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Original

On the effectiveness of elastic wave measurements for monitoring the response of caprocks / Ciancimino, A.; Foti, S.; Volontè, G.; Musso, G.. - In: GÉOTECHNIQUE LETTERS. - ISSN 2045-2543. - (2026), pp. 1-7. [10.1680/jgele.25.00071]

Availability:

This version is available at: 11583/3011097 since: 2026-05-20T07:08:22Z

Publisher:

Emerald Publishing

Published

DOI:10.1680/jgele.25.00071

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On the effectiveness of elastic wave measurements for monitoring the response of caprocks

by

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Abstract

This study investigates the effectiveness of elastic wave measurements in tracking the mechanical degradation of a structured clay under monotonic and cyclic loading. Triaxial tests were carried out on both intact and reconstituted specimens monitoring the evolution of the material state through ultrasonic transducers. The S-wave propagation velocity V_s is shown to be affected by limited variations (< 6%). This can be explained considering that material destructuration occurs in a rather narrow shear band. Conversely, the normalized cross-correlation coefficient $\hat{\rho}_s$ appears to be a more sensitive indicator of structural degradation, showing a significant decrease – up to 40% – as failure is approaching. Such an effect reflects the changes in signal amplitude and shape associated with the formation of the shear band. The $\hat{\rho}_s$ evolution also mimics brittle and ductile responses, demonstrating its potential as a robust parameter for monitoring the in-situ state of caprocks in underground storage applications.

Keywords

Underground gas storage; wave measurements; monitoring; fabric/structure of soils; cyclic triaxial tests; UN SDG 7: AFFORDABLE AND CLEAN ENERGY; UN SDG 13: CLIMATE ACTION

24 **1 Introduction**

25 Innovative geomechanics applications include exploiting depleted hydrocarbon reservoirs to store natural
26 gas or hydrogen for use as an energy vector (e.g., Aminu et al., 2017; Heinemann et al., 2021). Such
27 applications pose several challenges due to complex interactions between reservoir and non-native fluids. For
28 example, seasonal storage operations can induce cyclic loadings on the caprock, potentially compromising its
29 sealing integrity (e.g. Jeanne et al., 2020). Reliable monitoring systems are therefore essential to assess the
30 impact of such operations.

31 Elastic wave properties are promising monitoring parameters, as the small-strain stiffness of geomaterials
32 is strongly influenced by their state in terms of void ratio, saturation degree, stress state and structure, the latter
33 intended as a combination of particle arrangement and interparticle bonding (e.g., Santamarina et al., 2001;
34 Clayton, 2011). Upon chemo-hydro-mechanical loading, the material state evolves, leading to changes in
35 elastic stiffnesses and hence in wave propagation parameters (e.g., Shibuya, 2000; Falcon-Suarez et al., 2016).
36 This has been widely observed in laboratory studies on soils and rocks under monotonic (e.g., Stanchits et al.,
37 2006; Montoya & De Jong, 2015; Dutta et al., 2020) and cyclic (e.g., Zhou & Chen, 2005; Xiao et al., 2010)
38 loadings.

39 Wave velocity measurements are also attractive as wellbore sonic logs are typically recorded for site
40 characterization during hydrocarbon production operations. However, a potential limitation lies in the small
41 changes often observed in structured soils and rocks as failure approaches (e.g. Stanchits et al., 2006; Montoya
42 & De Jong, 2015). This paper proposes an alternative approach based on changes in shape and amplitude of
43 the recorded signals. The methodology is applied to wave measurements taken alongside monotonic triaxial
44 testing on either intact or reconstituted caprock specimens to highlight the differences between brittle or more
45 ductile responses. To demonstrate its effectiveness in relation to fatigue loading, the technique is then applied
46 to cyclic triaxial tests.

47 **2 Materials and methods**

48 Monotonic and cyclic consolidated undrained triaxial tests were performed on Santerno clay, a clayey
49 caprock from the Po valley in Italy (e.g. Benetatos et al., 2023), retrieved from a depth of approximately
50 1150 m and characterised by a relevant post-sedimentation structure.

51 The tests were carried out using the medium pressure triaxial apparatus of the Politecnico di Torino (see
52 Barla et al., 2010). The testing protocol included an initial saturation stage which involved a flushing step and
53 a back-pressure sequence. This ensured that the specimen and the drainage lines were completely saturated.
54 The back-pressure procedure was considered concluded when Skempton's B-values larger than 0.97 were
55 achieved. Thereafter, the specimens were subjected to anisotropic consolidation. Intact specimens were
56 consolidated up to the expected lithostatic stresses: $p'_0 = 8.1$ MPa and $q_0 = 6.3$ MPa, except one which was
57 consolidated at twice the in-situ stress. The lithostatic stress state at the relevant depth was computed by
58 integrating direct borehole measurements with the analysis of log data (Ciancimino et al., 2024). Reconstituted
59 specimens were prepared by starting from a slurry composed of the same material with a water content of 1.5
60 times the liquid limit, compacted one-dimensionally to an axial effective stress $\sigma'_{ax} = 9$ MPa, and then
61 triaxially consolidated to p'_0 and q_0 . The consolidation of test MR-TX 01 included a loading-unloading step
62 at constant stress ratio q_0 / p'_0 to achieve an over-consolidation ratio $OCR = 1.5$. Monotonic compression
63 tests were performed by imposing constant axial strain rates $\dot{\epsilon}_{ax}$ of either 0.01 %/min or 0.0005 %/min, while
64 cyclic stress-controlled tests imposed one-way sinusoidal deviatoric loadings of amplitude A , with a
65 maximum deviator q_{max} , a mean deviator $q_{mean} = q_{max} - A$, and a period $T = 5$ min (corresponding to a
66 frequency of 0.0033 Hz).

67 A summary of the tests is given in Table 1. More details about the experimental procedures and setup,
68 along with a comprehensive analysis of the time-dependent monotonic and cyclic response of the material can
69 be found in Ciancimino et al. (2024; 2026).

70

71

Table 1: Summary of the anisotropically consolidated undrained triaxial tests

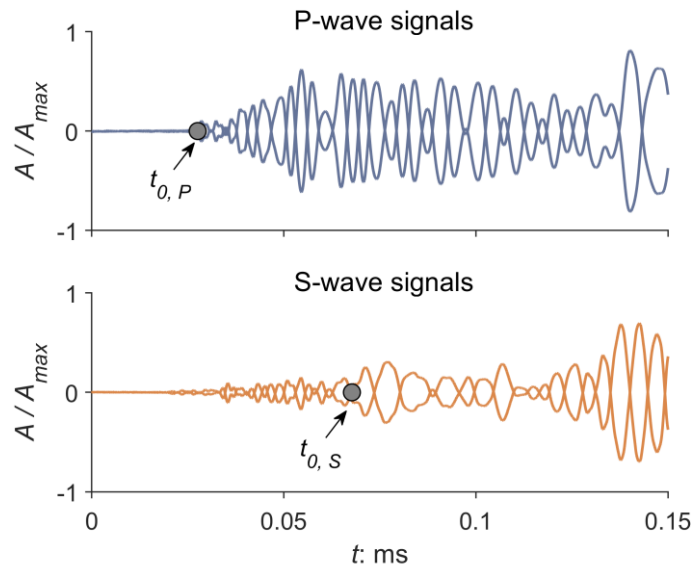
<i>ID</i>	<i>Material</i>	$\dot{\epsilon}_{ax} :$ %/min	$p'_0 :$ MPa	$q_0 :$ MPa	$q_{max} :$ MPa	$A :$ MPa	N_f	<i>Reference</i>
MI-TX 01	Intact	0.0005	8.1	6.3	-	-	-	Ciancimino et al. (2024)
MI-TX 02	Intact	0.01	16.2	12.6	-	-	-	This study
MR-TX 01	Reconstituted $OCR = 1.5$	0.0005	8.1 (12.2)†	6.3 (9.5)†	-	-	-	This study
MR-TX 02	Reconstituted <i>NC</i>	0.01	8.1	6.3	-	-	-	This study
CI-TX 01	Intact	-	8.1	6.3	13	3.25	18	Ciancimino et al. (2024)
CI-TX 09	Intact	-	8.1	6.3	12.5	4.25	173	Ciancimino et al. (2026)

† Maximum stress applied during the consolidation stage

72

73 The top cap and the base of the device are instrumented with compression (P-wave) and shear (S-wave)
 74 transducers, which can receive and transmit high-frequency ultrasonic pulses. The measurements were carried
 75 out by imposing as input signal a square pulse with a 1 μs duration. Signals were recorded with a scan time of
 76 500 μs and a sample time of $8 \cdot 10^{-3}$ μs .

77 For both P- and S-waves, the received signals were processed based on a reference scan x_0 recorded at
 78 the end of consolidation. For this scan, the first-arrival time t_0 is obtained by manually picking out signals
 79 with reverse polarization, in order to identify the instant at which the recorded waves appear coherent with
 80 each other. To illustrate this, Figure 1 shows the manual picking carried out for P- and S-wave reference signals
 81 for test MI-TX 01. It should be noted that the exact definition of t_0 has only a minor impact on the results, as
 82 the analysis focuses more on relative variations in wave parameters than absolute values.



83
 84 Figure 1: P- and S-wave reference signals with reverse polarization taken during test MI-TX 01

85 For any other scan x_i , the variation of the first-arrival time Δt_i is obtained by a cross-correlation
 86 algorithm. Specifically, x_i is shifted by a tentative time-lag m , and the normalized cross-correlation
 87 coefficient $\rho(x_0, x_i)$ is calculated:

$$\rho(x_0, x_i) = \frac{R_{x_0, x_i}(m)}{\sqrt{R_{x_0, x_0}(0) \cdot R_{x_i, x_i}(0)}} \quad (1)$$

88 where $R_{x_0, x_i}(m)$ denotes the cross-correlation of signals x_0 and x_i , with x_i shifted by m . The time-lag Δt_i is
 89 identified as the m value associated with the maximum normalized coefficient $\hat{\rho}(x_0, x_i)$. When analysing two

90 identical signals shifted in time, $\hat{\rho}(x_0, x_i) = 1$. In general, x_0 and x_i differ in shape and amplitude, with $\hat{\rho}(x_0, x_i)$
91 somehow reflecting these variations.

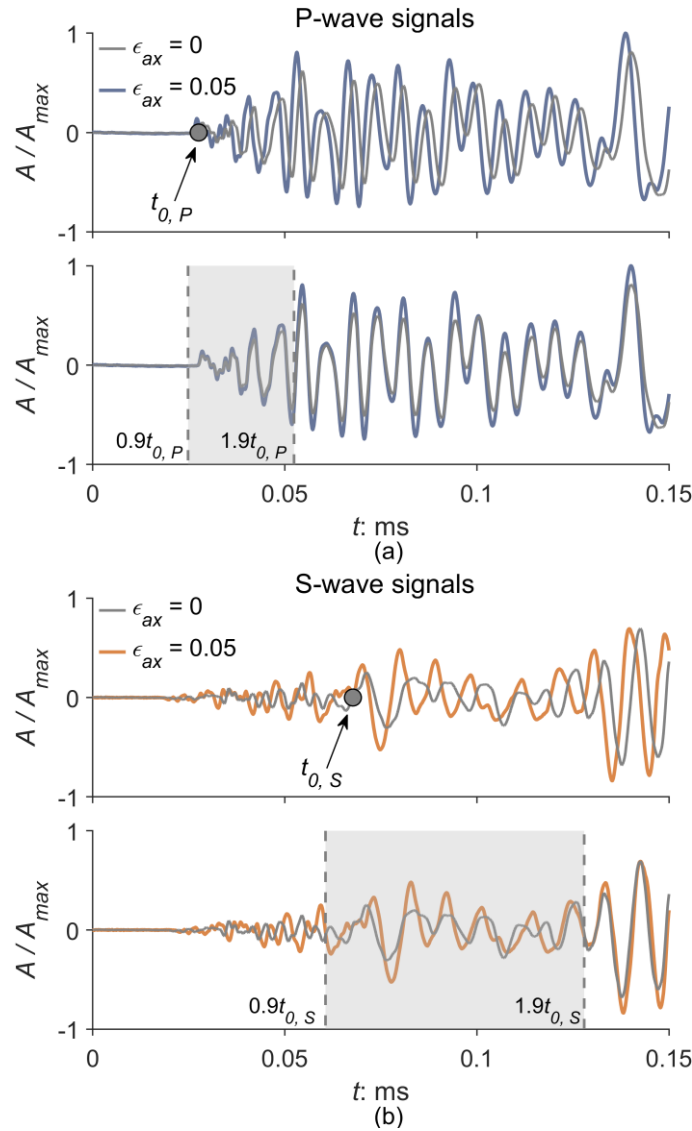
92 The first-arrival time t_i for the x_i signal and the associated propagation velocity are therefore:

$$t_i = t_0 + \Delta t_i \quad (2)$$

$$V_i = \frac{H_i}{t_i} \quad (3)$$

93 with H_i being the current specimen height measured using an external transducer calibrated to eliminate
94 spurious displacements caused by the deformability of the apparatus (after Ciancimino et al., 2026).

95 The above procedure applies to signals acquired for both P- and S-waves, resulting in the corresponding
96 coefficients $\hat{\rho}_P$ and $\hat{\rho}_S$, and velocities V_P and V_S . Figure 2 shows its application for two pairs of normalized
97 signals acquired during test MI-TX 01. The signals at $\varepsilon_{ax} = 0$ (i.e. grey lines) were used to pick the reference
98 times, $t_{0,P}$ and $t_{0,S}$, as shown in the upper plots along with scans taken after monotonic shearing (i.e. for ε_{ax}
99 = 0.05). The cross-correlation was applied in a time interval ranging from 0.9 to 1.9 of the reference times to
100 achieve a balance between robustness (since it includes a few periods) and accuracy (as non-direct waves are
101 less likely to be observed). The bottom plots show the good match after shifting the $\varepsilon_{ax} = 0.05$ signals by the
102 identified Δt_i values.



103
 104 Figure 2: P- and S-wave signals (a and b plots, respectively) taken during test MI-TX 01 before the start and at the end
 105 (i.e. for $\epsilon_{ax}=0.05$) of the shearing phase; the upper plots show the raw data, the lower plots show the signals after
 106 realignment

107 Experimental studies have shown the potential impact of the selected input frequency on ultrasonic wave
 108 testing (e.g., Ferreira et al., 2021). However, preliminary checks were performed in this study, showing that
 109 results were not significantly affected by the duration of the input pulse. Indeed, the proposed technique is
 110 based on differential output signal analysis and therefore the impact of spurious wave groups is limited.
 111 Moreover, the imposed input generates a broad frequency range. For instance, the frequency spectra of the
 112 signals presented in Figure 2 are characterised by a peak amplitude at around 150 kHz for S-waves, while the
 113 peak occurs at around 120 kHz for P-waves.

114 It is worth mentioning that the experimental tests considered in this study were deliberately chosen to
 115 cover a wide range of material states and loading conditions (see Table 1). The relevant differences in loading
 116 protocols (e.g. monotonic or cyclic), imposed strain rate (or frequency) and initial material state (e.g. intact vs.

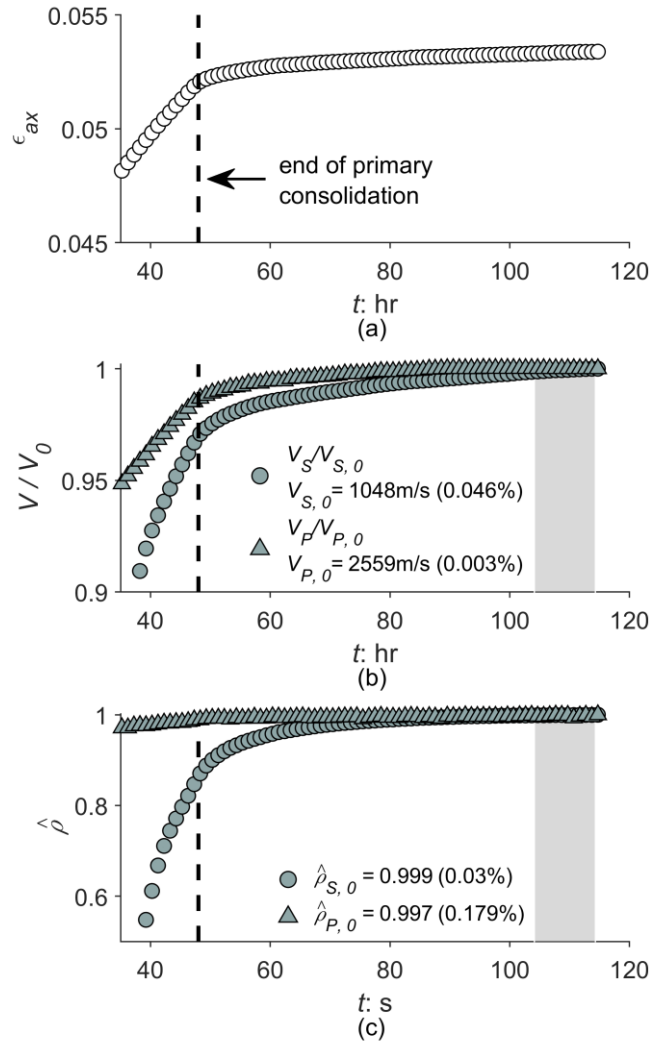
117 reconstituted) are known to result in markedly different stress-strain responses. Consequently, the selected tests
118 provide a robust benchmark against which the capabilities and limitations of the proposed methodology can
119 be assessed.

120 **3 Results**

121 **3.1 Consolidation**

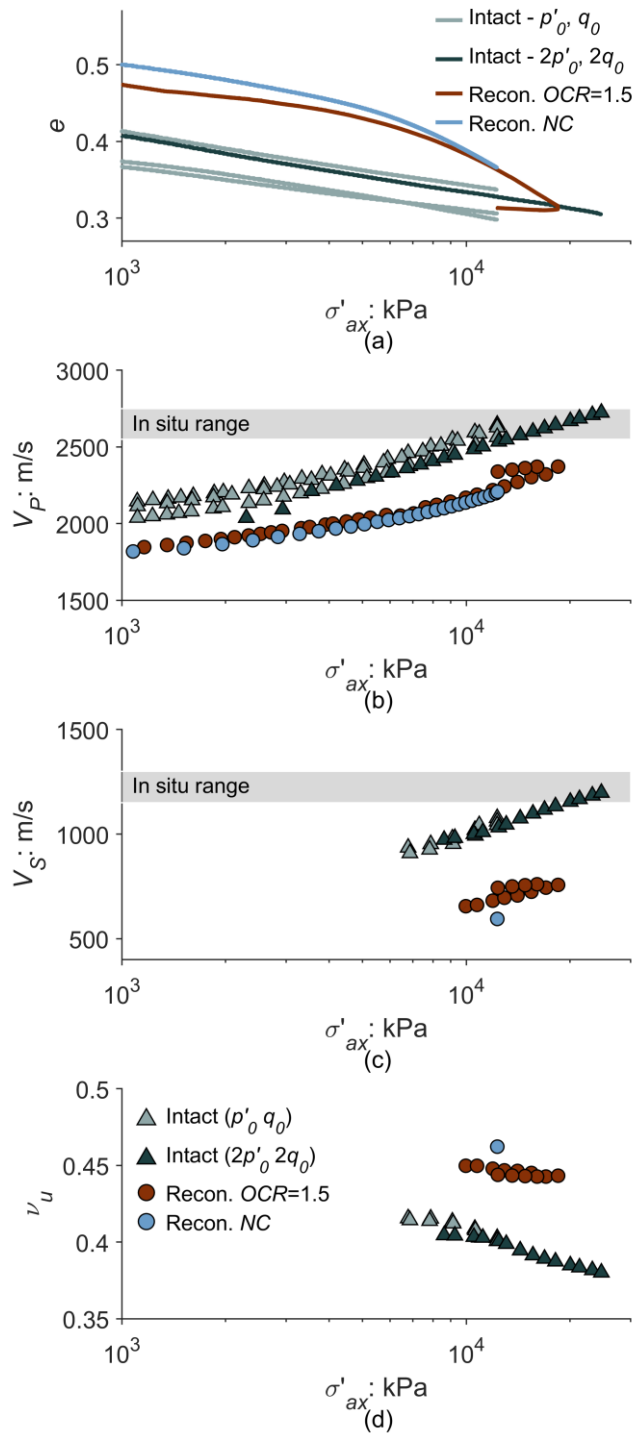
122 Figure 3 shows a detailed analysis of the results of the consolidation stage for test MI TX-01. The stage
123 lasted five days: 48 hours of primary consolidation up to p'_0 and q_0 , followed by 70 hours of constant external
124 load. ε_{ax} increases significantly up to the end of primary consolidation, after which a smoother increase is
125 observed due to dissipation of residual excess pore pressure and creep phenomena (Figure 3a). As expected,
126 ε_{ax} progressively stabilizes over time.

127 Wave measurements were taken every hour, and the data were processed adopting the last acquisition as
128 reference. Figure 3b shows the evolution of P- and S-wave velocities normalised to the values measured at the
129 end of consolidation, $V_{P,0}$ and $V_{S,0}$ respectively. The results mimic the ε_{ax} trends, revealing a steep increase
130 during primary consolidation, followed by progressive stabilisation and almost constant values for the final 10
131 hours (shadowed zone in Figure 3). This interval was therefore used to assess the robustness and the reliability
132 of the proposed methodology, computing the average values and the corresponding coefficients of variation
133 which are reported in Figure 3b. The corresponding uncertainty is less than 0.1% upon stable conditions. Figure
134 3c shows the corresponding trends for the coefficients $\hat{\rho}_p$ and $\hat{\rho}_s$. P-wave measurements appear to be more
135 stable, with $\hat{\rho}_p$ values just below unity. In contrast, $\hat{\rho}_s$ appears to be more affected by p' , probably because
136 of the weaker coupling between the transducers and the specimens at low pressures and the more substantial
137 observed changes in V_s . Once again, over the last 10 hours, both values have remained almost identical,
138 demonstrating the excellent repeatability of the wave measurements.



139
 140 Figure 3: Evolution of the material state with time upon consolidation for test MI-TX 01 (intact material; p'_0, q_0): (a)
 141 effective mean stress p' ; (b) axial strain ϵ_{ax} ; (c) normalized P- and S-wave velocities $V_P/V_{P,0}$ and $V_S/V_{S,0}$; and (c)
 142 normalized P- and S-wave cross-correlation coefficients $\hat{\rho}_P$ and $\hat{\rho}_S$; the shaded area shows the results used to compute
 143 the average values and the associated coefficients of variation (in brackets)

144 Figure 4 shows, for each specimen, the evolution of the material state with σ'_{ax} in terms of void ratio e ,
 145 V_P, V_S , and undrained Poisson's ratio ν_u , the latter computed as a function of V_P/V_S . V_S data are shown
 146 only over a certain range of σ'_{ax} , as S-waves were overlapped by undesired parasite waves at low pressures.



147

148 Figure 4: Evolution of the material state with σ'_{ax} upon consolidation: (a) void ratio e ; (b) P-wave velocity V_P ; (c) S-
 149 wave velocity V_S ; and (d) undrained Poisson's ratio ν_u

150

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152

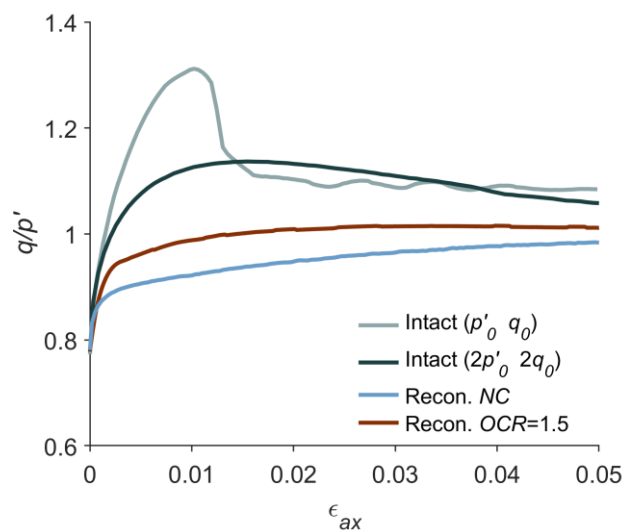
153

Intact specimens exhibit a stiff response, suggesting that no substantial yielding occurred during the consolidation, even up to twice the in-situ state (Figure 4a). Conversely, reconstituted specimens show an elasto-plastic response for $\sigma'_{ax} > 9$ MPa, with the specimen characterized by $OCR = 1.5$ reaching a void ratio consistent with the intact material.

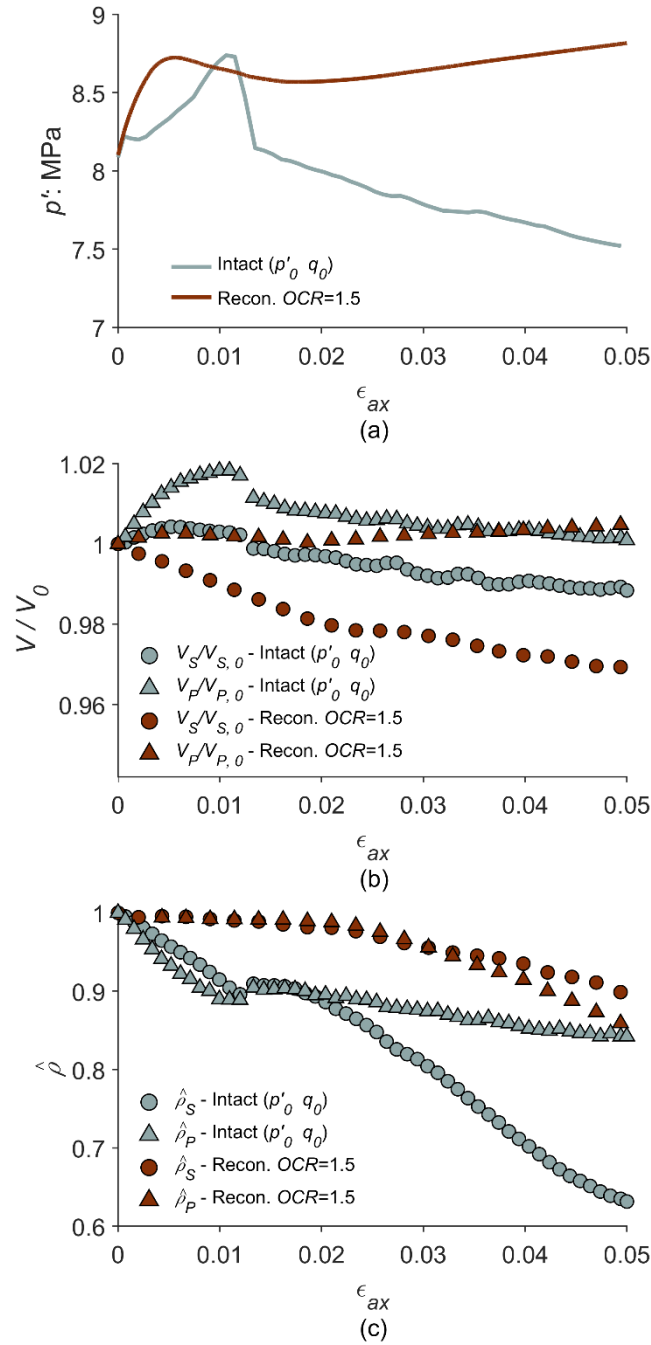
154 For intact specimens as e decreases, both V_p and V_s increase (Figure 4b-c), approaching the in-situ
 155 ranges. The latter were obtained through continuous sonic logging within the caprock formation (data after
 156 Ciancimino et al., 2024). For reconstituted specimens, a larger increase in V_p is observed after yielding.
 157 However, it never reaches the values measured for the intact material. Consolidation also induces a decrease
 158 of v_u (Figure 4d), which is more significant for intact specimens, while it is barely visible for reconstituted
 159 ones. By the end of the consolidation, v_u is about 0.38 and 0.45 for intact and reconstituted specimens,
 160 respectively. These differences are again attributed to the natural post-sedimentation structure, which implies
 161 a larger bulk modulus of the soil skeleton and, therefore, a lower v_u for the intact Santerno clay. These trends
 162 are consistent with those observed in other experimental studies involving stiff clayey materials retrieved from
 163 similar or shallower depths (see, e.g., Mavko et al., 1998; Musso et al., 2015; Shibuya, 2000).

164 3.2 Monotonic Shear

165 Figure 5 presents the monotonic undrained responses in terms of q/p' against the imposed ϵ_{ax} upon
 166 shearing. Test MI TX-01 shows a fragile response of the intact material when consolidated at in-situ stresses.
 167 After reaching the peak shear strength, pronounced softening towards the post-rupture strength occurs due to
 168 the degradation of the natural structure and the formation of a narrow shear band (Ciancimino et al., 2024).
 169 Such brittle behaviour is partially inhibited by increasing the consolidation pressure, as shown in test MI TX-
 170 02. Conversely, whether normally consolidated (test MR TX-02) or lightly over-consolidated (test MR TX-
 171 01), the reconstituted material shows ductile behaviour. Consistently with previous findings (e.g. Burland et
 172 al., 1996), both natural and reconstituted specimens tend toward similar $q/p' = 1$ at large strains.



173
 174 Figure 5: Results of the monotonic undrained triaxial tests on intact and reconstituted specimens of Santerno clay

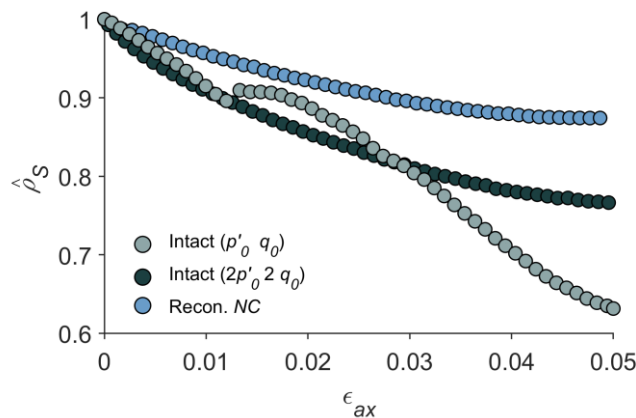


175
 176 Figure 6: Evolution of the material state with imposed ϵ_{ax} upon monotonic shearing for tests MI-TX 01 (intact material;
 177 p'_0, q_0) and MR-TX 01 (reconstituted, $OCR = 1.5$): (a) effective mean stress p' ; (b) normalized P- and S-wave
 178 velocities $V_P / V_{P,0}$ and $V_S / V_{S,0}$; and (c) normalized P- and S-wave cross-correlation coefficients $\hat{\rho}_P$ and $\hat{\rho}_S$

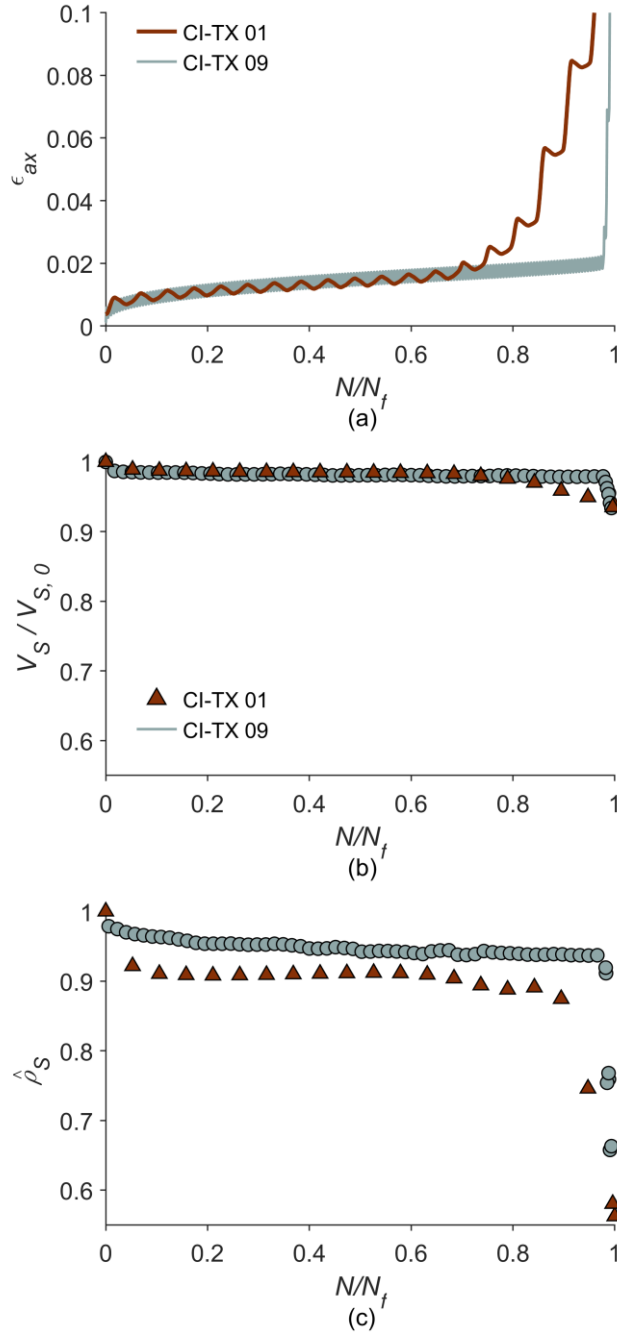
179 The material state evolution was tracked via the cross-correlation procedure. Figure 6 shows the results
 180 for tests MI-TX 01 (intact) and MR-TX 01 (reconstituted, $OCR = 1.5$), consolidated to the in-situ stress state.
 181 The propagation velocities are shown after normalization with respect to the initial values $V_{P,0}$ and $V_{S,0}$. The
 182 intact material shows an initial increase in $V_P / V_{P,0}$ and $V_S / V_{S,0}$ (Figure 6b) which is due to a corresponding
 183 increase in p' (Figure 6a). For axial strains larger than 0.015, the sudden mechanical softening produces a
 184 relatively steep decrease in the velocities, followed by a more gradual reduction. On the contrary, the

185 reconstituted material shows a continuous slight increase in $V_P / V_{P,0}$, probably due to the observed increase in
 186 p' , while a gradual reduction in $V_S / V_{S,0}$ is observed. The distinction observed for intact and reconstituted
 187 material between a sharp or more gradual reduction in velocity closely matches with the deviatoric responses
 188 shown in Figure 5. However, the variations in propagation velocities appear to be quite small in amplitude,
 189 with a maximum decrease of about 2%.

190 The changes in the material state can also be inferred by means of the cross-correlation coefficients $\hat{\rho}_P$
 191 and $\hat{\rho}_S$ (Figure 6c). For the reconstituted material, $\hat{\rho}_S$ slightly decreases. Conversely, an abrupt drop to 0.6 is
 192 observed for the intact specimen, especially after the peak shear strength is reached, reflecting the softening
 193 associated with the formation of the shear band. Similar trends can be observed for $\hat{\rho}_P$, although the drop for
 194 intact material after peak strength is attained appears much less pronounced. This difference can be attributed
 195 to the minor influence that the destructuration process has on P-waves propagating through the shear band
 196 compared to S-waves propagation. Consequently, in the following the discussion will be limited to the
 197 evolution of $\hat{\rho}_S$, even though similar but less evident patterns can be observed for $\hat{\rho}_P$. Figure 7 compares $\hat{\rho}_S$
 198 values of test MI TX-01, with the trends obtained in tests MI TX-02 and MR TX-01, performed respectively
 199 on intact material consolidated to twice the in-situ stress state and on reconstituted normally consolidated
 200 material. Interestingly, both tests present a rather gradual reduction in $\hat{\rho}_S$. In particular, the results of test
 201 MI TX-02 suggest that $\hat{\rho}_S$ is not only a reliable indicator of progressive destructuration, as shown by the
 202 significant reduction observed, but its evolution also appears influenced by the mechanical behaviour of the
 203 material. Indeed, for test MI TX-01 it reflects the brittle nature of the mechanical response shown in Figure 5,
 204 which is somewhat inhibited by the higher consolidation pressures achieved in test MI TX-02.



205
 206 Figure 7: Evolution of the normalized S-wave cross-correlation coefficient $\hat{\rho}_S$ with imposed ϵ_{ax} upon monotonic
 207 shearing for tests MI-TX 01 (intact; p'_0, q_0), MI-TX 02 (intact; $2p'_0, 2q_0$), and MR-TX 02 (reconstituted, NC)



208

209 Figure 8: Evolution of the intact material state upon cyclic loading for tests CI-TX 01 and CI-TX 09: (a) effective mean
 210 stress p' ; (b) normalized S-wave velocity $V_S / V_{S,0}$; and (c) normalized S-wave cross-correlation coefficient $\hat{\rho}_S$

211 3.3 Fatigue Loading

212 The results of two cyclic tests on intact specimens (see Table 1) are plotted in Figure 8 as a function of
 213 cycle number normalized to fatigue life N / N_f . The stress-controlled cyclic loading induces inelastic axial
 214 strain accumulation, leading to progressive destructuration and ultimately brittle failure (Figure 8a). In the first
 215 cycle, a sudden (although limited in amplitude) drop in $V_S / V_{S,0}$ is observed, likely due to initial pore pressure
 216 build-up (Ciancimino et al., 2026), while subsequently it stabilizes (Figure 8b). As failure approaches, $V_S / V_{S,0}$

217 further decreases, following the trends observed for ε_{ax} . Consistently with the monotonic tests, the decrease
218 is quite limited, with $V_S / V_{S,0}$ reaching a minimum of 0.94.

219 Similar trends are shown by the $\hat{\rho}_S$ evolution, which closely follows the brittle material response during
220 fatigue loading (Figure 8c). However, its decrease is more pronounced, dropping to 0.6 as the specimens
221 approach failure, indicating stronger sensitivity of $\hat{\rho}_S$ to material degradation with respect to $V_S / V_{S,0}$.

222 **4 Discussion and conclusions**

223 The in-situ state of caprocks must be properly monitored during seasonal gas storage operations, as cyclic
224 loadings can potentially compromise the formation integrity. The S-wave velocity is an attractive monitoring
225 parameter, as it is strongly influenced by the material structure and therefore affected by degradation. This is
226 partially confirmed by the experimental results presented here, as V_S decreases during mechanical loading.
227 However, the amplitude of the reduction is quite small. For brittle materials, failure is associated with the
228 formation of well-defined shear bands within which the degradation process occurs. In laboratory tests, V_S is
229 calculated as an average with respect to the specimen height, considering also those parts that are not affected
230 by destructuration. Therefore, the detected V_S changes are barely visible, although in principle large variations
231 are to be expected in correspondence of the shear band. The same phenomenon is expected to occur in-situ,
232 with the possible formation of shear banding patterns induced by fatigue loading. These would be difficult to
233 detect by averaged measurements, given the additional uncertainties of in-situ measurements.

234 An alternative lies in the analysis of the changes in amplitude and shape of acquired signals that occur as
235 the material approaches failure. Shear banding affects the propagation path of transmitted waves, resulting in
236 reflected and refracted waves that alter the received signals. These changes could be tracked using the S-wave
237 cross-correlation coefficient $\hat{\rho}_S$ computed between two successive acquisitions. The evolution of $\hat{\rho}_S$ is
238 strongly influenced by the degradation process, with a decrease of about 40% under both monotonic and cyclic
239 conditions when approaching failure. In addition, $\hat{\rho}_S$ also appears to be a sensitive index of different
240 mechanical behaviours. The same material can exhibit either a brittle or a ductile response depending on the
241 confining pressure and the initial state (i.e. intact or reconstituted). Consistently, $\hat{\rho}_S$ will evolve differently,
242 showing either a gradual or abrupt drop as the peak shear strength is approached.

243 The consistency of the results obtained under different loading and initial state conditions, together with
244 the magnitude of the observed variations, suggest that $\hat{\rho}_S$ could be a viable parameter for monitoring the

245 evolution of the material state on site. However, to confidently attribute the measured changes to the evolution
246 of the material state, repeatable and well-controlled source-receiver geometries must be adopted, such as those
247 of near-well or permanently installed monitoring systems.

248 **Data availability**

249 Data will be made available upon reasonable request.

250 **Acknowledgments**

251 Funding was provided by ENI SpA within the project “Hynergy”. The authors gratefully thank Eni SpA for
252 the authorization to publish this work.

253 **References**

- 254 Aminu, M. D., Nabavi, S. A., Rochelle, C. A., & Manovic, V. (2017). A review of developments in carbon dioxide storage.
255 *Applied Energy*, 208, 1389-1419. doi:10.1016/j.apenergy.2017.09.015
- 256 Burland, J. B., Rampello, S., Georgiannou, V. N., & Calabresi, G. (1996). A laboratory study of the strength of four stiff
257 clays. *Geotechnique*, 46(3), 491-514. doi:10.1680/geot.1996.46.3.491
- 258 Barla, G., Barla, M., & Debernardi, D. (2010). New triaxial apparatus for rocks. *Rock Mechanics and Rock Engineering*,
259 43(2), 225-230. doi:10.1007/s00603-009-0076-7
- 260 Benetatos, C., Rocca, V., Verga, F., Adinolfi, L. & Marzano, F. (2023). Deformation behavior of a regional shale formation
261 from integrated laboratory and well data analysis: insights for underground fluid storage in Northern Italy.
262 *Geoenergy Sci. Engng*, 229, 212109, 10.1016/j.geoen. 2023.212109.
- 263 Ciancimino, A., Cosentini, R., Foti, S., Messori, A., Ullah, H., Volonté, G., & Musso, G. (2024). A preliminary
264 investigation on the mechanical behaviour of a stiff Italian clay in the context of hydrogen storage.
265 *Geomechanics for Energy and the Environment*, 38. doi:10.1016/j.gete.2024.100562
- 266 Ciancimino, A., Cosentini, R., Foti, S., Volonté, G., & Musso, G. (2026). Experimental investigation on the monotonic
267 and cyclic behaviour of a structured clay at high confinement. *Geotechnique*, 1-13.
268 doi.org/10.1680/jgeot.25.00524
- 269 Clayton, C. R. I. (2011). Stiffness at small strain: Research and practice. *Geotechnique*, 61(1), 5-37.
270 doi:10.1680/geot.2011.61.1.5
- 271 Dutta, T. T., Otsubo, M., Kuwano, R., & O'Sullivan, C. (2020). Evolution of shear wave velocity during triaxial
272 compression. *Soils and Foundations*, 60(6), 1357-1370. doi:10.1016/j.sandf.2020.07.008
- 273 Falcon-Suarez, I., North, L., Amalokwu, K., & Best, A. (2016). Integrated geophysical and hydromechanical assessment
274 for CO2 storage: shallow low permeable reservoir sandstones. *Geophysical Prospecting*, 64(4), 828-847.
275 doi:10.1111/1365-2478.12396
- 276 Ferreira, C., Rios, S., Cristelo, N. & Viana da Fonseca, A. (2021). Evolution of the optimum ultrasonic testing frequency
277 of alkali-activated soil-ash. *Geotechnique Letters*, 11(3), 158-163. doi: 10.1680/jgele.21.00041
- 278 Heinemann, N., Alcalde, J., Miocic, J. M., Hangx, S. J. T., Kallmeyer, J., Ostertag-Henning, C., . . . Rudloff, A. (2021).
279 Enabling large-scale hydrogen storage in porous media-the scientific challenges. *Energy and Environmental*
280 *Science*, 14(2), 853-864. doi:10.1039/d0ee03536j
- 281 Jeanne, P., Zhang, Y., & Rutqvist, J. (2020). Influence of hysteretic stress path behavior on seal integrity during gas storage
282 operation in a depleted reservoir. *Journal of Rock Mechanics and Geotechnical Engineering*, 12(4), 886-899.
283 doi:10.1016/j.jrmge.2020.06.002
- 284 Mavko, G., Mukerji, T. & Dvorkin, J. (1998). *The Rock Physics Handbook: Tools for Seismic Analysis in Porous Media*.
285 Cambridge University Press, 208-210.
- 286 Musso, G., Cosentini, R.M., Foti, S., Comina, C., Capasso, G. (2015). Assessment of the structural representativeness of
287 sample data sets for the mechanical characterization of deep formations. *Geophysics*, 80 (5).
288 doi:10.1190/geo2014-0351.1
- 289 Montoya, B. M., & De Jong, J. T. (2015). Stress-strain behavior of sands cemented by microbially induced calcite
290 precipitation. *Journal of Geotechnical and Geoenvironmental Engineering*, 141(6).
291 doi:10.1061/(ASCE)GT.1943-5606.0001302
- 292 Santamarina, J. C., Klein, K. A. & Fam, M. A. (2001), *Soils and Waves: Particulate materials behavior, characterization*
293 *and process monitoring*, Wiley, ISBN: 0-471-49058-X.
- 294 Shibuya, S. (2000). Assessing structure of aged natural sedimentary clays. *Soils and Foundations*, 40(3), 1-16.
295 doi:10.3208/sandf.40.3_1

- 296 Stanchits, S., Vinciguerra, S., & Dresen, G. (2006). *Ultrasonic velocities, acoustic emission characteristics and crack*
297 *damage of basalt and granite*. Paper presented at the Pure and Applied Geophysics.
- 298 Xiao, J. Q., Ding, D. X., Jiang, F. L., & Xu, G. (2010). Fatigue damage variable and evolution of rock subjected to cyclic
299 loading. *International Journal of Rock Mechanics and Mining Sciences*, 47(3), 461-468.
300 doi:10.1016/j.ijrmms.2009.11.003
- 301 Zhou, Y. G., & Chen, Y. M. (2005). Influence of seismic cyclic loading history on small strain shear modulus of saturated
302 sands. *Soil Dynamics and Earthquake Engineering*, 25(5), 341-353. doi:10.1016/j.soildyn.2005.03.001