city (Plates 1 and 2).

In this investigation, the above-mentioned technique was not only performed for investigating the damage depth at

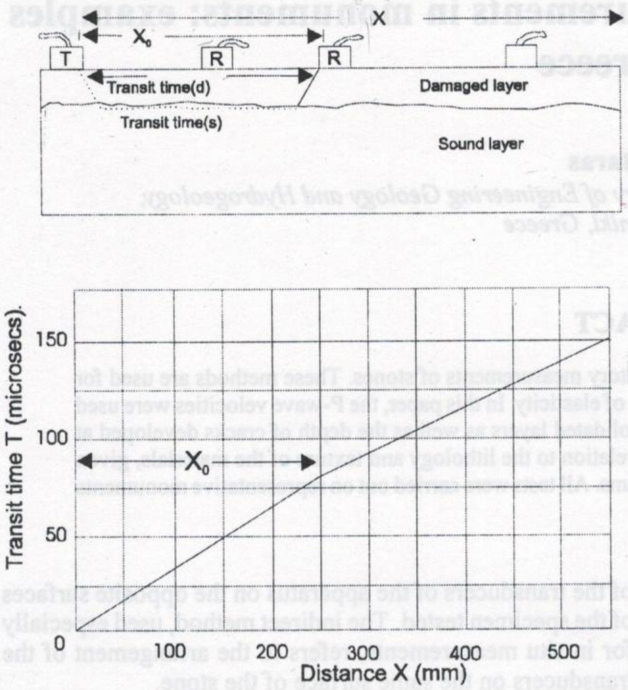

Fig. 2: Diagram showing the depth of the damaged layer according to the PUNDIT Manual

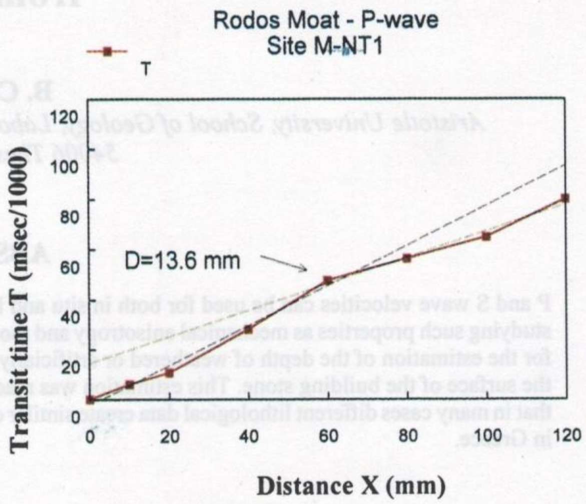

Fig. 3: Transit time versus distance plots measured on untreated surface of calcarenitic blocks. The change of the regression slope corresponds to the depth of the weathered zone.

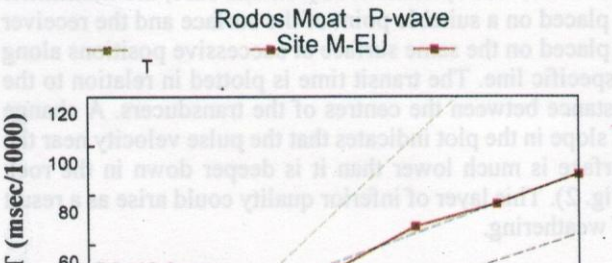

Fig. 4: Transit time versus distance plots measured on the surface of calcarenite blocks, treated with consolidation liquid. The change of the regression slope corresponds to both consolidation and weathering depths.

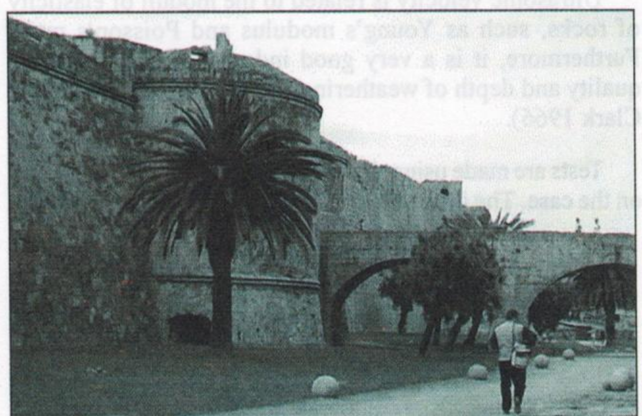

Plate 1: The moat around the medieval city of Rhode, where the tests of Fig. 3 and 4 were carried out.

the surface of the weathered building stones but also for evaluating the effectiveness of this method to estimate the consolidation depth at the stone surfaces, after treatment. This technique was found to be most useful in relation to the other non-destructive methods used in similar cases (Moropoulou and Bacolas 1998; Moropoulou et al. 1998).

A comparison of Fig. 3 with Fig. 4 reveals that there was an increase in the velocity at the external layer of the stone, corresponding to the consolidated zone after treatment. An intermediate, non-treated/damaged zone is also observed. The precise evaluation of the thickness of this zone depends on the spacing of the successive points of measurement. However, the offset of the regression line is directly related to the thickness of the non-consolidated/damaged zone.

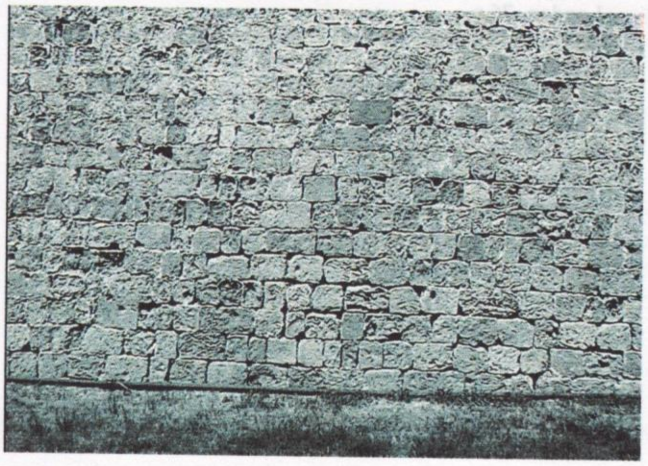

Plate 2: The calcarenite blocks where the measurements of Fig. 3 and 4 were carried out.

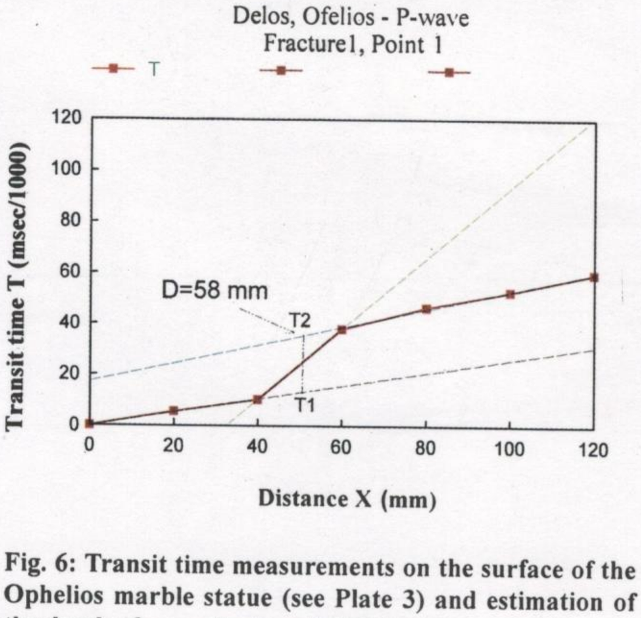

Fig. 6: Transit time measurements on the surface of the Ophelios marble statue (see Plate 3) and estimation of the depth of a crack along its left leg

Consequently, a fully consolidated layer gives a linear (without offsets) diagram (distance/time).

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, an offset of the regression line caused by the depth of the crack can be seen (Fig. 5). This depth (*h*) is estimated using the following equation:

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

Fig. 6 depicts the transit times measured along the leg of the statue of Gaios Ophelios on the Delos Island (Plate 3).

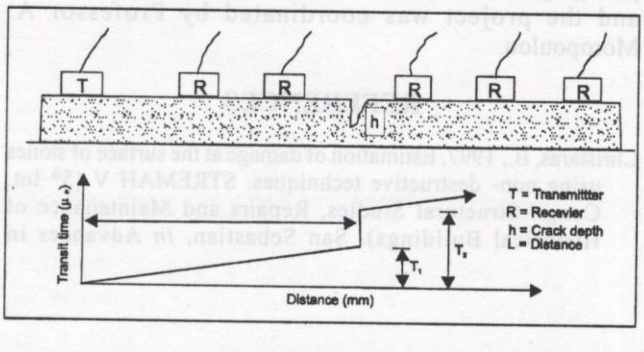

Fig. 5: Diagram showing the depth of a crack, on the surface of a stone (methodology according to the PUNDIT Manual)

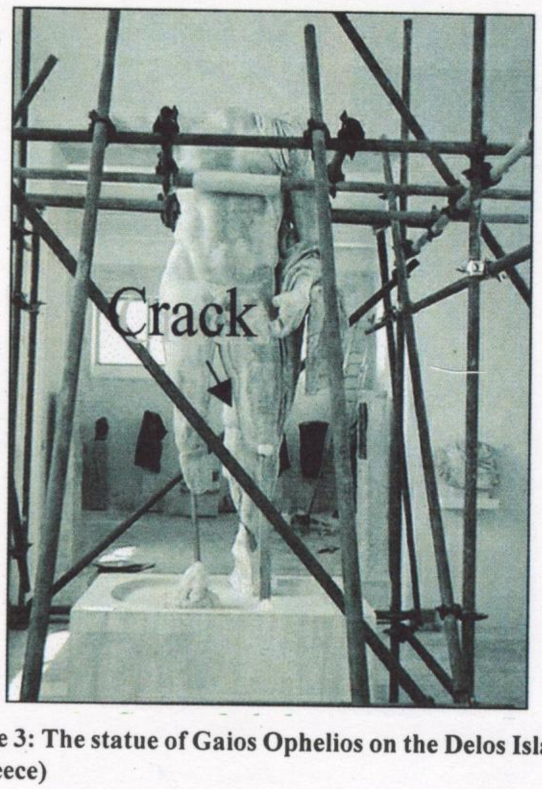

Plate 3: The statue of Gaios Ophelios on the Delos Island (Greece)

CONCLUSIONS

The change in P-wave velocity gives information on the depth of damage, or the quality change at the outer layers of stones. The depth of crack can also be evaluated using this method. Furthermore, the infiltration depth of chemicals used for consolidating the external (damaged) layer of the stones can also be estimated.

ACKNOWLEDGEMENTS

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