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Assessment of the degree of saturation in sands by bender element testing

Évaluation du degré de saturation dans les sables par des tests d'élément Bender

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ABSTRACT: The propagation of the P-wave is affected by the compressibility of the porous fluid in the granular media. This effect provides alternatives to estimate the degree of saturation of sands by measuring the P-wave velocity. In the laboratory, such an estimate is usually made using Skempton's B-value (or B-value). However, the B-value is not suitable for use in the field because undrained conditions cannot be guaranteed during measurement. This study aims to assess the degree of saturation in partially to fully saturated sands using P-wave velocity measurements obtained by bender element tests. The measurements of P-wave velocity were compared with theoretical predictions based on Biot-Gassmann theory of wave propagation in fluid-saturated granular media. Therefore, the P-wave velocity proved a more reliable approach to assess the degree of saturation, as shown by the good agreement between the theoretical predictions and experimental results.

RÉSUMÉ: La propagation de l'onde P est influencée par la compressibilité du fluide poreux dans les milieux granulaires. Cet effet offre des alternatives pour estimer le degré de saturation des sables en mesurant la vitesse de l'onde P. En laboratoire, cette estimation est généralement réalisée en utilisant la valeur B de Skempton (ou valeur B). Cependant, la valeur B n'est pas adaptée à une utilisation sur le terrain car les conditions non drainées ne peuvent pas être garanties lors de la mesure. Cette étude vise à évaluer le degré de saturation dans les sables partiellement à entièrement saturés en utilisant les mesures de la vitesse de l'onde P obtenues par des tests à élément bender. Les mesures de la vitesse de l'onde P ont été comparées aux prédictions théoriques basées sur la théorie de Biot de la propagation des ondes dans les milieux granulaires saturés de fluide. Par conséquent, la vitesse de l'onde P s'est avérée être une approche plus fiable pour évaluer le degré de saturation, comme le montre la bonne concordance entre la prédiction théorique et les résultats expérimentaux.

Keywords: Laboratory tests; wave propagation; sands; soil dynamics.

1 INTRODUCTION

The degree of saturation (*Sr*) significantly impacts the mechanical behaviour of sands as it affects pore pressure build-up (Ishihara, 1993). In the laboratory, *Sr* is typically estimated by the pore pressure coefficient B (or *B*-value) originally introduced by Skempton (1954). However, measurements of *B*-value in the field due to the difficulty in controlling undrained conditions (Gu et al., 2021; Naesgaard et al., 2007). This limitation has prompted the development of alternative methods for field-based Sr assessment.

According to (Biot, 1956), changes in the degree of saturation affect the propagation of P-waves. Studies conducted by diverse authors (Astuto et al., 2023; Kumar & Madhusudhan, 2012; Leong & Cheng, 2016; Tsukamoto et al., 2002) have demonstrated that alterations in *Sr* effectively result in variations of the P-wave velocity (V_P). This response is because P-wave travels through the fluid (a mixture of water and air) rather than through grains contacts. Consequently, in fluid-saturated granular media, *Sr* can be estimated by measuring *Vp*.

This paper assesses *Sr* by a novel and reliable procedure Bender Element (BE) tests to generate P-wave. based on V_P measurements. Experimental results were compared against theoretical predictions based on the wave propagation theory or Biot-Gassmann theory (Biot, 1956). The wave-based approach of this study has proven to be a method more reliable for estimating *Sr* in sands.

2 MATERIALS AND METHODS

In this study, TP-Lisbon sand was used. This sand is an alluvial granular soil with origin in the late Quaternary, which has sedimented next to the Tagus River in the historical centre of Lisbon (Molina-Gómez & Viana da Fonseca, 2021). Figure 1 exhibits the grain size distribution of TP-Lisbon sand. Table 1 summarises the parameters derived from the grain size distribution, specifically the mean diameter (D_{50}), the coefficient of curvature (Cc), the coefficient of uniformity (Cu) and the fines content (FC). This table also presents the following physical properties: the specific gravity of solids (G_s), the minimum void ratio ($e_{\min}$) and the maximum void ratio ($e_{\max}$).

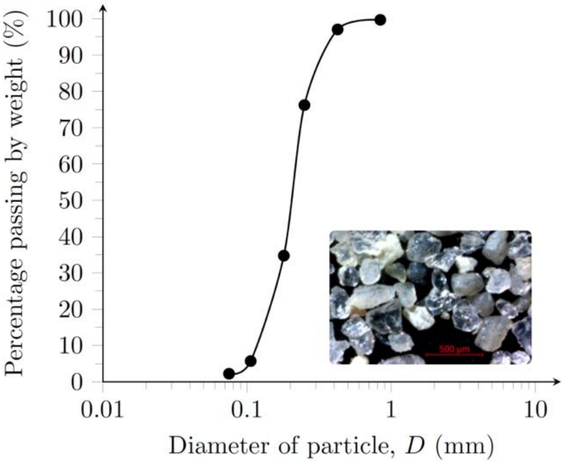


Figure 1. Grain size distribution of TP-Lisbon sand.

Table 1. Physical properties of TP-Lisbon sand.

Parameter	Value
D_{50} (mm)	0.21
Cu	1.69
Cc	1.13
FC (%)	2.21
Gs	2.66
$e_{\min}$	0.64
$e_{\max}$	1.01

A series of soil specimens were reconstituted to achieve a relative density (Dr) of 30% using the air pluviation method (Yamashita et al., 2009). This procedure allows replicating the initial fabric of alluvial soil deposits (Molina-Gómez et al., 2020). The tests were conducted in a triaxial cell equipped with a pair of BE to measure the seismic wave velocities, specifically P- and S-wave velocities (V_P and V_S).

These waves were generated by exciting the BE using sine-wave pulses with various frequencies (Ferreira et al., 2021). For P-wave, input frequencies (F) ranging from 30 to 75 kHz were employed; while S-wave F ranged from 1 to 10 kHz. BE testing involved the analysis of wave propagation using four different F (Viana da Fonseca et al., 2009). V_P and V_S were estimated by computing the ratio between the tip-to-tip distance (L_{tt}) and the travel time of wave propagation (t_t). L_{tt} was accurately monitored by local instrumentation, that is, a series of Hall-Effect transducers installed directly to the soil specimen (Molina-Gómez et al., 2023). The t_t was estimated by the identifying the first arrival time of the signals with different F.

As previously mentioned, the dry pluviation method was used, ensuring a $Sr = 0\%$ at the beginning of all tests. For soil saturation, the carbon dioxide method was implemented. After the carbon dioxide flushing, deaired water was flushed through the soil specimen under a constant hydraulic gradient, pushing out the carbon dioxide through the top drainage line. To guarantee the effective removal of the gas, the water volume should be twice the estimated volume of voids (Viana da Fonseca et al., 2021). An automatic volume change gauge was utilised to measure the volume of water that passed through the soil specimen. The water that did not remain in the specimen was estimated by collecting this water in a graduated cylinder.

Gas bubbles may remain in the soil skeleton even after flushing. To achieve the full saturation of the soil, the backpressure (BP) was gradually increased under a confinement pressure of 10 kPa. Measurements of Vp and Vs were conducted during BP increments of 50 kPa, corresponding to BP of 0, 50, 100, 150, 200, 250, and 300 kPa. Throughout the BP increments, the ingress of water into the soil specimen was monitored using a volume gauge, and changes in volume were measured by Hall-Effect transducers. This method ensures accurate estimation of Sr at each BP value by calculating the phase relationships (Molina-Gómez et al., 2023).

The soil was considered fully saturated when Vp exceeded 1482 m/s—the Vp of water (Astuto et al., 2023). All soil specimens reported the full saturation condition at the end of testing. The evolution of the Sr was confirmed by the final water content, ω_f, (Viana da Fonseca et al., 2021). To estimate ω_f, the specimens were carefully removed from the cell, avoiding possible loss of soil grains and water, as suggested by Verdugo & Ishihara (1996).

3 RESULTS AND DISCUSSION

Figure 2 displays the typical P- and S-wave signals obtained from BE tests. The analysis of the fist arrival time of seismic waves reveals that the P-wave propagation changes with the variation of Sr, while S-wave propagation remains constant. These results confirmed that the increment in *Sr* causes a V_P increasing, demonstrating that P-wave is effectively transmitted through the fluid-saturated granular media.

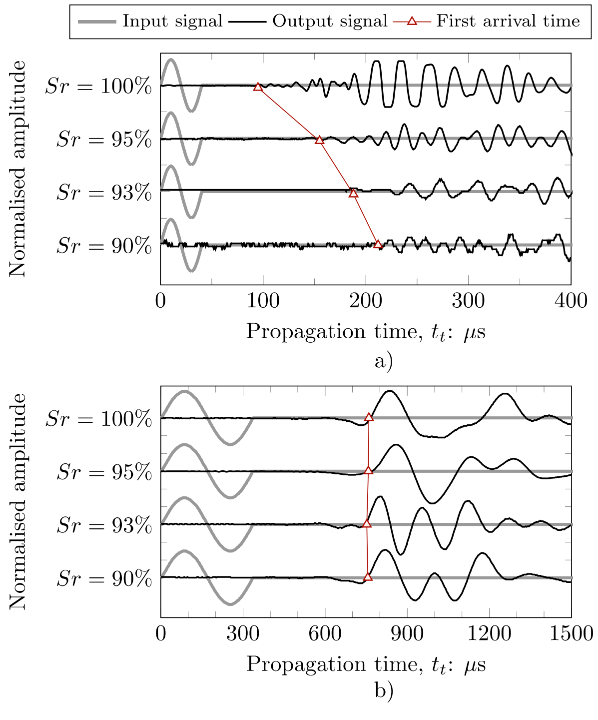
Figure 3 shows the evolution of *Vp* as a function of *Sr* in TP-Lisbon sand. Besides, Figure 3 compares experimental data against theoretical predictions performed based on Biot-Gassmann theory:

$$Vp = \sqrt{\frac{K_{soil} + \frac{4}{3}G_{soil}}{\rho_{soil}}} \qquad (1)$$

where K_{soil} is the bulk modulus of the soil (comprising the sum of the bulk moduli of soil grains, K_g, and suspension K_{sus}), G_{soil} is the shear modulus of the soil and ρ_{soil} is the density of the soil. *Vs* measurements were used for estimating the soil stiffness using the shear modulus of the soil ($G_{soil} = \rho_{soil}Vs^2$). ρ_{soil} was estimated by:

$$\rho_{soil} = (1-n)\rho_g + n[(1-Sr)\rho_a + Sr\rho_w] \qquad (2)$$

where *n* is the porosity, ρ_{soil} is the density of grains, ρ_a is the density of the air/gas, and ρ_w is the density of the water. In this study, K_g equal to 3.5 GPa was adopted, as suggested by Santamarina *et al.* (2005); Kumar and Madhusudhan (2012). K_f computation involved the bulk modulus of liquid (i.e. water equal to 2.2 GPa) and gas (i.e. carbon dioxide equal to 0.1 GPa).



a)

b)

Figure 2. Typical BE signals: a) P-wave; b) S-wave.

Figure 3 demonstrates the effects of *Sr* in V_P due to a good agreement between experimental results and theoretical predictions based on Biot-Gassmann theory. This agreement establishes a solid framework to assess the *Sr* in partially saturated sands, i.e. *Sr* ranging from 80% to 100%. From Figure 3, it can be observed that *Vp* has a gradual change until *Sr* of about 85%. Afterwards, *Vp* sharply increased until converging to a *Vp* value exceeding 1500 m/s. This *Vp* increment was attributed to the partially saturated condition of the soil, where occluded air bubbles are present in the fluid without interacting with the soil grains. In this state, the P-wave propagation is controlled by the fluid instead of the contacts in the granular medium, clarifying the sharp increment in *Vp*, as also observed by Leong and Cheng (2016); Gu *et al.* (2021).

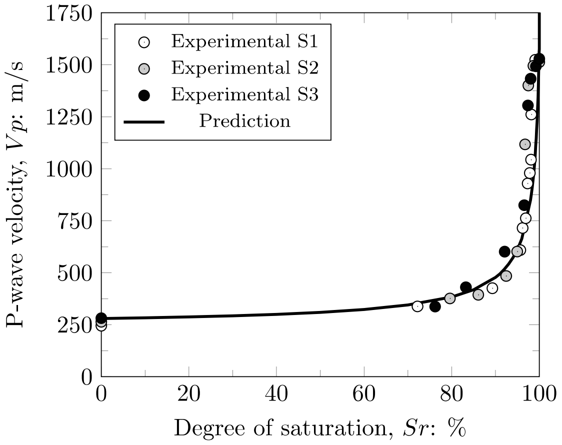


Figure 3. Relationship between V_P and Sr.

Figure 4 demonstrates the effectiveness of the P-wave-based approach by providing a direct comparison between the experimental V_P results and the theoretical V_P values for the same *Sr*. This comparison fits within a difference factor of ±10% for all soil specimens. These results validate that the approach proposed herein can estimate *Sr* with an accuracy well within the ±10% range.

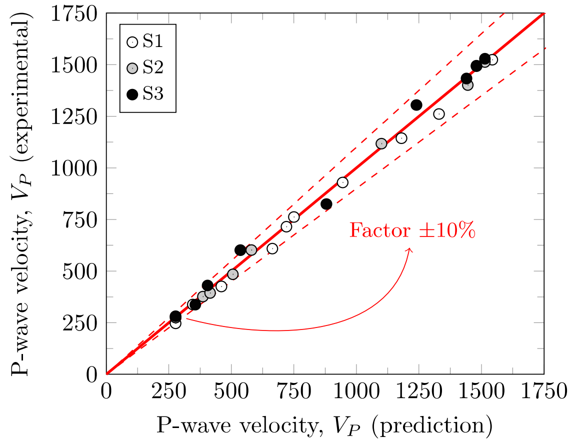


Figure 4. Experimental results vs. predicted values.

4 CONCLUSION

This study has evaluated the use of *Vp* for estimating the degree of saturation in sands, utilising BE testing. Tests involved reconstituted soil specimens of TP-Lisbon sand with a relative density of 30%. The P-wave propagation changes with the *Sr* variation due to the compressibility of the pore fluid type and occluded air/gas bubbles in the soil skeleton. A comparison between experimental results and theoretical predictions based on Biot-Gassmann theory validated this approach. The results offer a versatile method for degree of saturation estimation in sands, demonstrating the effectiveness of P-wave estimation in both laboratory and field testing.

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