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TOWARDS A METHODOLOGY FOR USE OF SONIC AND ULTRASONIC TESTS IN EARTHEN MATERIALS

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Abstract. *In many regions around the world, earth has been used through history as a traditional building material. Nowadays, there is a significant revival of its use due to its ecological value and architectural performance. However, there is still a significant lack of knowledge about its actual mechanical properties and behavior. This work aims at the development of consistent methodologies for the characterization of this building material based on non-destructive tests, NDT's. Ultrasonic and sonic tests on prismatic rammed earth specimens and adobe bricks were carried out. The paper presents an optimized method for estimating S-waves and P-waves based on direct and indirect non-conventional sonic testing methods. Finally, the paper discusses methodological issues for estimating the earthen material properties through the propagation velocity of sonic waves.*

1 INTRODUCTION

The careful evaluation of earthen constructions in order to make the most of the existing building is imperative prior to restoration and rehabilitation. A good approach is to use non-destructive testing methods, NDT's, providing the necessary characteristics of the materials without causing damage. This paper presents a new methodology based on the use of sonic tests (ST) and ultrasonic tests (UST) for prismatic rammed earth specimens and adobe bricks.

The discussion allowed having a better perception of the test limitations and potentialities, as well as on the difficulties and peculiarities of these techniques. The application of non-destructive tests on earthen materials can be frustrating in that the interpretation of results is often not straightforward and may be potentially misleading. This is partly because it is a heterogeneous composite material and it presents non-linear and non-isotropic behavior under mechanical destructive tests [1, 2]. It should also be noted that these techniques come mostly from other fields of research, namely geophysical exploration, so proper calibration is required [3–6].

The wave propagation time in ST and UST is the time lapse between the generation of a wave and the respective arrival time at the receiver location. The arrival time and traveling distances of the waves are often not accurately recognizable even when it does correspond to a first arrival as well as the corresponding type of wave. The study involving determining the velocity of waves has been much discussed in the last 50 years, because it allows deriving several properties of the materials namely the elastic moduli [7]. In the present research work, ST and UST are being applied conventionally and non-conventionally on laboratory assembled prismatic rammed earth specimens and adobe bricks elements and the respective results are analyzed and compared.

The results provide qualitative information to develop a predictive methodology of failure and mechanical behavior. The tested rammed earth samples contains the same composition and particle size distribution of a construction recently built within the framework of the Eramus+ Project "LearnBION - Learn Building Impact Zero Network (2015-2028) 2015-1-PT01-KA204-013132" in Valverde del Burguillos, Spain (Figure 1).

Figure 1: Rammed earth building in Valverde del Burguillos, Spain.

2 SONIC AND ULTRASONIC TEST THEORY

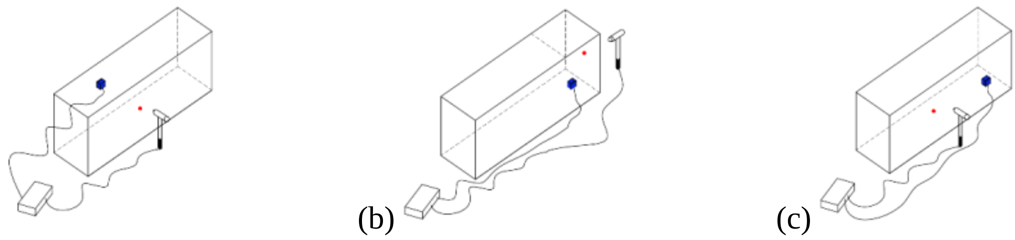
Using direct and indirect sonic tests, it is possible to obtain propagation velocities of P, R and S waves and then estimate values of Poisson's ratio, Young's modulus and shear modulus.

The ST may operate using the direct, refraction or reflection propagation paths of the emitted signals, the receiver(s) being positioned in different configurations in relation to the shot-point, SP. The energy may propagate from the point where it is generated namely as compressive P-waves, surface R-waves and shear S-waves. P-waves being the fastest are often more easily and accurately identified using the ST direct configuration, Figure 2, a).

The waves are generated by the impact of a hammer instrumented with a piezoelectric sensor that records the force of the impact. The generated signal is received by piezoelectric accelerometer transducers used as sensors (receivers) in preset positions and orientations. The acquisition of the readings was performed using a data acquisition board, connected via USB to a laptop computer with software specifically developed in LabVIEW. The analysis of the hammer and accelerometers recorded signals, to identify the initial point of the impact of the hammer and the point of arrival of the waves [8–11].

The frequency and amount of energy of the thrust force are governed by the characteristics of the hammer, the impacted material as well as the impact force. The hammer mass, tip hardness and impact force determine the amplitude and duration of the pulse, where harder tips generate shorter duration signals and broader frequency bandwidths. The material vibrations related to the propagation of the sonic waves are measured as varying voltages by means of transducers such as accelerometers fixed to the surface of the masonry. In the tests carried out, the aluminum tip was chosen as this guarantees shorter contact times and consequently broader frequency bandwidths.

To carry out ST, three different conventional configurations are considered regarding the relative position between the emitter and the receiver and depending on the type of waves to be studied (P, S or R): direct, semi-direct and indirect test configurations (Figure 2).



(a) (b) (c)

Figure 2: Sonic test (a) direct, (b) semi-direct and (c) indirect.

The direct test assumes a linear wave direct transmission through the thickness of the element to be tested, being the shot-point and receiver in opposite sides of the element, which aims to determine P-waves velocity. The velocity of the P-waves is dependent on the quality and consistency/density of the section tested, i.e. it is directly related to the mechanical properties of the material.

In the semi-direct test, the shot-point and receiver are in adjacent faces of the element.

In the indirect test, the shot-point and receiver are on the same face of the element and it is conventionally assumed a linear wave direct transmission, along the surface of the tested element. The waves obtained by this configuration are conventionally assumed to be those that cross mainly the outermost part of the element, so the quality and consistency of the most superficial layer of the material are considered to mainly govern the acquired wave velocities.

The identification of the waves depends on the intrinsic characteristics of each type and the type of configuration test to be performed. In indirect configurations, P-waves are not always clearly identified despite being the fastest (first arrival) waves, having comparatively with R-waves lower energy content. Note that despite their higher energy content, R-waves are not always readily detectable, being the acquired signal the result of different contributes, namely P-waves and S-waves.

According to the literature, [12–16], UST is more accurate than ST to calculate wave propagation velocities when using the direct configuration. According to [17], this method is widely used and consolidated for concrete samples.

3 METHODOLOGY

3.1 Materials and geometry

An adobe specimen (Figure 3) is a brick made of earth, sand and fiber molded and sun-dried. The earth composition determines the physical behavior, cohesion and mechanical properties being influenced by the proportion of sand, silty clay and clay presented in the earth. Generally, the content of silty clay is between 20% and 40%, the content of clay is between 10% and 25% [18]. Furthermore, size and length of fiber are determinant parameters, their modification affects mechanical properties [19]. The adobe tested is composed of natural fibers (straw) of 5-10 cm length. The adobe bricks presented the following nominal dimensions: [320x160x80] mm in order to comply with the Peruvian recommendations of NTE0.80 [20]. The selected soil was collected from the riverbank of the Guadalquivir River in Seville (Spain).

The rammed earth is a clayey soil (earth) compacted into a formwork. That soil has suitable proportions of sand, gravel, clay. The earth composition varies greatly but contains no organic component. Compaction is carried out using an optimum water content; this value can be obtained by Proctor compaction test. The rammed earth is made of layers of earth. After compaction, the thickness of each layer should be comprised of between 8 and 10 cm [1].

Figure 3: Adobe specimens.

Two size specimens of rammed earth (Figure 4) were produced with the following nominal dimensions: [200x175x220] mm^3 (1st Group) and [100x100x220] mm^3 (2nd Group). The specimens were produced by molding the soil mixture preparation into a wood framework. The manufacturing process was carried out following two different compaction methodologies: manual compaction for specimens of the 1st Group and automatic compaction for 2nd Group. The selected soil was collected from the local quarry of Valverde del Burguillos in Badajoz (Spain). The specimens were stored in a stable laboratory environment for approximately 100 days (approximately 24 ºC and 50% relative humidity) until the hygrometric equilibrium was reached. The moisture content of specimens was not measured at NDT, therefore the eventual influence of this parameter in the propagation velocities was not evaluated.

(a) (b)

Figure 4: (a) Rammed earth specimens – samples E, F and G; (b) Adobe samples – A and Rammed earth specimens – samples B and C.

The list of specimens tested and their dimensions are summarized in Table 1.

Table 1: Specimens tested

Code	Samples	Dimensions (mm)	Direct ST	Indirect ST	Direct US
Adobe brick	Adobe brick - A	322x170x80	X	X	X
1st Group	Rammed earth - B	200x175x245	X	X	X
	Rammed earth - C	200x175x235			X
	Rammed earth - D	200x175x218	X	X	X
2nd Group	Rammed earth - E	105x95x222			X
	Rammed earth - F	105x105x222			X
	Rammed earth - G	100x105x222	X		X

3.2 Test set-up and equipment

Two ST sequences were performed, using direct and indirect configurations. The indirect configuration was developed using the conventional and a non-conventional approach, so-called 'key methodology' (Figure 5), aiming at improving the generation and estimation of S-waves velocity. An ordinary key was used to provide a different impact direction that paralleled the reception axis of the accelerometer. The rammed earth specimens were tested in two different directions: the compaction (hereafter C) and non-compaction (hereafter NC) directions during the manufacturing process.

Figure 5: "Key" methodology.

The tests were conducted following some recommendations of international standards, which were developed for other materials (rocks and concrete) [21–23]. An instrumented hammer and two accelerometers were used for the sonic tests. The signal conditioning has carried out by a National Instrument device; the data acquisition and analysis were performed by software LabView designed, from LESE (FEUP), for this proposal.

The UST were also developed using indirect and direct configurations (Figure 6). The ultrasonic equipment used was Proceq brand, PUNDIT device, with an 82 kHz emitter. The value of transmitter pulse amplitude is 500 V and the receiver probe gain is 10x. The Geotechnical Laboratory of FEUP provided this equipment.

The procedure steps are the following: calibrate the equipment and perform a new calibration whenever atmospheric conditions change, select the location of the transducers, keep the surfaces clean and smooth, mark and measure the distance between these points, apply the gel conductor, compress the transducers against the surface until it stabilizes and perform the reading following signal generation.

The eventual gel conductor effects in the ultrasound velocities have not been included in the present experimental campaign. The application of the gel conductor can affect the contact surface quality between transducers and specimen. The gel application repeatedly on earthen materials can produce softening on the external surface and loose sand and gravel, worsening the transducer coupling.

This equipment consists of a central unit, which includes a pulse generator with frequencies between 20 and 150 kHz, an emitter transducer, a receiver transducer, an amplifier and a device for measuring the time between sending and receiving the pulse. Some of these tests were performed for comparison with the ST results.

The indirect configuration for UST was applied in the specimens (Figure 6a). However, it has not been possible to detect, confidently enough, R-waves. The close proximity between emitter-receiver and the used frequencies may be the cause. So, R-waves travel-times have not been included in the investigation.


(a)


(b)

Figure 6: (a) indirect UST and (b) direct UST.

4 RESULTS AND ANALYSIS

This section summarizes the results obtained with the ST and UST on all samples described above. These results are presented by box-plot graphs, being separated according to the identified wave type (P or S). On each graph, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the '+' symbol.

In these preliminary results, the P-wave velocities are showed based on mixing two test methodologies to obtain qualitative information depending on compaction rate. The graph of Figure 7 shows all P-wave propagation velocity values for both ST and UST.

Variations of the compaction methodologies of samples influence the results. Sample A (adobe) presented a different value from the other samples, this was expected due to its differentiated composition. Samples B, C, D, E, F and G are composed of the same material (rammed earth) but have different dimensions and compaction methodologies. First group with samples B, C and D had approximated median velocity values to each other. The second group of samples E, F and G presents different median velocity values. This was expected since they have different compaction methodologies between these two groups, therefore the internal structure and particle distribution can be affected by compaction process.

The graph in Figure 8 presents the results of S-wave propagation velocity. These are samples B and D, both are of rammed earth and with the same dimensions. These samples present approximated median velocity values. There are no difference between UST or ST, and Compaction (C) or Non-Compaction (NC) direction as shown in Figure 7 and Figure 8.

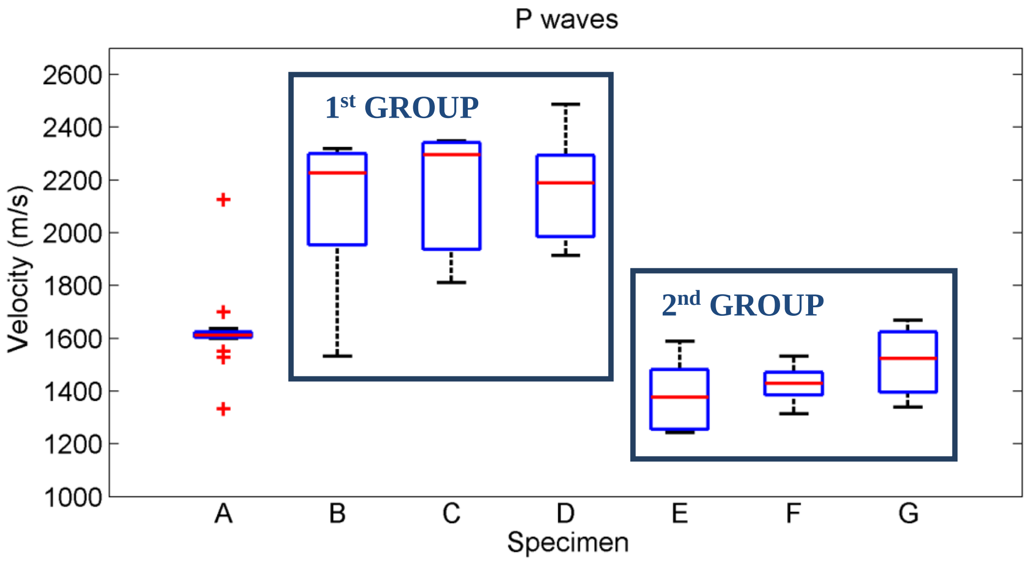


Figure 7: P-waves velocity with UST and ST, direct configuration.

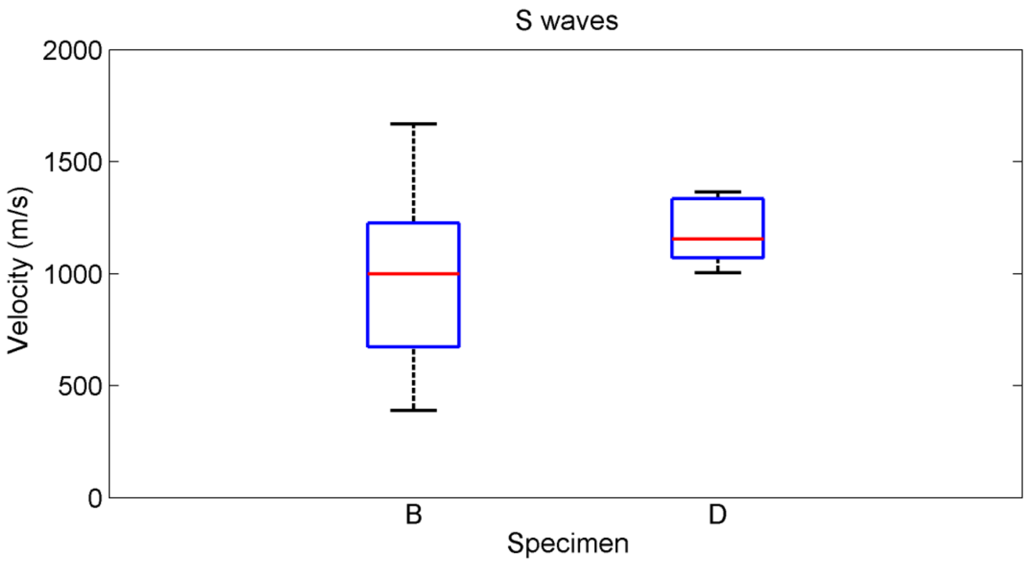


Figure 8: S-waves velocity, ST – "key" methodology.

The graph in Figure 9 shows all P-wave propagation velocity values for UST only. As in Figure 7, variations in compaction process influence the results. Sample A (adobe) presented a different value from the other samples. The first group with samples B, C and D had approximate average velocity values. The second group of samples E, F and G have different but also approximate median velocity values, which was expected due to the different compaction methodologies between these two groups. There is no difference between C and NC directions.

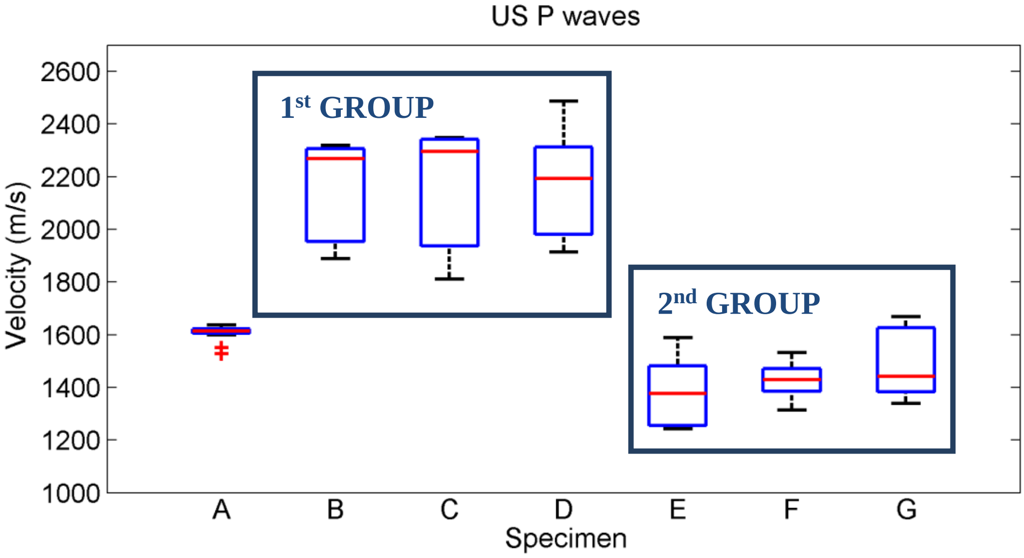


Figure 9: P-waves velocity, UST, direct configuration.

The graph in Figure 10 presents the P-wave propagation velocity results obtained by the UST, as well as indicating the C and NC variations. As in the previous results, the samples were divided into two groups according to their geometric characteristics. The second group has lower P-wave propagation velocity values than the first group, due to its compaction method. In this graph it is also possible to see, in the first group, the influence of the effect that the compaction samples have, since they have lower velocity values.

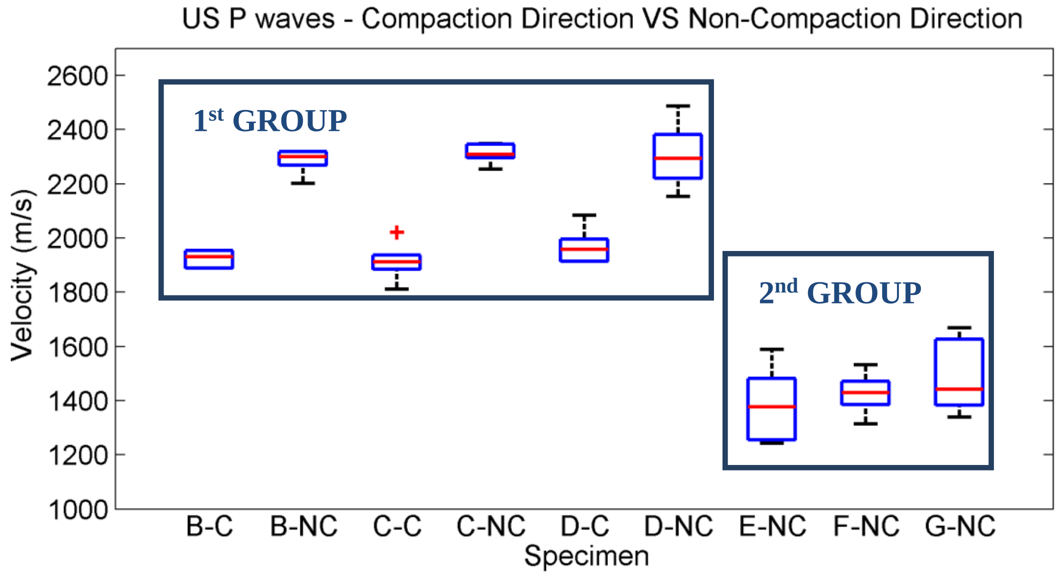


Figure 10: P-waves velocity, UST.

5 CONCLUSIONS

This paper presents an exploratory study that used the well-known ST and UST in earthen materials. The results show a high degree of scattering due to the heterogeneity and anisotropy of the tested material.

These methodologies allowed to obtain some preliminary reference P and S-waves velocity values for this material used in a rammed earth building (Valverde del Burguillos, Spain).

Currently, several non-destructive tests on specimens of different size are being carried out to estimate mechanical properties and obtain correlations with those obtained from compression tests.

Ongoing work is also focused on in-situ investigating the wave propagation velocities of the building walls recently constructed (Valverde del Burguillos, Spain).

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