

Article

Experimental Investigation for Shear Wave Velocity and Dynamic Characteristics of Unsaturated Sand–Clay Liners

Ahmed Alnuaim ^{*}  and Ahmed M. Al-Mahbashi 

Department of Civil Engineering, College of Engineering, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia; aalmahbashi@ksu.edu.sa or ena_almahpashi@hotmail.com

* Correspondence: alnuaim@ksu.edu.sa

Abstract: This study aims to investigate the shear wave velocity and dynamic characteristics of unsaturated sand–expansive clay liners (SECLs) over a wide range of suctions. Liner layers have gained significant interest as environmentally friendly materials for several geotechnical and geoenvironmental applications. These materials are typically found in an unsaturated state as compacted layers and are exposed to dynamic loads from natural phenomena or manmade activities. In such circumstances, sustainable and stable performance should be ensured during the operation and lifetime of these layers by addressing the dynamic characteristics of these materials and possible degradation. Several specimens belonging to different liners of sand and expansive clay were prepared at different suction levels. The shear wave velocity was determined using the bender element technique (BELs). The specimens were then subjected to extensive cycles of dynamic loads up to 500 cycles in the triaxial dynamic loading system. The shear wave velocity and dynamic characteristics of both liners, such as shear modulus (G), damping ratio (D), and degradation index (δ), were determined on the basis of soil suction and loading cycles. Results indicated a descending trend of shear wave velocity with an increase in suction up to 130 MPa, and a significant reduction in shear modulus was detected. Meanwhile, the damping ratio demonstrated a significant increase with the increase in the suction levels of both liners. The reported results are of great significance for sustainable design and modeling of the unsaturated behavior of liner layers in several applications of geotechnical and geoenvironmental problems.

Keywords: dynamic loads; unsaturated sand–expansive clay liners; suction; shear wave velocity



Citation: Alnuaim, A.; Al-Mahbashi, A.M. Experimental Investigation for Shear Wave Velocity and Dynamic Characteristics of Unsaturated Sand–Clay Liners. *Sustainability* **2023**, *15*, 15681. <https://doi.org/10.3390/su152215681>

Academic Editor: Anjui Li

Received: 21 August 2023

Revised: 29 October 2023

Accepted: 30 October 2023

Published: 7 November 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The compacted layers of sand–expansive clay liners (SECLs) have been widely used for several applications in the geotechnical and geoenvironmental fields, such as backfills, clay barriers, buffers for radioactive waste disposal, and protection layers in the sites of oil and gas drilling [1–4]. The key role of these layers is to control the flow of water or leachate of decomposite waste to prevent contamination of underlying water. In addition, the lifts of these layers have been utilized in the protection of road shoulders and side slopes of horizontal or vertical lifts [5]; the seepage through these lifts has been reduced by several orders of magnitude depending on the materials used.

Sand with filling materials such as expansive clays or bentonite was used in the design of liner layers. The materials were mixed together and then constructed as compacted layers for the aforementioned application (i.e., hydraulic barriers, cover systems, protection layers, etc.). Compacted liner layers mostly existed in an unsaturated state in nature or due to seasonal changes and ground water fluctuation. In such cases, the capillary combined with absorptive mechanics enhanced the inter-particle forces, and suction plays a significant role in the behavior of these layers. The unsaturated characteristics of liners made of sand–clays have been studied in terms of their strength [6–8], suction, and soil–water interaction [4,9,10]. The results indicated the important role of suction on these properties.

Other studies on the permeability performance of liner layers were conducted (i.e., [11,12]). Cui et al. [13] used the instantaneous profile method to determine the unsaturated hydraulic conductivity of a sand–bentonite mixture. The study also considered the volume stability effects during testing. The results indicated that a double trend of unsaturated permeability was observed over the considered range of suction. The suction plays an important role by changing the macropores in cases of constant volume and free swell conditions. Al-Mahbashi and Dafalla [14] studied the long-term efficiency of the different liners of sand with expansive clay and bentonite under continuous flow. The results showed significant changes in permeability during the initial periods of flow. These changes are attributed to the migration of fine particles with the flow, which should be considered for the rational design of liner layers.

The compacted layers of liners constructed on several geotechnical or environmental projects are possibly exposed to dynamic or repeated loads such as traffic loads, machine vibration, and other natural sources [15,16]. The performance of these layers during the lifetime of the project is judged by the efficiency of these layers to sustain the expected dynamic loads. At this point, the dynamic characteristics of these materials such as shear modulus, damping ratio, degradation index, and shear wave velocity will inevitably be investigated. In the literature, the dynamic characteristics of liners and the effect of dynamic loads on the main properties of liners in saturated and unsaturated states are rarely addressed in previous research, warranting further attention. Al-Mahbashi and Alnuaim [17] studied the effect of dynamic cyclic loading on the saturated permeability of liners during a continuous flow in the instantaneous and long-term conditions. The results indicated a significant drop in permeability in the short term before applying a continuous flow. In the long-term conditions, the permeability trend reached equilibrium within 100 days. These changes are attributed to the changes in soil structure during dynamic loads. The output highly supports the inclusion of dynamic characteristics in such cases to enhance sustainability, durability, and economy, which are key parameters in the design of SECLs.

Yan et al. [18] investigated the shear modulus of unsaturated silty fine sand. Nonlinearity has been observed describing the trend of the shear modulus with suction and net stresses. The different trends can be explained by the different sand behaviors (linear elastic, elastoplastic, and plastic) along with a small strain ranging from 10^{-6} to 10^{-3} . Głuchowski et al. [19] reported an increase in the maximum shear modulus for the unsaturated silty clay soil due to the limited suction increase up to 200 kPa.

Lu and Sabatier [20] studied the velocity of acoustic P-waves on the body of a silty clay–sand mixture. Several factors, including moisture content and water potential, have been considered. The results indicated the dependency of wave speed on the moisture potential force rather than moisture content. Whalley et al. [21] conducted a shear wave velocity test for two soils of loamy sand and sandy clay loam at different suction levels (near 400 kPa) using the Bishop and Wesley triaxial cell. A nonlinear relation was established between the shear wave velocities over the considered range of suction.

Indraratna et al. [22] investigated the effect of compaction energy on the dynamic properties of silty sand on both sides of the dry and wet states of the optimum moisture content. The dynamic properties related to the values of suction corresponding to the studied range of moisture content (i.e., up to suction of 1 MPa) were measured. The results showed an increase in the shear wave velocity when the moisture content decreased, or the soil suction increased. Leng et al. [23] indicated that the specimen of the unsaturated soil shows more resistance to the deformation induced by dynamic loads and high strength. Only a limited number of studies have addressed the dynamic properties of the unsaturated liners. The majority of these studies were conducted at a low range of suction. This study aims to evaluate the dynamic properties of two liners in saturated and unsaturated conditions. Different suction levels (from low to high) were considered to cover the different stages of the soil water characteristic curves of these materials.

2. Materials Used and Characterization

In this study, two different liners of sand and expansive clay (SECL) were used, the first one contains 70% sand and 30% expansive clay, hereinafter named SECL30. The other liner contains 80% sand and 20% expansive clay, hereinafter referred to as SECL20. The selection of liner materials in this study is based on the previous studies conducted for the same materials and recommended the minimum percentages of clay to satisfy the requirements of hydraulic conductivity (about 10^{-7} cm/s) for these layers (i.e., [24]).

The sand material was sourced from Al-Riyadh city. The laboratory characterizations were performed. The basic results are shown in Table 1. According to the unified classification system ASTM D2487 [25], the sand is classified as poorly graded sand (SP).

Table 1. Geotechnical characteristics of sand and expansive clay.

Title	Specification	Value
Sand		
Specific Gravity, G_s	ASTM D854 [26]	2.67
Uniformity Coefficient, C_u	ASTM D6913 [27]	1.75
Coefficient of Concavity, C_c	ASTM D6913 [27]	0.95
Classification	ASTM D2487 [25]	SP
Expansive soil		
Specific Gravity, G_s	ASTM D854 [26]	2.71–2.77
Liquid Limit, w_L (%)	ASTM D4318 [28]	160–170
Plastic Limit, w_P (%)		60
Shrinkage Limit (%)		11–15
Plasticity Index (%)		100–110
Unified Soil Classification	ASTM D2487 [25]	CH
Swelling Potential (%)	ASTM D 4546 [29]	26
Swelling Pressure (kPa)	ASTM D 2435 [30]	450
Passing #200 (%)	ASTM D 422 [31]	95
Clay Percentage (%)		74

Expansive soil involved in the design of used liners has been obtained from the eastern province of Saudi Arabia, specifically from Al-Qatif City. In this region, the sediment formations of rock, and shales of calcareous clay belonging to the Quaternary age are dominant with other argillaceous rocks. The clay belongs to the calcareous clay formations, which contain calcium carbonate-rich sediment; more details about this formation and geological origin are available in the technical literature [32–34]. The samples were brought from an excavated test bed and pulverized. The portion passing sieve 40 has been used. The geotechnical characterization of this clay is shown in Table 1. The swelling characteristics, strength, and hydromechanical behavior of this soil have been examined in several studies (i.e., [35]). The mineralogical composition of this soil has been studied through X-ray diffraction analysis, and the result indicates the existence of swelling minerals, such as montmorillonite [36]. The amount of these minerals could be estimated at 23% [37]. The microstructural analysis conducted through mercury intrusion porosimetry to determine the pore size and pore volume distribution indicates that the majority (approximately 80%) of the medium pores fall within the range of $0.01\text{--}6\text{ }\mu\text{m}$ [38].

3. Experimental Work

3.1. Mixture Preparation and Compaction Characteristics

The dry sand was thoroughly mixed with dried expansive clay carefully by the percentage mentioned before (70% and 80% sand) to produce the different liners SECL30 and SECL20. For each mixture, an amount of water has been added and a series of standard compaction tests [39] were performed in the laboratory to determine the compaction characteristics of maximum dry density and maximum moisture content. In both examined

mixtures (SECL30 and SECL20), the optimum water contents are 13.7% and 13.6%, while the maximum dry densities are 18.03 and 18.29 kN/m³, respectively.

3.2. Specimen Preparation and Suction Equalization

A series of compacted specimens were prepared at the initial molding of the optimum moisture content and maximum dry density, following compaction curves outlined in ASTM D698 [39]. A special plunger mold, as specified in BS EN 13286–53 [40], was used for the compaction process. The specimens were compacted in five layers to a height of 100 mm and diameter of 50 mm. Furthermore, two disks with a center protrusion (1.5 mm high and 15 mm length) were prepared and attached to the top and bottom of the compaction mold. These protrusions on the attached disks provide special grooves on the top and bottom of the specimen (Figure 1a,b). Moreover, these grooves fit the bender elements (Figure 1c,d) that are attached to the upper and lower surfaces of the specimen to conduct the shear wave velocity test.

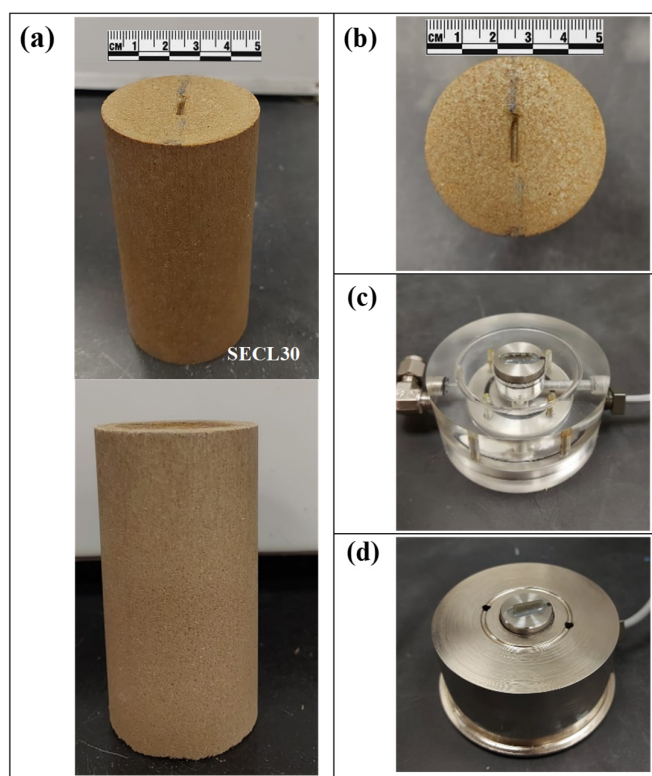


Figure 1. Testing setup of (a,b) compacted specimens with grooves, (c) upper bender element probe, and (d) lower bender element probe.

The compacted specimens were subjected to a suction equalization or saturation. This process has been designed to cover the entire range of suction during testing. At high suction levels, the vapor equilibrium technique was applied using different saturated salt solutions [41] with varying nominal suctions. The potentiometer WP4C provided by Decagon® [42] was used to identify the actual suction value, which will be used in this study. The salt solutions used in this study are potassium carbonate (K₂CO₃) and potassium nitrate (KNO₃). The nominal suction values of these salts are 113.435 and 10 MPa. The saturated salt solutions were prepared and placed in an isolated box. Moreover, the soil specimen was hung above this salt using plastic mesh. The specimen was periodically weighed to detect the equilibrium condition when the successive readings of weight showed no difference. The equilibrium was examined, as shown in Figure 2. In the moderate range of suction, the compacted specimens were prepared and tested in their state after measuring the suction with a WP4C device.

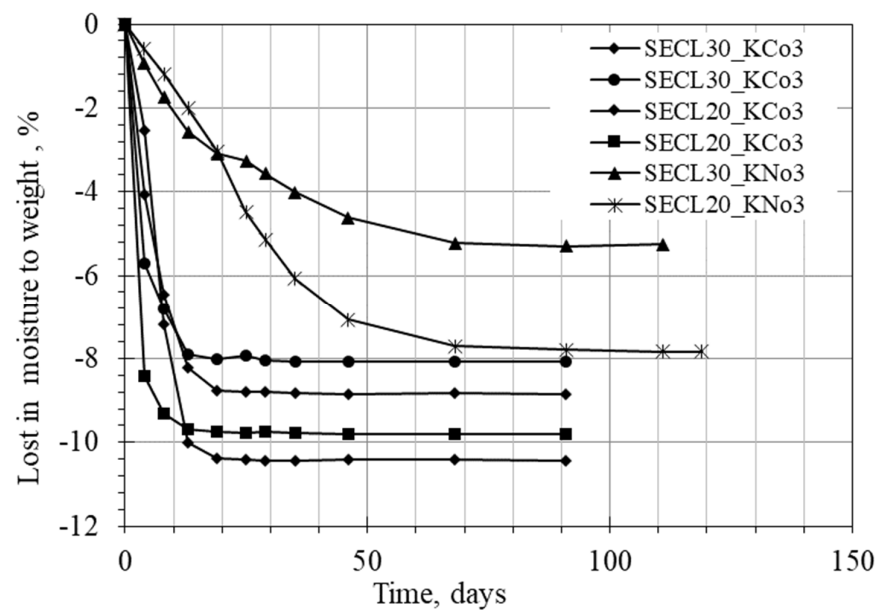


Figure 2. Equalization process for specimens of both liners.

Another series of specimens underwent saturation in the cell of the triaxial dynamic device to achieve the lowest suction range close to zero. The saturation was fulfilled through several stages with increments of back pressure (i.e., 30 kPa). Flushing was performed in the first stage to expel the entrapped air on the specimen and system. The pore water pressure and volume were monitored during this stage. Each stage could be extended to several days. When no further changes were observed in the water volume, the Skempton pore pressure parameter (B-value) was measured and checked. Several stages of saturation were performed up to 450 kPa of back pressure, and the saturation as per B-value measurements reached more than 96%. The suction values corresponding to the water contents that represent the soil water characteristic curves of the tested materials are shown in Figure 3. The entire range can be identified into three stages: the boundary effect zone, where the soil pores are filled with water; desaturation commences and extends over the second zone (transition stage); and desaturation reaches the final residual stage (Figure 3).

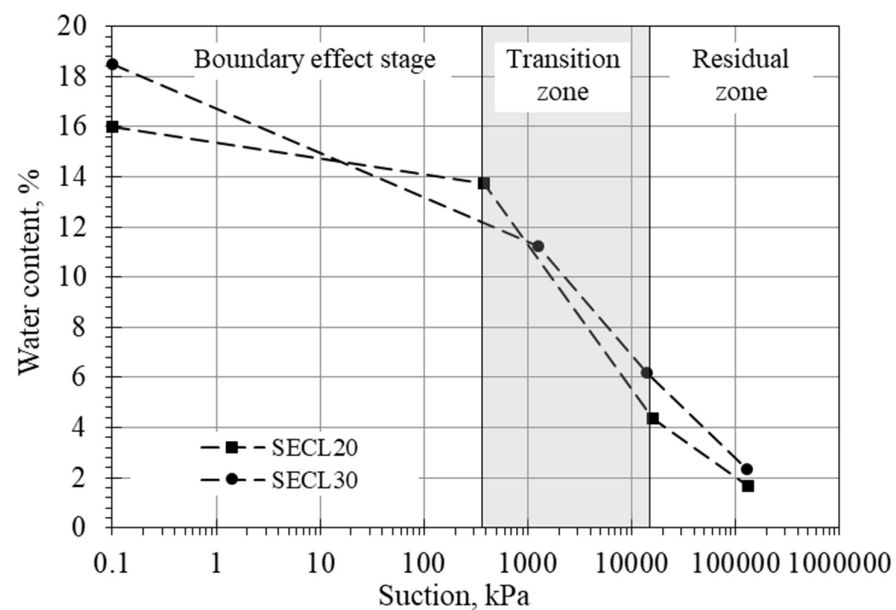


Figure 3. Suction versus water content for equalized specimens.

After completion of the equalization and saturation, the specimens were isotropically consolidated under 100 kPa. The consolidation pressure was achieved by a gradual increase in the cell pressure at the rate of 8 kPa/h.

3.3. Testing Procedures

The dynamic characteristics of the liners were measured using the triaxial dynamic system shown in Figure 4. The device mainly consists of a device cell, pore water, pore pressure controllers, and a dynamic actuator connected to the load cell. Moreover, the device was provided with two pairs of bender elements attached to the pedestal and top cap to measure the shear wave velocity. The following section describes the conducted tests in detail.

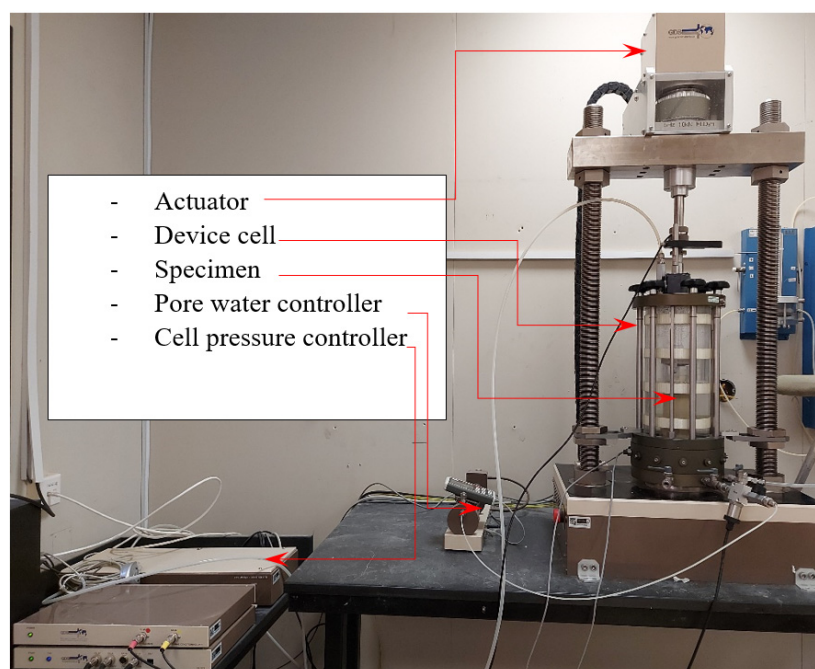


Figure 4. Schematic of the triaxial dynamic loading device.

3.3.1. Shear Wave Velocity Test

As previously mentioned, the dynamic triaxial system used in this study was used with two pairs of bender element (BELs) devices. The first element was fixed at the bottom pedestal, as shown in Figure 1d, and the other one was attached to the upper cap. The lower pedestal and upper cap host the outlet and inlet channels of pore water and back pressure. The pore metallic disks were placed on the top and bottom of the soil specimen to allow water to transfer from or into the specimen. The element at the bottom of the specimen was a wave generator. The other element on the top of the specimen was a wave receiver. The type of S wave was generated from the bottom element. This wave was transferred through the effective length of the specimen (L_t) and received by the element attached to the upper end. These pulses provided reliable measurements [43]. Further details about the different types of applied waves can be found in Da Fonseca et al. [44]. The frequencies adopted in this study ranged from 4 kHz to 10 kHz. Several waves were generated and received for each frequency. In every attempt, the time versus wave intensity was recorded for the generated and received waves.

3.3.2. Dynamic Cyclic Loading

The consolidated specimens were subjected to cyclic dynamic loading by applying 500 cycles using the dynamic triaxial machine, the study conducted by Al-Mahbashi and Alnuaim [17] revealed a stable trend at this level of cycles (500 cycles). This stage has been conducted under stress control conditions. The constant-stress loading could well describe the expected loads on the subbase layers rather than the strain-control loading. The amplitude used for all specimens was 0.14, and the cyclic stress ratio of 0.35 was considered and applied at 1 Hz frequency. A representative section of the applied stress versus time for cycles of dynamic loads up to cycle 20 is shown in Figure 5; the same figure also shows the developed strains up to 100 cycles for specimens at lower and higher levels of suction.

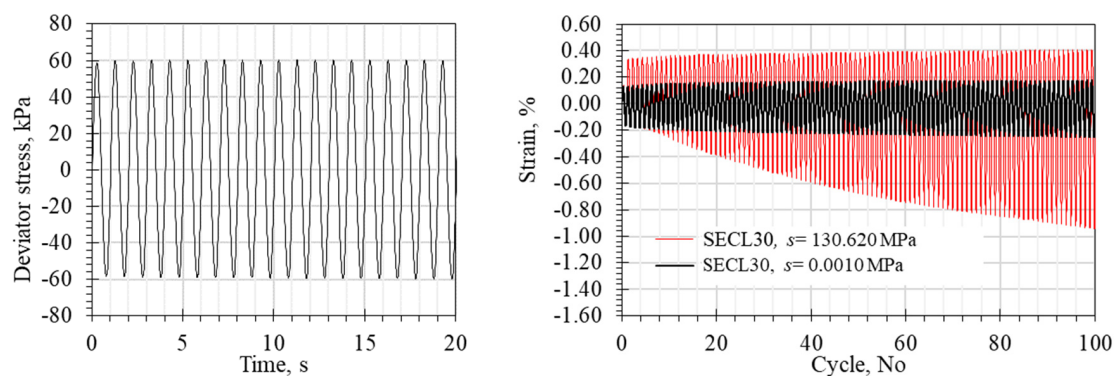


Figure 5. Sample of dynamic testing.

4. Results and Discussion

4.1. Stiffness and Stress–Strain Behavior

The behavior of the materials under the dynamic cyclic loads was analyzed by studying the relation between deviator stress and strain. Figure 6 illustrates the stress–strain hysteresis loop of the selected cycles of dynamic loads (i.e., 1, 100, and 500) for both liners at the considered levels of suction.

The results revealed that the hysteresis loop became larger as the suction level increased. This behavior was attributed to the hardening/softening response of the tested materials under repeated loading or varying suction conditions [45–47]. Higher strains have developed on the extension side, indicating greater deformation compared with those on the compression side.

The soils show varying responses at different suction levels. This phenomenon may be attributed to the different stiffnesses, and the nonlinearity was increased with an increase in the suction level. Han and Vanapalli [48] evaluated the stiffness–suction relation of the different unsaturated soils, ranging from coarse-grained to expansive clays. The results revealed a correlation with the soil water characteristic curve (suction–moisture relation) in the suction range of 800 kPa (boundary effect and transition zone). The study findings show how the stiffness of the unsaturated soils increased within the range of applied suction. The stress–strain behavior is a key characteristic. The consideration of the unsaturated soil stiffness under expected dynamic loads provides an accurate and rational design of geotechnical structures [49].

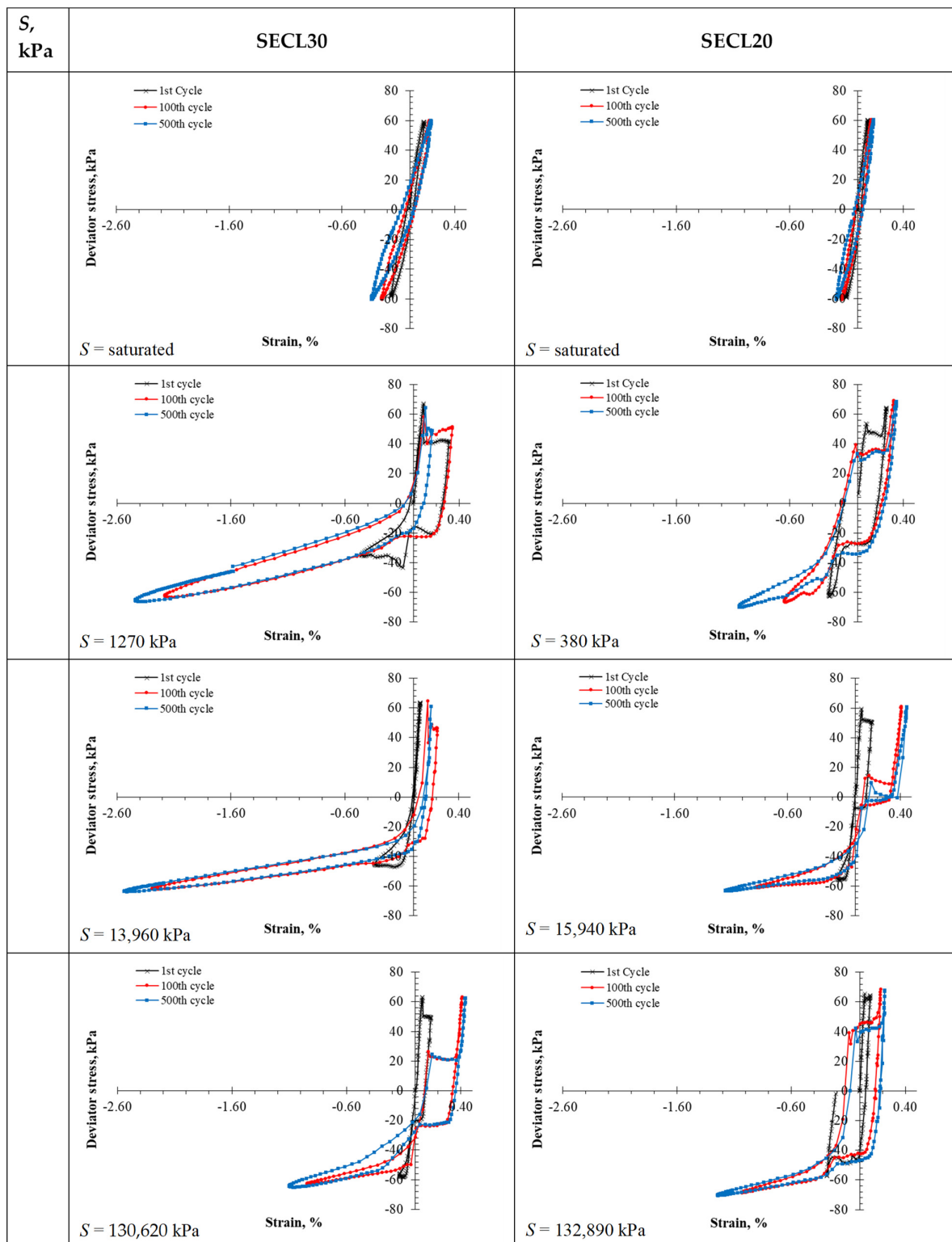


Figure 6. The hysteresis loop of stress–strain for both liners and at different suction levels.

4.2. Shear Wave Velocity

As previously mentioned in Section 3.3.1, several experiments were conducted by inducing sinusoidal waves at different frequencies (ranging from 4 kHz to 10 kHz) using a pair of bender elements connected to the pedestal of the triaxial dynamic device. Figure 7a shows the propagation of these waves through the length of the tested specimen. Figure 7b depicts the referenced transmitted wave. Time transmitted and arrival times were deter-

mined using the beak-to-beak method. The time domain technique allowed for the rational measurements of the shear wave velocity. The relationship between wavelengths (i.e., $n = F \times t$) and frequency was established for all measurements conducted for each specimen to calculate the shear wave velocity following the π -method [44,50]. Figure 8a,b depict these relations for specimens tested at different levels of suction belonging to SECL30 and SECL20. The best fit for the reliable measurements was established, and the arrival time has been estimated (t). The shear wave velocities (V_s) calculated based on Equation (1), the term L_{tt} in referred to the effective length of soil specimen, the results are presented in Figure 9.

$$V_s = \frac{L_{tt}}{t} \quad (1)$$

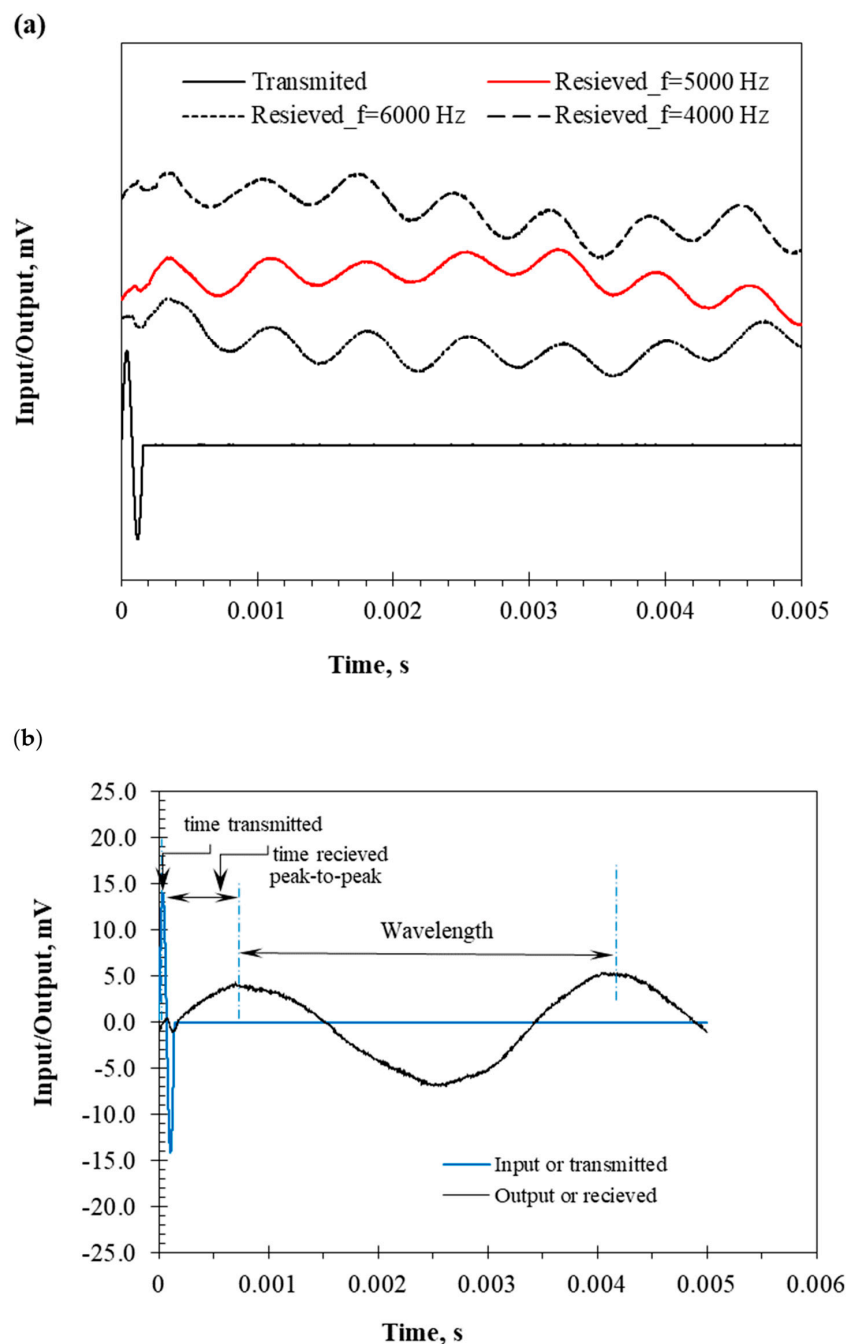


Figure 7. Schematic pattern for (a) transmitted and received waves at different frequencies and (b) beak-to-beak analysis.

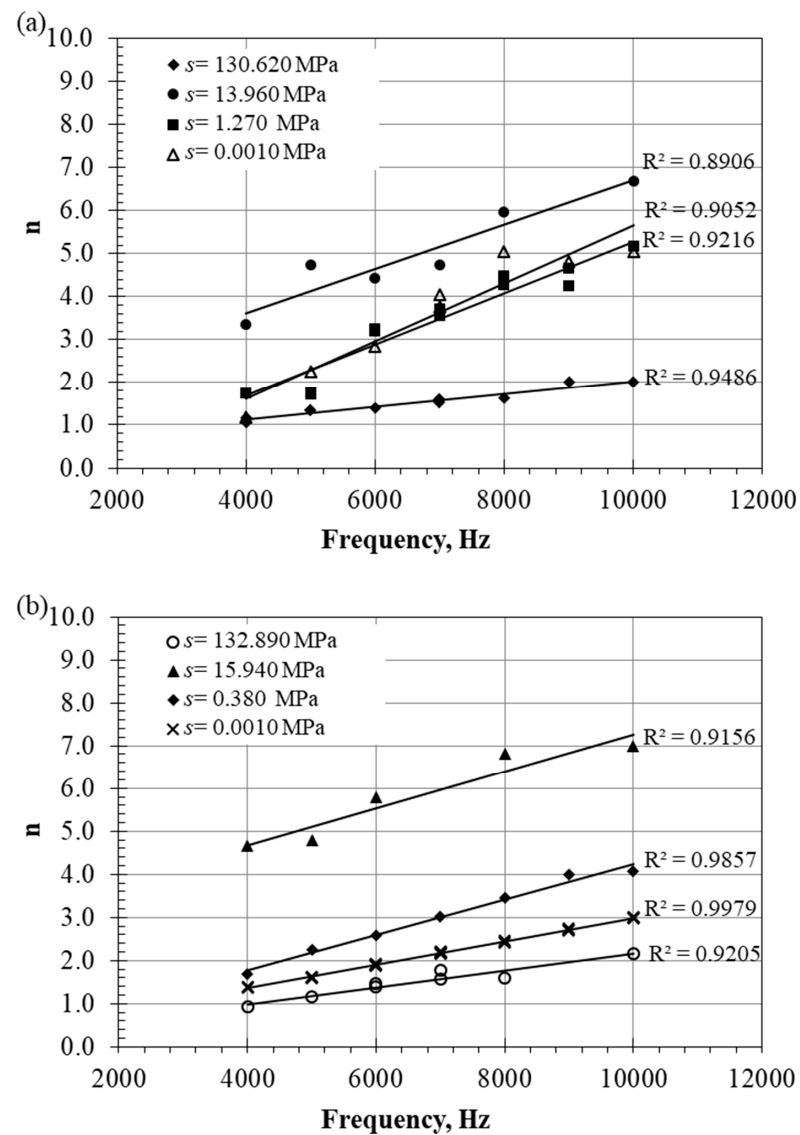


Figure 8. The wavelengths versus frequencies for (a) SECL30 and (b) SECL20.

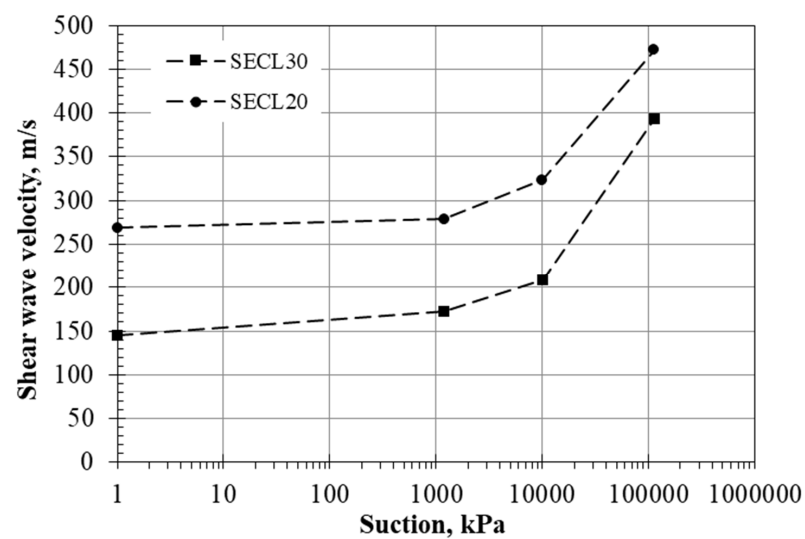


Figure 9. Shear wave velocity versus suction for both liners.

The results show a slight increase in the shear wave velocity with an increase in suction at the boundary effect stage (i.e., before air entry value, Figure 3). Similar studies have reported that the shear wave velocity exhibited marginal changes at low suction levels [51–53]. At this stage, the pores are mostly filled with water, and the change in soil moisture marginally affects soil rigidity. Some of the previous studies also reported a slight increase.

When the suction levels increase toward the transition and residual zones (Figure 3), the soil experiences desaturation, which intensifies at higher rates. This phenomenon results in a significant increase in the shear wave velocity due to the enhanced stiffness and rigidity of the soil skeleton [54]. The shear wave velocity exhibited a nonlinear increase at these zones.

Lu and Sabatier [20] indicated that the shear wave velocity shows a linear increase in the moisture content of 17–40% (boundary stage). Meanwhile, a nonlinear increase in shear wave velocity is observed at the residual stage below 17%. The mixture with a higher fine clay percent (SECL30) shows higher velocities than the other one (SECL20), confirming the dependency of the wave velocity on the density and soil voids [55].

4.3. Shear Modulus and Degradation Index

The secant shear modulus was calculated from the hysteresis loop of stress–strain for the saturated specimens. The values corresponding to loading cycles are calculated and shown in Figure 10a,b for SECL20 and SECL30, respectively. In the case of unsaturated soil specimens, considering the irregularity and nonlinearity of the hysteresis loop, the secant shear modulus (G_{sec1}) was taken into account in this study. This modulus represents the slope of the line connecting the origin point to the shear stress point corresponding to the maximum shear strain. Furthermore, the stress–strain hysteresis loop exhibits irregularities with the increase in the dynamic loading cycles. These values were calculated up to the level where the characteristics of the hysteresis loop are consistent enough to perform these calculations.

The results shown in Figure 10a,b demonstrate a reduction in the shear modulus of the unsaturated specimens tested at different suction levels. In the first 100 cycles, this reduction exhibited minor differences due to the variations in stiffness and responses observed at different suction levels (i.e., boundary, transition, and residual zone). Yan et al. [18] found that the sand exhibits different responses at a small strain range of 10^{-6} to 10^{-3} , including linear elastic, elastoplastic, and plastic, depending on the magnitude of strain. The suction value influenced the material behavior, causing it to exhibit either hardening or softening characteristics, which are functions of the soil suction [46].

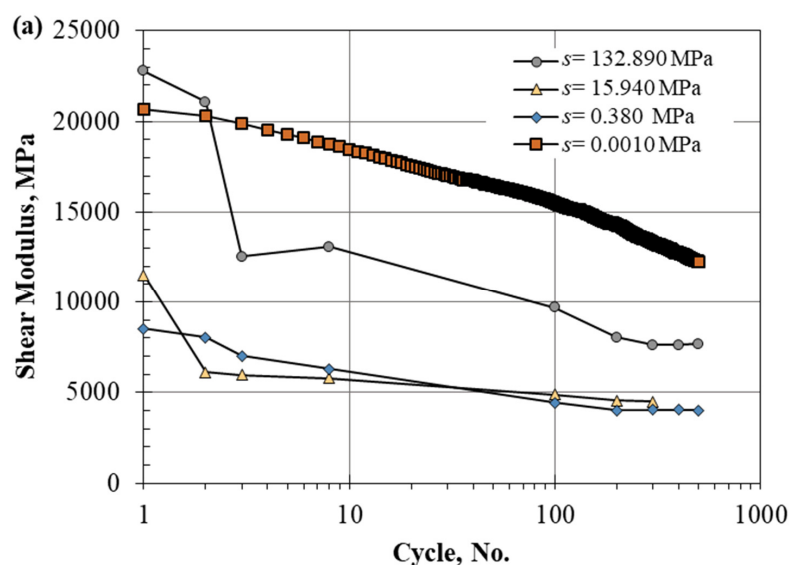


Figure 10. Cont.

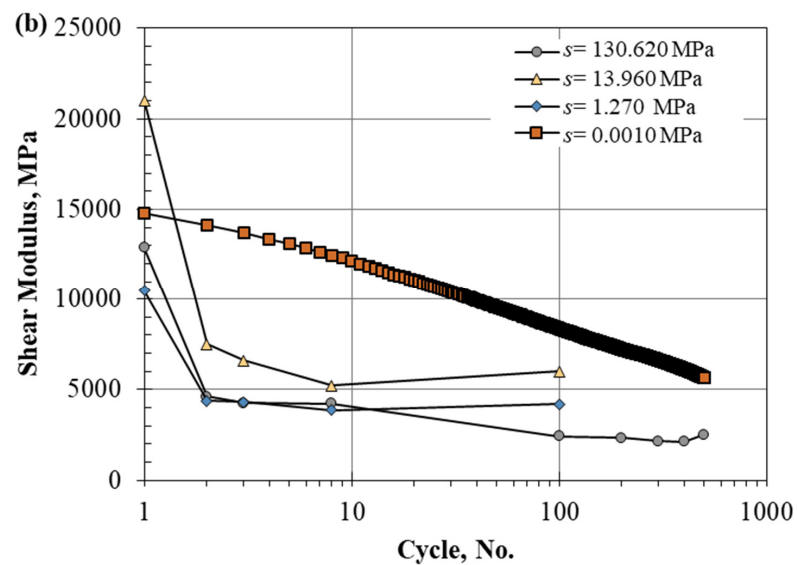


Figure 10. Shear modulus versus dynamic loading cycles at different suction levels for (a) SECL20 and (b) SECL30.

After the first 100 cycles, the values were constant and close to each other, regardless of the suction level. A dual trend of shear modulus was observed at the considered suction levels. Yan et al. [18] reported a similar wavy trend.

The degradation index (δ) based on the shear modulus is presented in Figure 11a,b for both mixtures. Suction induced a sharp reduction in the degradation index. In the first five cycles, the degradation index experienced an approximately 50% to 60% decrease. The higher plasticity soils showed a lower degradation index with the progress of the dynamic loading cycles [56].

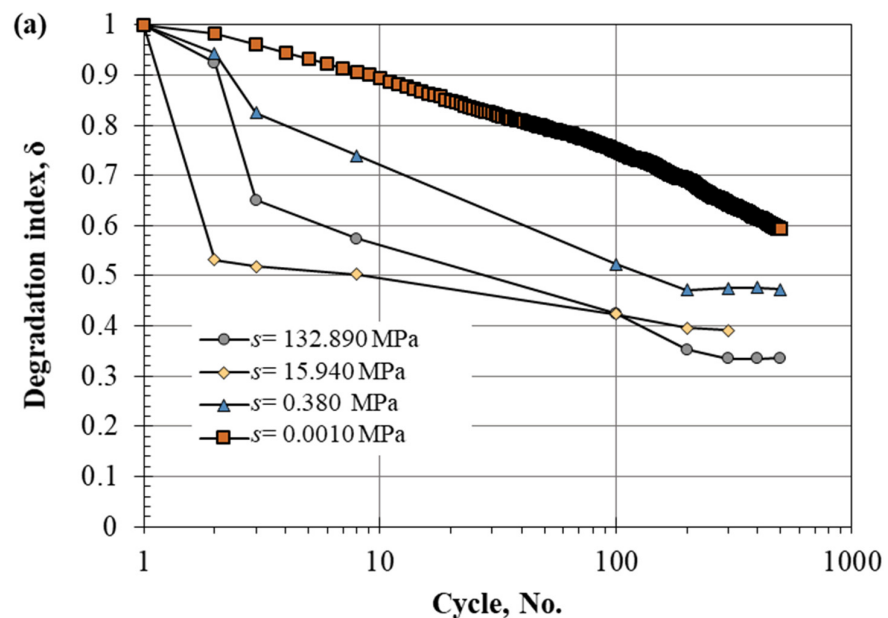


Figure 11. Cont.

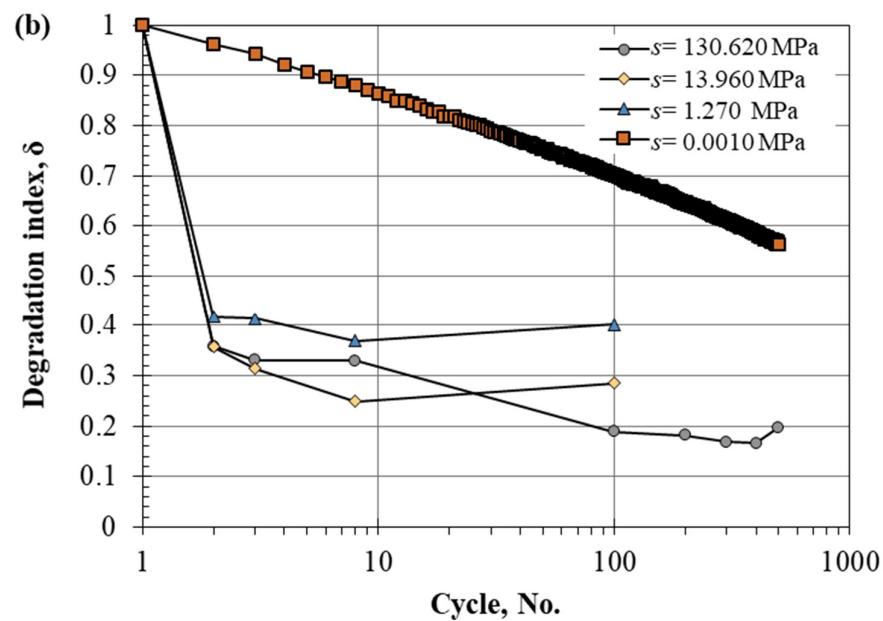


Figure 11. Degradation index versus dynamic loading cycles at different suction levels for (a) SECL20 and (b) SECL30.

4.4. Damping Ratio

The damping ratio of a material is a measure of the energy loss or dissipation during every cycle of dynamic load and can be estimated from the stress–strain relation for each cycle. The ASTM D3999 [57] standard provides the procedures for estimating the damping ratio. This factor is calculated as a percentage of the hysteresis loop area (A_L) to the area of the triangle (A_Δ), which represents the strain energy of the compression zone (Equation (2)) for a symmetric hysteresis loop, as shown in Figure 12a. The obtained results are shown in Figure 13a,b for both mixtures at the considered levels of suction. The application of suction resulted in a significant increase in the damping ratio, with the increment reaching approximately five and four times for SECL20 and SECL30, respectively. Suction plays a key role in modifying the material's stiffness [46,48]. The hysteresis loop becomes asymmetric due to this variation in soil stiffness, as previously mentioned in Section 4.1. In such cases, the estimation of the damping ratio following these procedures can result in either overestimation or underestimation of the actual damping ratio. The procedures proposed by Kokusho [58] and adopted by Kumar et al. [59] to estimate the damping ratio under asymmetric conditions considered the symmetry of the hysteresis loop. In this study, similar approaches are adopted to determine the damping ratio, taking into account the asymmetric conditions. The strain energy in the first quarter of the compression zone has been extended to comprise the shaded areas of $A_{\square}$ and $A_{\Delta 2}$, as shown in Figure 12b and formulated in Equation (3). The specimens that were tested at the suction level corresponding to the optimum moisture content for molding were used in this investigation to calculate the damping ratio following the modified procedures of the asymmetric hysteresis loop. The results shown in Figure 14a,b indicate that the damping ratios of the specimens of mixtures SECL30 and SECL20 experienced a significant reduction ranging from 10% to 80% and 18% to 69%, respectively. This reduction in the damping ratio increased to a certain level until reaching a certain threshold with the increase in the cycle number. Kumar et al. [59] and Hussain and Sachan [60] reported a similar reduction in the damping ratio of approximately 70% when applying the procedures for the asymmetric hysteresis loop.

$$D_{\%} = \frac{A_L}{4\pi A_{\Delta}} \times 100 \quad (2)$$

$$D\% = \frac{A_L}{\pi(A_{\Delta 1} + A_{\square} + A_{\Delta 2})} \times 100 \quad (3)$$

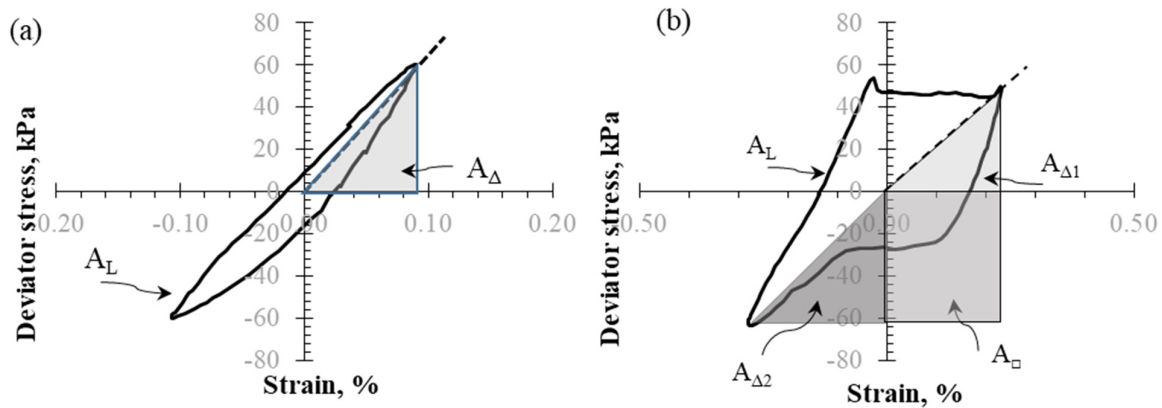


Figure 12. Procedures for damping ratio calculations (a) symmetric, (b) asymmetric hysteresis loop.

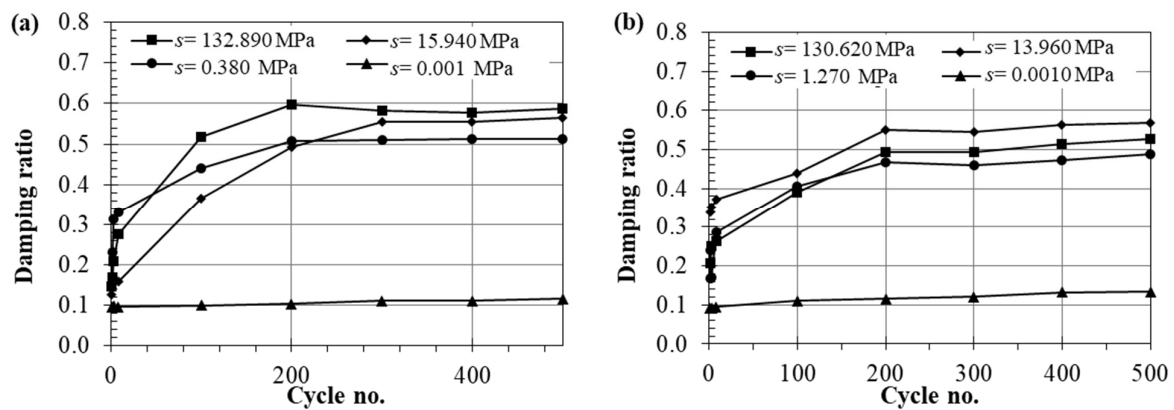


Figure 13. Damping ratio versus dynamic loading cycles at different suction levels for (a) SECL20 and (b) SECL30.

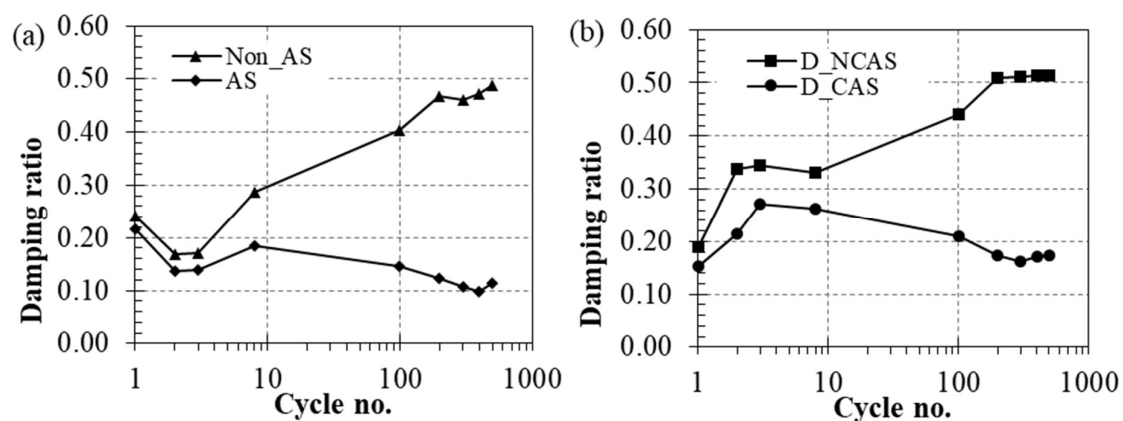


Figure 14. Damping ratio with considering asymmetric conditions for (a) SECL30 and (b) SECL20.

Later on, the theoretical models for predicting the shear modulus and damping ratio for soils under expected dynamic loads were developed to provide initial estimation for these parameters based on the basic soil properties; others developed the laboratory results obtained from conducted tests using such empirical models. Most of the available models

deal with saturated soils; regarding unsaturated soils, the studies are limited or rare, and challenges are in controlling suction, especially at high ranges. Recently, new studies on unsaturated soils were conducted to develop models for shear modulus and damping ratio over limited suction (i.e., [61–63]). The output could fit with the obtained results in this study, which showed that a clear degradation developed with dynamic load cycles. In addition, the trends were obtained with considered suction.

5. Summary and Conclusions

In this study, the dynamic properties of two sand–expansive clay liners were evaluated in saturated and unsaturated states. The specimens were prepared at different levels of suction covering the entire range as per soil water characteristic curves for these materials and tested in the laboratory with the dynamic triaxial device.

1. The study findings demonstrate the variability of unsaturated soil stiffness within the range of applied suction, with the hysteric loop showing a nonlinear and asymmetric behavior. The stress–strain behavior is a key characteristic, and accounting for this variation under expected dynamic loads ensures an accurate and adequate design.
2. The shear wave velocities of both liners exhibit a nonlinear relation with suction. A minor change was observed at the earliest stage of low suction (boundary effect zone). This change has been significant with an increase in suction up to the residual stage.
3. The results revealed a dual trend of shear modulus over the entire range of suction. The degradation index of the shear modulus reached approximately 60% at the first fifth cycles, and the change is marginal beyond the 100th cycle.
4. The application of suction resulted in a significant increase in the damping ratio, with the increment reaching approximately five and four times for SECL_20 and SECL_30, respectively. Implementing the new procedures to estimate the damping ratio, taking into account the asymmetric conditions of the hysteresis loop, resulted in a reduction in the damping values varying from 10% at the first cycle to 80% after 500 cycles.
5. The achievements of this study will guide practitioner engineers to conduct a sustainable and stable design for clay–sand layers under expected dynamic loads.

This study was performed under the confining pressure of 100 kPa, and further work under different confining pressures for different levels of suction is highly recommended.

Author Contributions: Conceptualization, A.M.A.-M. and A.A.; methodology, A.M.A.-M.; software, A.M.A.-M.; validation, A.M.A.-M.; formal analysis, A.M.A.-M.; investigation, A.M.A.-M.; resources, A.M.A.-M. and A.A.; data curation, A.M.A.-M.; writing—original draft preparation, A.M.A.-M.; writing—review and editing, A.M.A.-M. and A.A.; visualization, A.M.A.-M.; supervision, A.A.; project administration, A.M.A.-M. and A.A.; funding acquisition, A.A. All authors have read and agreed to the published version of the manuscript.

Funding: The Deputyship for Research and Innovation, “Ministry of Education” in Saudi Arabia for funding this research (IFKSUOR3-382-1).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used to support the findings of this study are included in the figures shown.

Acknowledgments: The authors extend their appreciation to the Deputyship for Research and Innovation, “Ministry of Education” in Saudi Arabia for funding this research (IFKSUOR3-382-1).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Zhang, M.; Zhang, H.; Cui, S.; Jia, L.; Zhou, L.; Chen, H. Engineering properties of GMZ bentonite-sand as buffer/backfilling material for high-level waste disposal. *Eur. J. Environ. Civ. Eng.* **2012**, *16*, 1216–1237. [\[CrossRef\]](#)
2. Nowamooz, H.; Jahangir, E.; Masrouri, F.; Tisot, J.P. Effective stress in swelling soils during wetting drying cycles. *Eng. Geol.* **2016**, *210*, 33–44. [\[CrossRef\]](#)
3. Vilarrasa, V.; Rutqvist, J.; Martin, L.; Birkholzer, J. Use of a dual-structure constitutive model for predicting the long-term behavior of an expansive clay buffer in a nuclear waste repository. *Int. J. GeoMech.* **2016**, *16*, D4015005. [\[CrossRef\]](#)
4. Al-Mahbashi, A.M.; Dafalla, M.; Shaker, A.; Al-Shamrani, M.A. Sustainable and Stable Clay Sand Liners over Time. *Sustainability* **2021**, *13*, 7840. [\[CrossRef\]](#)
5. Daniel, D.E. Clay liners. In *Geotechnical Practice for Waste Disposal*; Springer: Boston, MA, USA, 1993; pp. 137–163.
6. Likos, W.J.; Wayllace, A.W.; Godt, J.G.; Lu, N. Modified Direct Shear Apparatus for Unsaturated Sands at Low Suction and Stress. *ASTM Geotech. Test. J.* **2010**, *33*, 286–298.
7. Goh, S.G.; Rahardjo, H.; Leong, E.C. Shear strength of unsaturated soils under multiple drying-wetting cycles. *J. Geotech. Geoenviron. Eng.* **2014**, *140*, 06013001. [\[CrossRef\]](#)
8. Elkady, T.Y.; Shaker, A.A.; Dhowain, A.W. Shear strengths and volume changes of sand-attapulgitic clay mixtures. *Bull. Eng. Geol. Environ.* **2015**, *74*, 595–609. [\[CrossRef\]](#)
9. Elkady, T.Y.; Dafalla, M.A.; Al-Mahbashi, A.M.; Al-Shamrani, M. Effect of Compaction State on the Soil Water Characteristic Curves of Sand-Natural Expansive Clay Mixtures. *Eur. J. Environ. Civ. Eng.* **2017**, *21*, 289–302. [\[CrossRef\]](#)
10. Seiphoori, A.; Laloui, L.; Ferrari, A.; Hassan, M.; Khushefati, W.H. Water retention and swelling behaviour of granular bentonites for application in Geosynthetic Clay Liner (GCL) systems. *Soils Found.* **2016**, *56*, 449–459. [\[CrossRef\]](#)
11. Abdolazadeh, A.M.; Lacroix Vachon, B.; Cabral, A.R. Evaluation of the effectiveness of a cover with capillary barrier effect to control percolation into a waste disposal facility. *Can. Geotech. J.* **2011**, *48*, 996–1009. [\[CrossRef\]](#)
12. Sobti, J.; Singh, S.K. Techno-economic analysis for barrier materials in landfills. *Int. J. Geotech. Eng.* **2017**, *11*, 467–478. [\[CrossRef\]](#)
13. Cui, Y.J.; Tang, A.M.; Loiseau, C.; Delage, P. Determining the unsaturated hydraulic conductivity of a compacted sand-bentonite mixture under constant-volume and free-swell conditions. *Phys. Chem. Earth A/B/C* **2008**, *33* (Suppl. S1), 462–471. [\[CrossRef\]](#)
14. Al-Mahbashi, A.M.; Dafalla, M. Impact of placement and field conditions on hydraulic conductivity and lifetime of liners. *J. King Saud Univ. Sci.* **2021**, *33*, 101410. [\[CrossRef\]](#)
15. Li, D.; Selig, E.T. Cumulative Plastic Deformation for Fine-Grained Subgrade Soils. *J. Geotech. Eng.* **1996**, *122*, 1006–1013. [\[CrossRef\]](#)
16. Abdelkrim, M.; Bonnet, G.; de Buhan, P. A computational procedure for predicting the long term residual settlement of a platform induced by repeated traffic loading. *Comput. Geotech.* **2003**, *30*, 463–476. [\[CrossRef\]](#)
17. Al-Mahbashi, A.M.; Alnuaim, A. Effect of Dynamic Loads on the Long-Term Efficiency of Liner Layers. *Buildings* **2023**, *13*, 688. [\[CrossRef\]](#)
18. Yan, K.; Wang, Y.; Yang, Z.; Lai, X.; Chen, C. Experimental study on small-strain shear modulus of unsaturated silty-fine sand. *Appl. Sci.* **2022**, *12*, 8743. [\[CrossRef\]](#)
19. Gluchowski, A.; Skutnik, Z.; Biliniak, M.; Sas, W.; Lo Presti, D. Laboratory characterization of a compacted-unsaturated silty sand with special attention to dynamic behavior. *Appl. Sci.* **2020**, *10*, 2559. [\[CrossRef\]](#)
20. Lu, Z.; Sabatier, J.M. Effects of soil water potential and moisture content on the sound speed. *Soil Sci. Soc. Am. J.* **2009**, *73*, 1614–1625. [\[CrossRef\]](#)
21. Whalley, W.R.; Jenkins, M.; Attenborough, K. The velocity of shear waves in unsaturated soil. *Soil Tillage Res.* **2012**, *125*, 30–37. [\[CrossRef\]](#)
22. Indraratna, B.; Heitor, A.; Rujikiatkamjorn, C. Effect of compaction energy on shear wave velocity of dynamically compacted silty sand soil. In *5th Asia-Pacific Conference on Unsaturated Soils*; Jotisankasa, A., Sawangsuriya, A., Soralump, S., Mairaing, W., Eds.; Kasetsart University: Pattaya, Thailand, 2012; Volume 2, pp. 538–543.
23. Leng, W.; Xiao, Y.; Nie, R.; Zhou, W.; Liu, W. Investigating Strength and Deformation Characteristics of Heavy-Haul Railway Embankment Materials Using Large-Scale Undrained Cyclic Triaxial Tests. *Int. J. Geomech.* **2017**, *17*, 04017074. [\[CrossRef\]](#)
24. Dafalla, M.A. Efficiency of Sand Clay Liners in Controlling Subsurface Water Flow. In *Engineering Geology for Society and Territory—Volume 3: River Basins, Reservoir Sedimentation and Water Resources*; Springer: Cham, Switzerland, 2014; pp. 497–499.
25. ASTM D2487; Standard Practice for Classification of Soils for Engineering Purpose (United Soil Classification System). ASTM International: West Conshohocken, PA, USA, 2017.
26. ASTM D854-14; Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer. ASTM International: West Conshohocken, PA, USA, 2014.
27. ASTM D6913-09; Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis. ASTM International: West Conshohocken, PA, USA, 2009.
28. ASTM D 4318; Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils, Vol. 4.08. D-18 Committee on Soils and Rocks: West Conshohocken, PA, USA, 2000.
29. ASTM D 4546; Standard Test Methods for One-Dimensional Swell or Collapse of Cohesive Soils, Vol. 4.08. D-18 Committee on Soils and Rocks: West Conshohocken, PA, USA, 2003.

30. ASTM D 2435; Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading, Vol. 4.08. D-18 Committee on Soils and Rocks: West Conshohocken, PA, USA, 2003.
31. ASTM D 422; Standard Test Method for Particle-Size Analysis of Soils, Vol. 4.08. D-18 Committee on Soils and Rocks: West Conshohocken, PA, USA, 2002.
32. Slater, D.E. Potential Expansive Soils in Arabian Peninsula. *J. Geotech. Eng.* **1983**, *109*, 744–746. [[CrossRef](#)]
33. Abduljawad, S.N.; Azam, S.; Al-Shayea, N.A.; Al-Amoudi, O.S.B. The behaviour of geological formations containing expansive clay and calcium sulphate phases. In Proceedings of the 8th International Congress of the International Association of Engineering Geology, Vancouver, BC, Canada, 21–25 September 1998; Moore, D., Hungr, O., Eds.; A.A. Balkema: Rotterdam, The Netherlands, 1998; Volume 1, pp. 169–175.
34. Azam, S. Influence of mineralogy on swelling and consolidation of soils in eastern Saudi Arabia. *Can. Geotech. J.* **2003**, *40*, 964–975. [[CrossRef](#)]
35. Al-Mahbashi, A.M.; Al-Shamrani, M.A.; Abbas, M.F. Hydromechanical behavior of unsaturated expansive clay under repetitive loading. *J. Rock Mech. Geotech. Eng.* **2021**, *13*, 1136–1146. [[CrossRef](#)]
36. Al-Mahbashi, A.M.; Dafalla, M. The distribution and mineralogy of expansive clay in a semi-arid region. *Arab. J. Geosci.* **2023**, *16*, 283. [[CrossRef](#)]
37. Rafi, A. Engineering Properties and Mineralogical Composition of Expansive Clays in Al-Qatif Area. Ph.D. Thesis, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, 1988. Available online: <https://core.ac.uk/download/pdf/242408217.pdf> (accessed on 10 August 2019).
38. Chittoori, B.C.S.; Moghal, A.A.B.; Pedarla, A.; Al-Mahbashi, A.M. Effect of unit weight on porosity and consolidation characteristics of expansive clays. *J. Test. Eval.* **2017**, *45*, 94–104. [[CrossRef](#)]
39. ASTM D698-12; Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft³ (600 kN-m/m³)). ASTM International: West Conshohocken, PA, USA, 2012.
40. BS EN 13286-53; Unbound and Hydraulically Bound Mixtures. Methods for the Manufacture of Test Specimens of Hydraulically Boundmixtures Using Axial Compression. British Standard Institute: London, UK, 2004.
41. ASTM E 104; Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions. ASTM Standards: West Conshohocken, PA, USA, 2007.
42. ASTM D 6836; Standard Test Methods for Determination of the Soil Water Characteristic Curve for Desorption Using a Hanging Column, Pressure Extractor, Chilled Mirror Hygrometer, and/or Centrifuge (Vol. 15.09). ASTM Standards: West Conshohocken, PA, USA, 2002.
43. Blewett, J.; Blewett, I.J.; Woodward, P.K. Phase and amplitude responses associated with the measurement of shear-wave velocity in sand by bender elements. *Can. Geotech. J.* **2000**, *37*, 1348–1357. [[CrossRef](#)]
44. Da Fonseca, A.V.; Ferreira, C.; Fahey, M. A framework interpreting bender element tests, combining time-domain and frequency-domain methods. *Geotech. Test. J.* **2009**, *32*, 91–107.
45. Alonso, E.E.; Gens, A.; Josa, A. A constitutive model for partially saturated soils. *Geotechnique* **1990**, *40*, 405–430. [[CrossRef](#)]
46. Alonso, E.E.; Romero, E.; Hoffmann, C.; García-Escudero, E. Expansive bentonite–sand mixtures in cyclic controlled-suction drying and wetting. *Eng. Geol.* **2005**, *81*, 213–226. [[CrossRef](#)]
47. Zhong, Z.; Zou, H.; Hu, X.; Liu, X. Experimental study on stiffness softening of soil-rock mixture backfill under metro train cyclic load. *Adv. Mater. Sci. Eng.* **2021**, *2021*, 3024490. [[CrossRef](#)]
48. Han, Z.; Vanapalli, S.K. Stiffness and shear strength of unsaturated soils in relation to soil-water characteristic curve. *Géotechnique* **2016**, *66*, 627–647. [[CrossRef](#)]
49. Ng, C.W.W.; Zheng, G.; Ni, J.; Zhou, C. Use of unsaturated small-strain soil stiffness to the design of wall deflection and ground movement adjacent to deep excavation. *Comput. Geotech.* **2020**, *119*, 103375. [[CrossRef](#)]
50. Greening, P.D.; Nash, D.F.T. Frequency Domain Determination of G₀ Using Bender Elements. *Geotech. Test. J.* **2004**, *27*, 288–294.
51. Yang, S.R.; Lin, H.D.; Kung, J.H.S.; Liao, J.Y. Shear wave velocity and suction of unsaturated soil using bender element and filter paper method. *J. GeoEng.* **2008**, *3*, 67–74.
52. Yang, S.R.; Lin, H.D. Influence of soil suction on small-strain stiffness of compacted residual subgrade soil. *Transp. Res. Rec.* **2009**, *2101*, 63–71. [[CrossRef](#)]
53. Lu, Z. A Review of the High-Frequency Multi-Channel Analysis of Surface Wave Method for Proximal Soil Sensing. *Int. J. Earth Environ. Sci.* **2021**, *6*, 180.
54. Das, B.M. *Fundamentals of Soil Dynamics*; Elsevier: New York, NY, USA, 1983.
55. Albers, B. Linear elastic wave propagation in unsaturated sands, silts, loams and clays. *Transp. Porous Media* **2011**, *86*, 537–557. [[CrossRef](#)]
56. Vucetic, M.; Dobry, R. Effect of soil plasticity on cyclic response. *J. Geotech. Eng.* **1991**, *117*, 89–107. [[CrossRef](#)]
57. ASTM D3999/D3999M-13; Standard Test Methods for the Determination of the Modulus and Damping Properties of Soils Using the Cyclic Triaxial Apparatus. ASTM: West Conshohocken, PA, USA, 2013.
58. Kokusho, T. Cyclic triaxial test of dynamic soil properties for wide strain range. *Soils Found.* **1980**, *20*, 45–60. [[CrossRef](#)]
59. Kumar, S.S.; Krishna, A.M.; Dey, A. Evaluation of dynamic properties of sandy soil at high cyclic strains. *Soil Dyn. Earthq. Eng.* **2017**, *99*, 157–167. [[CrossRef](#)]

60. Hussain, M.; Sachan, A. Effect of loading conditions and stress history on cyclic behavior of Kutch soil. *Geomech. Geoeng.* **2020**, *15*, 233–251. [[CrossRef](#)]
61. Vassallo, R.; Mancuso, C.; Vinale, F. Modelling the influence of stress–strain history on the initial shear stiffness of an unsaturated compacted silt. *Can. Geotech. J.* **2007**, *44*, 463–472. [[CrossRef](#)]
62. Biglari, M.; Jafari, M.K.; Shafiee, A.; Mancuso, C.; d’Onofrio, A. Shear Modulus and Damping Ratio of Unsaturated Kaolin Measured by New Suction-Controlled Cyclic Triaxial Device. *Geotech. Test. J.* **2011**, *34*, 525–536.
63. Biglari, M.; Ashayeri, I. An empirical model for shear modulus and damping ratio of unsaturated soils. In Proceedings of the 5th Asia-Pacific Conference on Unsaturated Soils; Kasetsart University: Pattaya, Thailand, 2012; pp. 591–596.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.