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Shear Wave Velocity Response of Compacted Kaolin during Drying-Wetting Cycles

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Abstract. Previous studies indicate that that post-compacted changes in moisture and suction significantly influence small strain response, often this is not routinely monitored during operation. Thus, assessing the impacts of seasonal variation on performance is critical for gauging the geomechanical behaviour of compacted soils underlying typical transport infrastructure. In this paper the influence of drying-wetting cycles on small strain stiffness is investigated on compacted kaolin specimens by measuring shear velocity using ultrasonic testing methods. The drying-wetting cycles were applied to specimens using fixed levels of gravimetric water content. This more closely mimics near surface unsaturated site conditions rather than adopting fixed suction levels using the axis translation technique. As expected, the results show that the shear wave velocity exhibits a hysteretic response during drying-wetting cycles. However, as the cycles are controlled by gravimetric water content, higher shear wave velocity values were recorded for the drying paths rather than wetting paths as previously reported in suction controlled testing. Furthermore, for the subsequent drying-wetting cycle, the shear wave velocity continues to show an hysteretic response while also exhibiting increasing velocities for a given gravimetric water content level, indicating that specimens are undergoing some form of hydraulic ageing.

1 Introduction

Small strain properties are integral for evaluating the performance of compacted subgrade soils incorporated in earth structures that are subject to dynamic loading due to passing traffic, such as embankments. The non-linearity of shear modulus with increasing strain makes accurate determination of small strain properties essential for accurate determination of ground movements, for example changes in rolling stock from passenger to freight [1, 2].

However, after compaction during their service life, these soils are exposed to environmental conditions, most notably the effects of extreme climatic events associated with climate change [3]. This results in persistent moisture and suction changes that are caused by infiltration (wetting) and evaporation (drying) (Figure 1). As a consequence unsaturated conditions significantly influence the post-compacted small strain response of geomaterials over time.

Previous studies indicate shear waves are influenced by void ratio, saturation, matric suction and net stress [4, 5]. In unsaturated conditions hysteresis of the wetting and drying path has also been shown to significantly impact the geomechanical behaviour of compacted soils. Ng et al. [6] and Ng and Xu [7] found marked hysteresis in shear modulus at constant suction; the wetting shear modulus presenting higher than the drying path. Similar observations were also noted by Khosravi and McCartney [8] on Bonny silt and Ngoc et al. [9] on kaolin sand mixture. Testing of compacted silty soils has also shown that small strain stiffness increases in line with the shape of the soil water retention curve (SWRC). Further work presented by Heitor et al. [10] showed the presence of larger hysteresis amplitudes for samples compacted using lower energy levels and illustrated the significant influence of suction history on the small strain stiffness response during drying-wetting cycles.

Several other researchers have also investigated the effect of drying-wetting cycles on the mechanical properties of compacted soils. Work presented by Stirling et al. [11] showed that successive drying-wetting cycles on compacted glacial till produced a decreases in suction and shear strength attributed to the formation of micro cracking, thus alteration of the pore structure. Similar findings were also presented by Azizi et al. [12] and Azizi et al. [13] who showed drying-wetting cycles significantly impacted the water retention properties of compacted clayey silt due to changes in pore structure determined from MIP analyses. However, Ngoc et al. [9] and Liu et al. [14] report that drying-wetting cycles produced an increase density and small strain stiffness at constant suction. This suggests that compacted soils behaviour during drying-wetting cycles is highly variable and depends on compaction characteristic, soil properties and unsaturated conditions.

In past studies, the assessment of the small strain response during drying-wetting cycles, have been typically conducted using bender elements. . However, this methods requires the specimens to be protruded which is turn causes some localised soil disturbance[15].

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More recently, an alternative non-destructive testing technique that relies on piezoelectric crystals bonded to a platen (i.e. ultrasonic testing) has shown great promise. Results reported by Leong et al. [16] and Nakagawa et al. [17] show success measuring compressional and shear waves in cohesive soils in both saturated and unsaturated conditions however, this method has not been utilised during drying-wetting testing. This may be advantageous as multiple measurements are required for a singular specimen where repeated penetration may be problematic.

In this paper, an ultrasonic testing system is used to monitor shear wave velocity during drying-wetting cycles of compacted kaolin. It also provides a novel insight into the ubiquitous influence of climate on the small strain stiffness of compacted soils at constant gravimetric water content rather than suction. Constant gravimetric water content more closely represents surface field conditions while also allowing for suction to remain dependant variable e.g. capture effect of volumetric changes on matric suction. The salient aspects regarding hysteresis of drying-wetting paths is also considered.

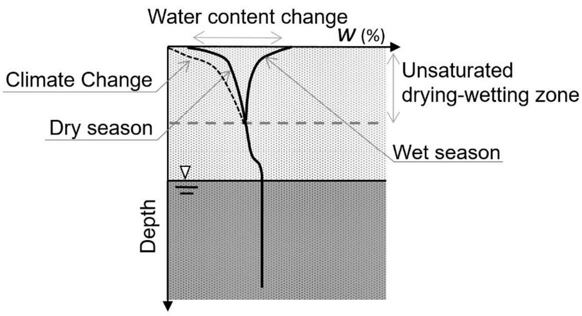

Fig. 1. Ground profile showing annual changes in moisture of geomatrials (modified after Heitor [18])

2 Experimental Work

2.1 Compaction characteristics

Statically compacted Imerys Kaolin (Polwhite E) was used in the study to form specimens for testing. The particle size distribution was composed of 100% fines of which 62% medium and fine silt and 38% clay fraction, determined using sedimentation by the hydrometer method [19]. The kaolin has a liquid limit of 56%, plasticity index of 23% and specific gravity of 2.61.

The testing programme included the determination of shear wave velocity in compacted specimens subjected to several drying-wetting (DW) cycles. Specimens were statically compacted to a stress of 1400kPa and prepared in a Ø38×76mm mould. A comparison between standard Proctor compaction curve (593.7 kJ/m³) (BS 1377-2:2022) and static compaction curve at 1400 kPa is presented in Figure 2. It can be observed that both compaction methods exhibit different compaction curves. For instance, static compaction shows a distinct maximum dry unit weight at 32% gravimetric water content, whereas, dynamic compaction exhibits a maximum unit weight at 28%.

The specimens used for drying-wetting cycles were prepared at the Proctor optimum moisture content. This water content level was selected to more closely simulate field compaction conditions. Consequently, compaction was undertaken at 93% of the maximum dry unit weight. The results of several static compaction tests, presented in Figure 2, show good repeatability between prepared specimens.

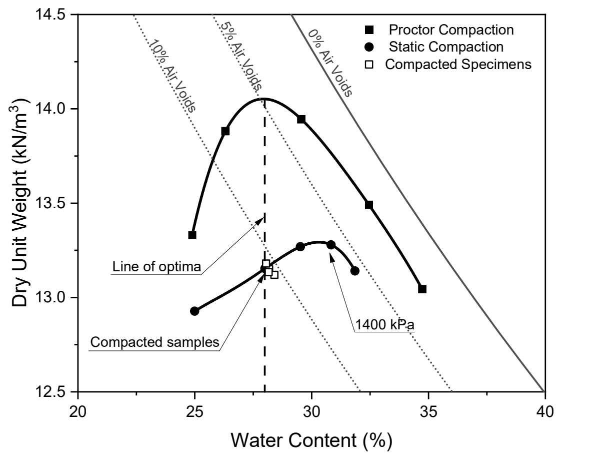

Fig. 2. Comparison between standard Proctor compaction and static compaction at 1400 kPa.

The initial conditions for specimens subjected to drying-wetting cycles are presented in Table 1.

Table. 1. Summary of initial conditions for drying-wetting series

Test ID	Gravimetric Water Content, w: %	Dry Unit Weight, γ_d: kN/m³	Void Ratio, e	SW Velocity: m/s
DW1	0.282	13.05	0.953	254.92
DW3	0.284	13.07	0.950	255.79

2.2 Drying-Wetting Tests

Drying-wetting was conducted on the prepared specimens using gravimetric water content as an independent variable. Unlike previous studies which imposed suction using the axis translation technique, the gravimetric water content was monitored during drying-wetting cycles to ensure specimens reached target water contents. In this study samples were air dried to 15% water content at a constant 40°C. The drying temperature was chosen to expedite drying, as it was expected to have little impact on the mechanical response of the soil as specimens were allowed to equilibrate with room temperature for greater than 24 hours before small strain stiffness testing was conducted. Furthermore, this temperature is commonly experienced by compacted soils in several countries.

Full saturation was achieved by submerging specimens in demineralised water under vacuum for 24 hours. Specimens were wrapped in filter paper to ensure homogenous distribution of moisture. A latex membrane encased the specimens while two endcaps restricted the entrance of water and porous stones ensured no loss of material. Wetting to chosen gravimetric water contents was then achieved in the similar conditions however, water was added by weight to target water contents. Figure 3 shows the apparatus configuration used to achieve saturation and wetting of specimens.

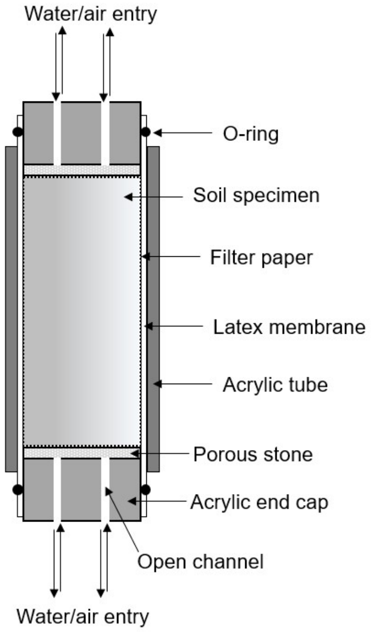

Fig. 3. Schematic diagram showing the configuration used during wetting specimens.

After drying-wetting, specimens were sealed and kept in relative constant temperature and humidity conditions for a minimum of 24 hours. This was determined by measuring the spatial distribution of gravimetric water content after several equilibration times. Samples were divided into 4 layers and then again into an outer and central portion, to measure both lateral and vertical distribution of water content variations. Once the equilibration period elapsed, moisture distribution was achieved to ensure the application of consistent hydraulic history throughout the compacted kaolin.

Drying and wetting measurements were made at 28% (compacted state), 21.5% and 15% gravimetric water contents. Figure 4 shows the main drying path of the compacted kaolin determined using the filter paper method, in accordance with ASTM D5298-10 [20], and fitted using the relationship proposed by van Genuchten [21]. The first scanning path is also shown which was determined using the WP4C Dewpoint Potentiameter. Shear wave velocity measurements were then made at these chosen intervals.

Studies by have shown that measurements for resolution of 100 kPa can be achieved using dewpoint potentiameter, which the manufacturer states has a 0.05 MPa accuracy between 0 and 5 MPa [22-24] This would indicate that although the difference between wetting and drying curves may not be accurately captured the position of the drying and wetting path is correct. The difference in suction observed between the main drying curve and first drying and wetting cycle can be accounted by the presence of significant irreversible volumetric changes that occurred during saturation of the specimens used to determine the SWRC.

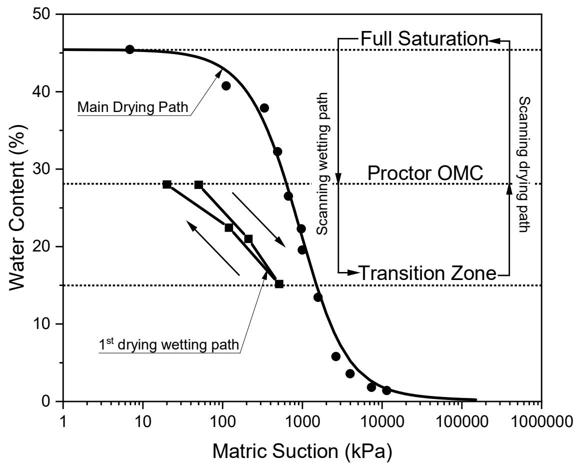

Fig. 4. The main drying path of the compacted kaolin also showing the position of the 1st drying-wetting scanning path.

2.3 Shear Wave Velocity

Ultrasonic Olympus contact transducers (V150-RB) were used to determine the shear wave velocity of the unsaturated kaolin. The ultrasonic signal was generated by the Pundit Lab testing system and received signal recorded by a digital oscilloscope with 12-bit resolution and 500 kHz sampling rate to ensure adequate resolution. Due to the higher frequencies used by the ultrasonic equipment (24-250 kHz), the impact of the near field effects was not visible as the ratio of wave path (L_{pp}) and wave length (λ) were greater than 2 [25]. Shear wave measurements were made without confining pressure. Shear wave couplant was placed between the specimens and platens to ensure contact and displacement of air.

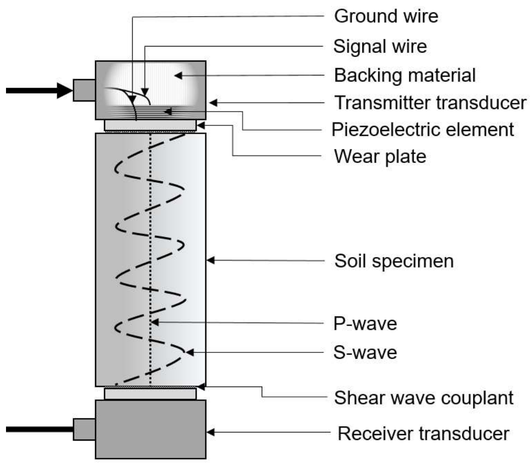

Fig. 5. Schematic diagram showing the ultrasonic transducers configuration during shear wave velocity determination

The shear wave velocity (V_s) was determined using the platen to platen distance (L_{pp}) and the travel time of the shear wave (Δt):

$$V_s = \frac{L_{pp}}{\Delta t} \quad (2)$$

Travel time (Δt) was taken at the first deflection. Figure 6 shows the typical shear wave trace collected for the kaolin for an input frequency of 24 kHz. The input frequency was determined from the wavelength and wave speed, between the initial input signal drop from 0V and its subsequent 2V step.

The P wave component can be seen to arrive earlier due to its quicker velocity. The S wave arrival was then taken from its first deflection, where it crosses 0 on the Y-axis to ensure consistency between readings. After shear wave velocity measurements the volume of the specimen was also recorded using vernier callipers for eight discrete point to allow for calculation of the average dimensions to ensure accuracy.

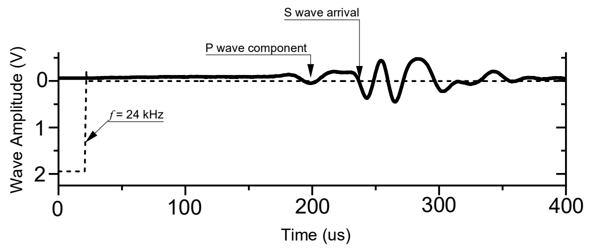

Fig. 6. Typical shear wave trace and input frequency of 24 kHz.

3 Results and Discussion

3.1 Shear Wave Velocity

Two of the compacted specimens were subjected to drying-wetting cycles according to the methodology. Ultrasonic testing was conducted at the chosen gravimetric water contents. The shear wave response during drying is presented in Figure 7 and shows expected response for decreasing water content as increasing suction results in increasing mean net stress and thus earlier arrival of S-waves. Cheng and Leong [15] reported masking of the shear wave arrival by the P-wave due to the reflection of S-waves at the soil-transducer interface (caused by differences in acoustic impedance). However, the ultrasonic testing apparatus used in this study shows clear distinction between P and S waves at differing water contents on both drying and wetting paths.

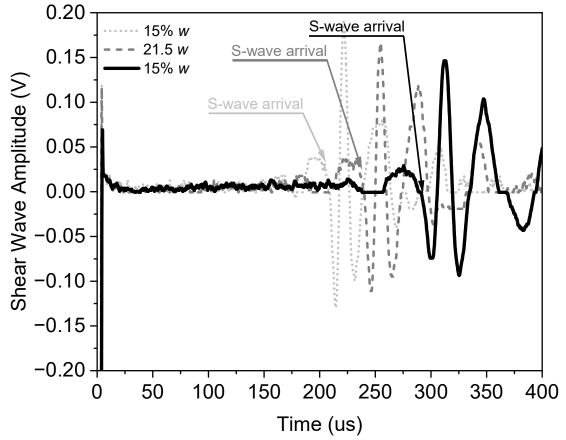

Fig. 7. Ultrasonic shear wave response of kaolin during first drying

The variation in void ratio and shear wave velocity for the initial drying-wetting cycle is shown in Figure 8 and Figure 9, respectively. As expected, a decrease in water content results in the reduction of void ratio and corresponding increase in shear wave velocity. While increasing water content results in an increase void ratio and decrease in shear wave velocity. The change in shear wave velocity is relatively linear which is expected as measurements are taking place within the linear portion of the transition zone for the water retention curve. Hysteresis between drying and wetting paths is also significant both in terms of void ratio and shear wave velocity.

Notably, the drying path presents a greater shear wave velocity when compared to the wetting path. This is contrary to data reported in past studies in which drying wetting cycles were controlled by suction [8-10, 26]. This discrepancy likely results from use of the axis translation technique which imposes a certain level of suction by using a pore-air - pore-water pressure differential [27]. Due to differences in contact angle and the ink bottle effect the water content of the samples would differ on the wetting and drying paths [28]. This likely results in the inversion of paths when plotted in the suction space.

After the application of two drying-wetting cycles between 15% gravimetric water content and fully saturated conditions ultrasonic tests were conducted at identical water contents. A comparison between both the initial drying-wetting cycle and 3rd drying-wetting cycle are presented in Figure 8 and 9. Similar trends were recorded after three drying-wetting cycles, whereby decreasing water content resulted in a decrease in void ratio and increase in shear wave velocity. After successive drying-wetting cycles a significant increase in shear wave velocity at the compacted water content was recorded, increasing by 28 m/s on the drying path and 18 m/s on the wetting path. However, at 15% gravimetric water content the shear wave velocity becomes unified with the original drying-wetting cycle. This may result from lower water contents approaching residual conditions which are primarily controlled by micro pore space. This would indicate some form of hydraulic ageing within the macro pore space after application of drying wetting cycles [29]. In this case hydraulic aging defines a change in a material properties as a function of its hydraulic history rather than time, as testing was conducted within short period [30]. The observed changes in behaviour are unlikely to be a consequence of variation caused by sample preparation as repeat testing also showed identical behaviour. The behavioural change can be linked to volumetric changes as the sample experienced a ε_{vs} of 3.8% when fully saturated after three drying-wetting cycles, which represents a significant change in volume.

Interestingly, void ratio increased in unsaturated conditions after application of drying-wetting cycles. However, several researchers report decreasing void ratio during drying-wetting cycles. For example, Ngoc et al. [9] reported a decrease in void ratio from 0.33 to 0.31 after three drying wetting cycles. The increase of void ratio for kaolin after drying has been previously reported by Vesga [31] and was shown to begin concurrently with the breakage of capillary contacts as drying increases the proportion of air within the pores. The increase in void ratio thus support the hypothesis regarding changes in pore structure of specimens after drying-wetting. The difference in observed behaviour when compared to the literature is most likely a result of differences in the packing of the particles. For example, Ngoc et al. [9] conducted tests on clayey sand, which likely consisted of a significantly larger pore size and compacted density. A study by Nowamooz et al. [32] showed that densely compacted specimens of a silt/bentonite mixture produced cumulative swelling during cyclic changes in suction, while loosely compacted specimens exhibited cumulative compression.

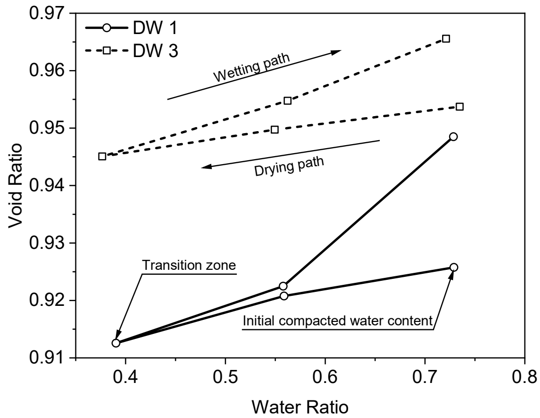

Fig. 8. Void ratio results for initial drying-wetting cycle (DW1) and 3rd drying-wetting cycle (DW3) at constant gravimetric water content.

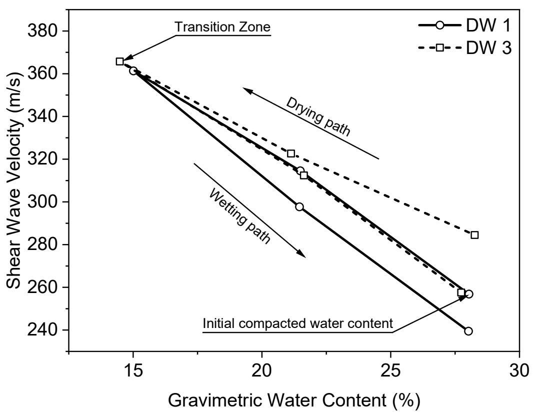

Fig. 9. Shear wave velocity results for compacted kaolin during initial drying-wetting cycle (DW1) and 3rd drying-wetting cycle (DW3) at constant gravimetric water content

Figure 10 shows the shear wave velocity and void ratio for the third drying-wetting cycle, normalised against the initially recorded cycle. It shows that both the void ratio and shear wave velocity experience similar increases albeit the degree of change for void ratio is less. This would also suggest increases in suction due to the decrease in saturation.

Along the drying path both void ratio and shear wave velocity also show larger increases when compared to the wetting path. However, at lower water contents the increase in void ratio and shear wave velocity is less on the drying path. It demonstrates the significance of void ratio on the shear wave response of compacted soils. It also again suggests that the increases in shear modulus on the drying path at the compacted water content results from the change in pore structure and suction.

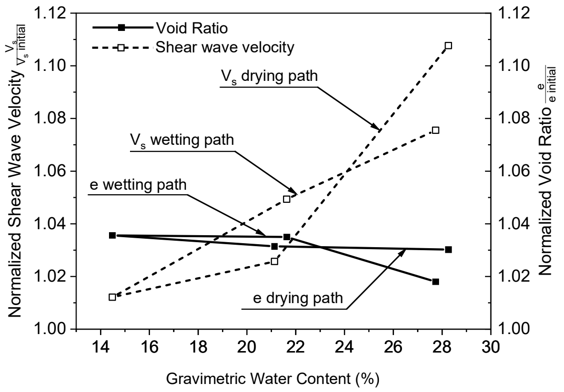

Fig. 10. Normalized shear wave velocity and void ratio for three drying-wetting cycles at constant water content.

4 Conclusion

After a number of ultrasonic tests on compacted kaolin measured at constant gravimetric water content, it was observed that three drying-wetting cycles had a significant hydraulic aging effect on the shear wave velocity. Use of an ultrasonic technique to measure shear wave velocity showed good shear wave response on both the drying and wetting path. Notably, measurements made at constant gravimetric water content showed that shear wave velocities on the drying path were greater than that on the wetting path, contrary to data collected at constant suction. This may be attributed to use of the axis translation technique. Application of three drying-wetting cycles resulted in an increase of both void ratio and shear wave velocity, the greatest increases occurring on the drying path at the compacted water content. Normalisation of both shear wave velocity and void ratio showed similar behaviour with the greatest increases occurring at the compacted water content on the drying path, indicating pore structure changes

Results not only highlight the importance of monitoring shear wave velocity during drying-wetting cycles but confirms field behaviour of small strain stiffness.

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