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Wave Velocities and Poisson Ratio in a Loose Sandy Martian Regolith Simulant Under Low Stresses: 1. Laboratory Investigation

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► **To cite this version:**

J. Betancourt, P. Delage, B. Caicedo, P. Lognonné, B. Banerdt. Wave Velocities and Poisson Ratio in a Loose Sandy Martian Regolith Simulant Under Low Stresses: 1. Laboratory Investigation. *Journal of Geophysical Research. Planets*, 2023, 128 (11), 10.1029/2023JE007988 . hal-04285747

HAL Id: hal-04285747

<https://hal.science/hal-04285747>

Submitted on 14 Nov 2023

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18 Abstract

19 Wave velocity measurements were performed on Fontainebleau sand samples used as Martian
20 regolith simulant to investigate the elastic properties of the surface material at the InSight landing
21 site on Mars (Elysium Planitia). Loose samples (density 1.4 Mg/m³, density index 6%) were
22 prepared by using the pluviation method, to mimic the low regolith density at the InSight landing
23 site. A novel device derived from triaxial testing was designed to measure wave velocities at low
24 stresses along a horizontal cylindrical specimen. Four tests were made, in which the confining
25 stress was applied by applying vacuum between 1 and 80 kPa. Wave velocities were measured by
26 using bender elements under stresses as low as 1.75 kPa, a very low value compared to the standard
27 stress ranges generally considered in terrestrial geotechnics (> 10 kPa). The changes in
28 compression and shear wave velocities obey a standard power law, with however two slightly
29 different exponents for V_p and V_s , indicating a not perfectly elastic behavior. Data showed greater
30 variability below 5 kPa, indicating some limitations of the bender elements technique in this range.
31 A slight decrease in Poisson ratio was detected below 5 kPa, which certainly deserves more
32 investigation. This investigation is useful to better analyze the data of the InSight mission, both in
33 terms of wave propagation at surface and to interpret some in-situ elastic tests carried out with the
34 scoop. These data are interpreted in the light of a granular contact mechanics theory in a companion
35 paper.

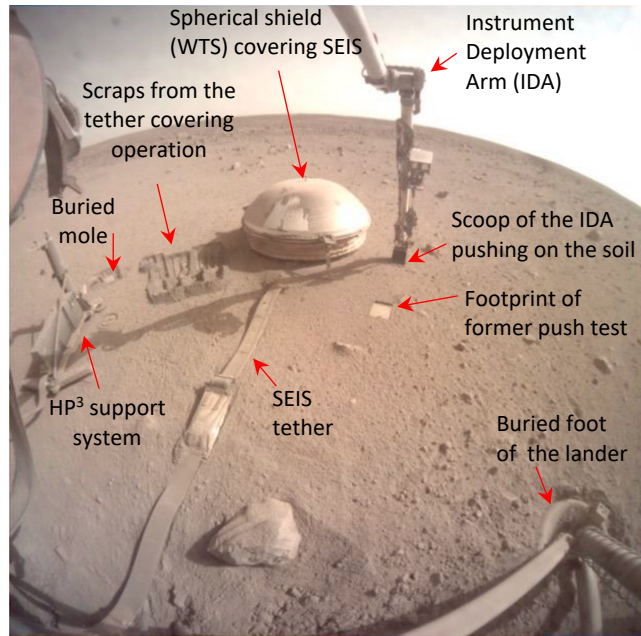
36 Plain Language Summary

37 The lander of the InSight mission placed on Mars a highly sensitive seismometer to detect seismic
38 waves from Marsquakes and meteorite impacts. To help analysing the seismic waves, a special
39 device was developed to measure wave velocities on a loose sandy simulant mimicking the surface
40 regolith, with wave emitting and receiving transducers placed on both sides of a cylindrical sand
41 sample submitted to an external stress. Due to reduced gravity, stresses, that control the wave
42 velocity (the larger the stress, the faster the waves) are very low at the surface of Mars. To impose
43 low stresses (down to 1.75 kPa), we used a horizontal sample with a careful stress calculation
44 along the sample axis, along which waves propagate. We determined the changes in wave velocity
45 with stress (governed by a power law) and observed greater variability under 5 kPa, showing the
46 limit of our transducers at low stresses. Based on the elasticity theory, we derived from waves
47 velocities some parameter governing the sample deformations under changes of strain. We suspect

48 a slight decrease of the Poisson ratio (that characterises the radial elastic strain of a cylindrical
49 sample submitted to an axial load) below 5 kPa. These data are deemed useful to better constrain
50 the response of Mars sandy surface materials, at the InSight site and also in other areas for future
51 missions on Mars.

52 **1 Introduction**

53 Recent interest into the elastic behavior at small strain of sands under low stresses has been
54 gained through the investigation of the mechanical properties of the surface layer at the InSight
55 landing site on Mars, submitted to reduced gravity ($g = 3.721 \text{ m/s}^2$). Briefly, the NASA InSight
56 mission is a geophysical mission landed on Mars (Elysium Planitia) in November 2018. The
57 InSight lander installed on Mars' surface a highly sensitive seismometer, funded by CNES (Centre
58 National d'Etudes Spatiales, the French Space Agency) aimed at investigating both the seismic
59 activity and the meteorite impact activity on Mars. The lander also installed the so-called HP³
60 thermal device funded by DLR (Deutsches Zentrum für Luft- und Raumfahrt, the German
61 Aerospace Center) that comprised a self-driving penetrometer aimed at measuring the thermal flow
62 emitted by Mars and at characterising the surface thermal properties (Spohn et al., 2018). The
63 seismometer (Lognonné et al., 2019, 2020) provided valuable information about the seismic
64 activity on Mars (e.g. Banerdt et al., 2018, Giardini et al. 2020, Hobiger et al., 2021) and about
65 meteorite impacts (e.g. Garcia et al., 2022; Posiolova et al., 2022). Unfortunately, the self-driving
66 penetrometer could not penetrate more than 40 cm deep, due to a lack of friction along its shaft
67 (Spohn et al., 2022a and b). It provided however the surface thermal conductivity (0.039 ± 0.002
68 $\text{W m}^{-1} \text{K}^{-1}$), in agreement with orbital and in-situ thermal inertia estimates. Thermal data also
69 allowed to derive a quite low surface density of 1.2 Mg/m^3 (Grott et al., 2021).



70

71 Figure 1. Image taken on Sol 1770 (i.e., the 1770th martian day of the mission) by the Instrument
 72 Context Camera of the Lander showing the hemispherical Wind and Thermal Shield (WTS, diameter 720
 73 mm) covering the SEIS instrument, with the Instrument Deployment Arm vertically pushing on the soil at
 74 the right of the SEIS. A flat footprint made by a former push test by the IDA can also be observed. These
 75 push tests were carried out to estimate the surface elastic properties based on the strain derived from the
 76 SEIS response. The (black) HP³ support system is observed on the left side, close to the place where the
 77 self-driving penetrometer has been buried. Some scraps made by the IDA scoop to cover the regolith tether
 78 for better thermal insulation can also be seen at the left of the WTS. All instruments are covered by a dust
 79 layer progressively brought by the Martian winds (Image Credit: NASA-JPL).

80

81 The InSight mission provided much information on the mechanical properties of the
 82 surface (Morgan et al., 2018, Spohn et al., 2021, Delage et al. 2022a, 2022b, 2023, Marteau et al.
 83 2021, 2022, 2023, Verdier et al. 2023). Significant input in this regard was gained by using the
 84 Instrument Deployment Arm (IDA). The IDA, designed to place the instruments on the surface of
 85 the planet, was also used in various scrapping and piling activities carried out with the scoop at its
 86 edge (Golombek et al., 2023). Figure 1 shows a photo taken by the Instrument Context Camera of
 87 the lander on sol 1771, close to the end of the mission, illustrating these activities. The photo shows
 88 that the landing site is flat and characterised by a sandy deposit with little rock abundance, as
 89 planned from orbiter data during the landing site selection (Golombek et al., 2017). The photo also
 90 shows the hemispherical Wind and Thermal Shield (WTS) placed above the SEIS seismometer
 91 and the scraps made by the Instrument Deployment Arm (IDA) placed with its scoop in contact
 92 with the soil on the right hand side of SEIS). One also observes, left of SEIS, the scraps made by
 the IDA scoop during the operation of covering the SEIS tether to improve thermal insulation and

93 reduce glitches in the seismic signals (Golombek et al. 2023). The support system of the self
94 penetrating thermal probe is observed on the left hand side, close to the place where the probe has
95 been penetrated. One can observe that all devices are covered by a dust layer that finally hampered
96 the functioning of the solar arrays, resulting in a too weak power supply to keep the instruments
97 working. This led to the end of the mission on 18 December 2022.

98 The surface layer properties are not fully understood. Due to long term wind saltation, Mars
99 regolith particles at surface are sub-rounded to rounded (Goetz et al. 2010). Direct visual
100 observations of the pits excavated by the rocket exhausts during landing evidenced a layer of
101 cohesive sandy matrix containing some pebbles, called duricrust (see Warner et al. 2022, Delage
102 et al. 2022a). It is suspected that the surface low density is made possible by inter-grains cemented
103 bonds within a loose arrangement of regolith particles. The inter-grains cement is suspected to be
104 due to salts deposited by thin films of water via interactions of atmospheric water vapor and soils,
105 as suggested by chemical measurements by Viking and Mars Exploration Rover spacecraft (Banin
106 et al. 1992, Haskin et al. 2005, Hurowitz et al. 2005).

107 The in-situ determination of the surface regolith elastic properties could be made by
108 recording with the seismometer the waves emitted during the hammering sessions of the
109 penetrometer (Brinkman et al., 2022). The mean values of compression and shear wave velocities
110 were $V_p = 119$ m/s and $V_s = 63$ m/s, respectively, in reasonable agreement with previous lab
111 estimations on loose sands used as regolith simulants (Delage et al., 2017).

112 In spite of the difference between the sandy simulants used in terrestrial lab testing
113 (Seiferlin et al. 2008, Delage et al. 2017, Delage et al. 2022b) and the regolith at the InSight landing
114 site, it was found interesting to further investigate the elastic properties of sandy simulants under
115 stresses lower than those currently considered in terrestrial Soil mechanics to better analyse the
116 properties of surface sandy regolith on Mars, that are submitted to very low stresses. To do so, a
117 specific device was developed in the laboratory to measure wave velocities in loose sand with
118 bender elements under low stresses. This paper presents the device and the results obtained in
119 terms of wave velocities and Poisson ratio. In a companion paper (Caicedo et al. 2023), the data
120 are analysed through a theory of contact mechanics accounting for the roughness of particles
121 (Bachrach et al. 2000, Bahrami et al. 2005, Bachrach and Avseth 2008, Butt et al. 2015).

122 2 Wave velocity and Poisson ratio in sands

123 The Poisson ratio ν of sands has been determined through wave velocity measurements by
 124 various authors, including Bates (1989), Nakagawa et al. (1996), Prasad (2002), Kumar &
 125 Madhusudhan (2010) and Suwal & Kuwano (2013). The expression of ν with respect to V_p and V_s
 126 is as follows, assuming an isotropic elastic medium:

$$127 \quad \nu = 0.5 \frac{\left(\frac{V_p}{V_s}\right)^2 - 2}{\left(\frac{V_p}{V_s}\right)^2 - 1} \quad (1)$$

128 where V_p and V_s are the compression and shear wave velocities, respectively, given by the
 129 following expressions:

$$130 \quad V_p = \sqrt{\left(K + \frac{4}{3}G\right) / \rho_b} \quad \text{and} \quad V_s = \sqrt{\frac{G}{\rho_b}} \quad (2)$$

131 where K and G are the bulk and shear elastic moduli, respectively, and ρ_b the bulk unit mass of the
 132 sample.

133 In the stress ranges considered by these authors, the Poisson ratio decreased under
 134 increased stress. Under high stresses, Prasad (2002) observed a decrease from 0.38 to 0.30 between
 135 1 and 10.2 MPa, with $\nu = 0.30$ up to 20 MPa. For Toyoura sand ($D_{50} = 0.19$ mm, $I_D = 0.68$), Suwal
 136 and Kuwano (2013) showed that ν decreased from 0.175 down to 0.15 between 50 and 400 kPa.
 137 Kumar and Madhusudhan (2010) investigated the effects of stress (between 100 and 500 kPa),
 138 density index I_D between 0.4 and 0.8 ($I_D = \frac{e - e_{min}}{e_{max} - e_{min}}$, where e_{max} and e_{min} are the sand
 139 maximum and minimum void ratios, respectively) and grain size of well-sorted sands. All the
 140 Poisson ratios measured were below 0.26 and decreased with increased density index. Some data
 141 under lower stresses in a dense random pack of identical glass beads were presented by Bachrach
 142 et al. (2000), with ν ranging between 0.130 and 0.151 for stresses between 5 and 40 kPa. They
 143 also conducted in-situ wave measurements in Moss Landing beach (California, dry angular sand)
 144 using a seismic line parallel to the shoreline of 20 geophones distant of 30 cm, and a hammer
 145 (about 50 kg) applied on a metal block as source. The Poisson ratio derived from the velocity
 146 profile between 0 and 5 m (vertical stress between 0 and 78.5 kPa with a dry unit mass of 1.7
 147 Mg/m³) was equal to 0.15, with no increase with depth. The Poisson ratios that they determined in
 148 the lab were between 0.13 and 0.26, with a tendency to decrease i) under increased stress - more

149 significantly for fine-grained sand - and ii) under increased density index, whereas the in-situ
 150 determination by Bachrach et al. (2000) evidenced a constant ν with respect to stress.

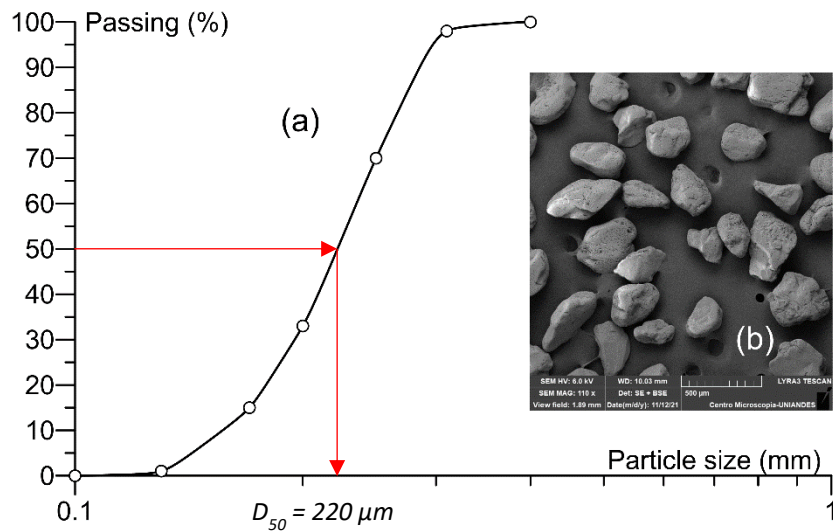
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152 3 Materials and Methods

153 3.1 Fontainebleau sand as a Martian Regolith simulant

154 To account for the rounded shape of regolith grains on Mars (Goetz et al. 2010), we adopted
 155 the NE34 Fontainebleau sand (see Delage et al. 2022b). It is a well-sorted silica sand (grain density
 156 $\rho_s = 2.651 \text{ Mg/m}^3$) from the Paris Basin with a median diameter D_{50} of $220 \mu\text{m}$, (see Figure 2,
 157 Benahmed 2005), to compare with the $175 \mu\text{m}$ diameter derived from thermal inertia
 158 measurements in the InSight landing site (Golombek et al. 2017). The uniformity coefficient C_u is
 159 equal to 1.65. The grain size distribution is presented in Figure 2a, together with a scanning
 160 electron microscope photo (b) that shows that grains are sub-rounded to rounded. The minimum
 161 and maximum void ratios are $e_{\min} = 0.54$ and $e_{\max} = 0.86$, respectively (Andria-Ntoanina 2011).

162



163

164

165 Figure 2. NE34 Fontainebleau Sand: (a) grain size distribution curve, and (b) SEM image.

166 3.2 Sample preparation

167 The sample was prepared, as for standard triaxial testing, by using a 170 mm high mould
 168 of internal diameter 100 mm into which a neoprene membrane, fixed to the base of the triaxial cell
 169 and the external face of the mould at the top by using two O-rings, was maintained by applying

170 vacuum (80 kPa). The pluviation technique (Kolbuszewski, 1948; Cresswell et al., 1999,
171 Benahmed, 2001, Hariprasad et al. 2016) was used to prepare a low density sample, adopting an
172 almost null fall height (resulting in an upward speed of the sieve of 3 cm/s) and a small sand flow.

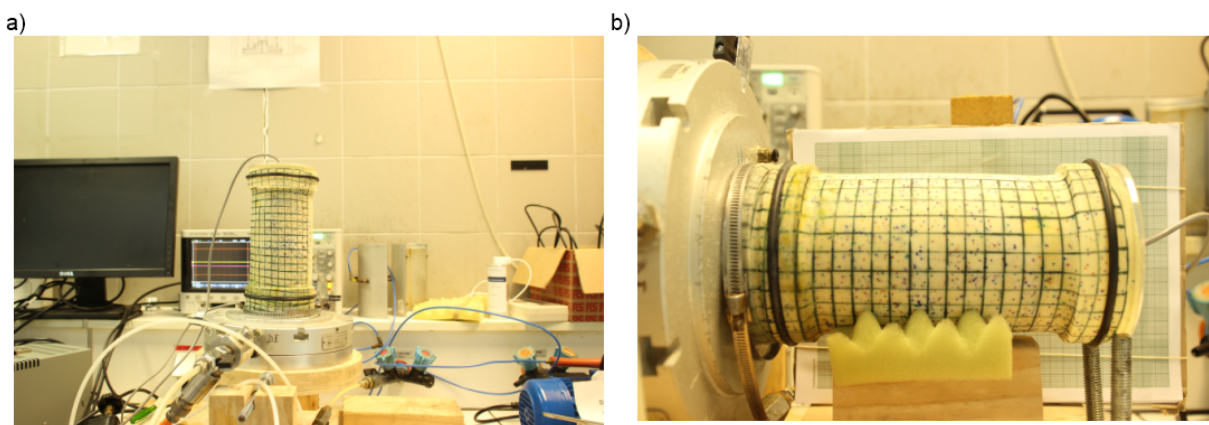
173 The final dimensions of the sample are 100 mm in diameter and 150 mm in height, with a
174 density around 1.4 Mg/m^3 (void ratio $e = 0.84 - 0.82$, density index $I_d = 6 - 10\%$). After
175 pluviation, the sand in excess was carefully removed, the top cap was carefully placed on the
176 flattened sand surface and the membrane was wrapped around it and fixed by an O-ring. Before
177 dismounting the mould, the vacuum was decreased to 10 kPa, a pressure that appeared to be high
178 enough to maintain the cylindrical shape of the sample.

179 3.3 Experimental setup at low stress

180 The wave velocity measurements were carried out by using 3 mm height bender elements
181 (GDS brand, able to send and receive both compression P and shear S waves) inserted into the top
182 and bottom ends of the sample. They were controlled via a signal generator producing sinusoidal
183 waves at a fixed frequency of 10 kHz and 14 V amplitude. An amplifier was used to increase the
184 magnitude of the received signal. Data acquisition was made through an oscilloscope, using two
185 channels spatially located the furthest from each other, thus reducing as much as possible the
186 crosstalk effect between bender elements (Lee & Santamarina, 2005).

187 In a vertical position, with a density of 1.4 Mg/m^3 , the vertical stress σ_v at the base is around
188 2.21 kPa (the weight of the soil column). Given the low-stress range considered (below 10 kPa),
189 the stress difference between the top and bottom of the sample was not acceptable. It was then
190 decided to place the sample in a horizontal position (Figure 3).

191



193 Figure 3. a) Sample preparation (vertical); b) Sample tested (horizontal).

194 The wave travel path along the axis of the horizontal cylindrical sample is submitted a total
 195 stress σ equal to the sum of three components:

$$196 \quad \sigma = \sigma_{vac} + \sigma_m + \sigma_{gh} \quad (3)$$

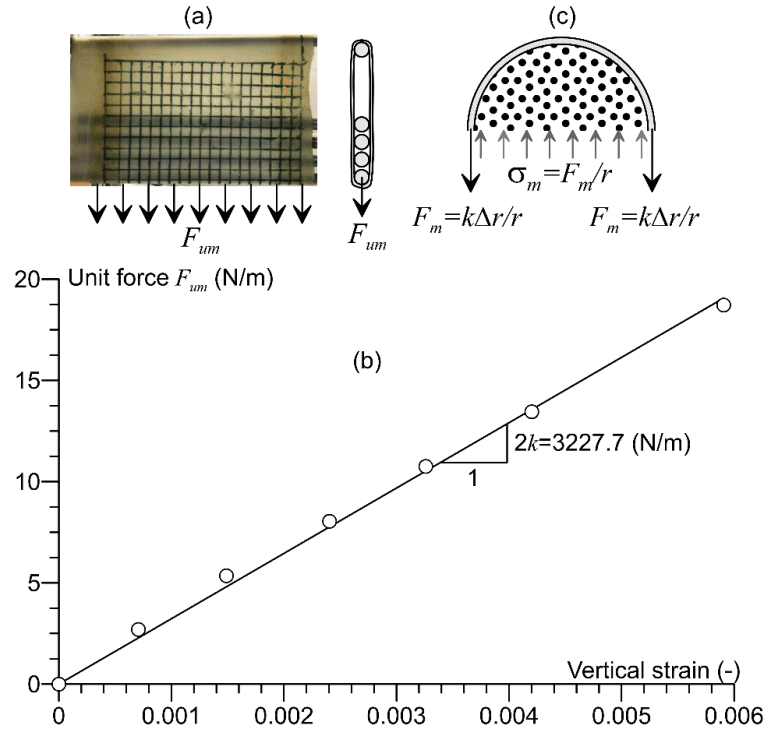
197 where σ_{gh} is the gravity-induced stress within the horizontal sample, σ_m the membrane isotropic
 198 confining stress and σ_{vac} the vacuum-induced isotropic stress.

199 The stress produced by the membrane was evaluated using the solution for a small wall
 200 cylinder under pressure as follows:

- 201 • The stiffness of the membrane was measured by imposing different forces on a membrane,
 202 as shown in Figure 4a. From the linear response obtained (Figure 4b), one can derive the
 203 spring coefficient k of the membrane as the ratio between the half of the applied unit load
 204 and the axial strain of the membrane. The data of the Figure provide $k = 1613.85$ N/m.
- 205 • The force F_m applied by the membrane around the sample (Figure 4c) is given by $F_m = k$
 206 $\Delta r/r$, where k is the membrane spring coefficient, Δr the increase in the radius of the
 207 membrane between the free state and the stressed state around the sample and r the sample
 208 radius. Δr was obtained by subtracting the sample perimeter from the length of the extended
 209 membrane, L_m , divided by 2π ($\Delta r = r - L_m/2\pi$).
- 210 • Using the solution for a small wall cylinder under pressure, as shown in Figure 4c, the
 211 radial stress σ_m applied by the membrane per unit length on the sample is $\sigma_m = F/r$.

212 With $k = 1613.85$ N/m, $\Delta r = 2.5$ mm and $r = 50$ mm, the confining stress due to the
 213 membrane is $\sigma_m = 1.6$ kPa, a result similar to that obtained by Henkel & Gilbert (1952) and
 214 Newland & Allely (1959).

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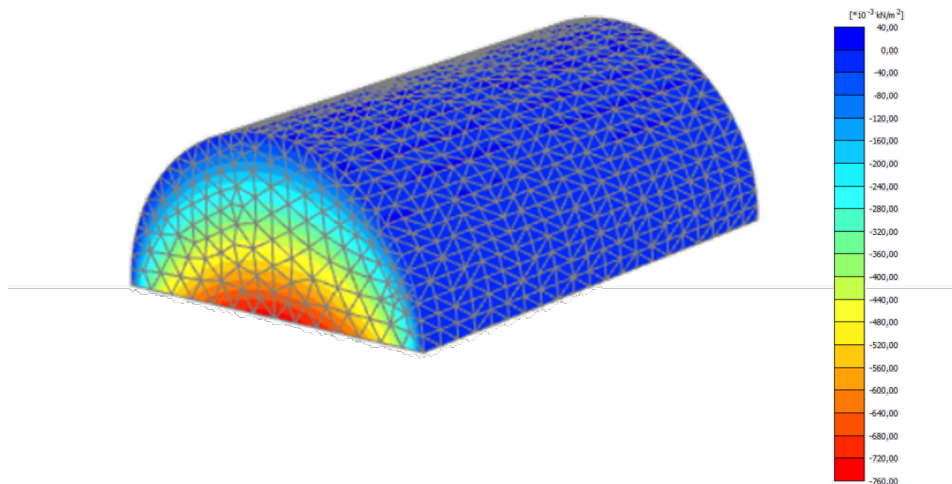


216

217 Figure 4. (a) Setup used for measuring the membrane stiffness; (b) Force/vertical strain elongation
 218 curve of the membrane; (c) Schematic drawing for computing the stress on a cylinder.

219 The gravity-induced stress was computed in elastic conditions by using the Plaxis 3D finite
 220 element code (see Figure 5), applying the membrane stress as a boundary condition, providing σ_{gh}
 221 $= 0.75 \text{ kPa}$ at a density of 1.4 Mg/m^3 .

222



223

224 Figure 5. FEM (Plaxis 3D) elastic analyses of the sample self-weight to estimate the horizontal
 225 stress σ_{gh} on the sample axis.

226 The constant stress due to both gravity and the membrane is $\sigma_m + \sigma_{gh} = 0.75$ kPa. The total
227 stress applied to the sample was changed by changing the vacuum applied within the sample. Once
228 the (vertical) sample pluviated and the membrane fixed around it, a 10 kPa vacuum was applied
229 before removing the mould and rotating the sample in the horizontal position, with no change
230 observed in its size. The total horizontal stress applied on the sample axis was obtained by adding
231 0.75 kPa to the applied vacuum. Then, the loading path was applied by changing vacuum as
232 follows:

- 233 • A step unloading path from 10 kPa to 1 kPa, (10 - 9 - 8 - 7 - 6 - 5 - 4 - 3 - 2 - 1 kPa) followed
234 by reloading back to 10 kPa.
- 235 • A step loading path from 10 kPa up to 80 kPa, (10 - 20 - 30 - 40 - 50 - 60 - 70 - 80 kPa).
236 Moreover, some tests were performed at 5 and 15 kPa to investigate eventual hysteresis
237 effects.

238 Various wave measurements were carried out at each stress to assess variability and
239 repeatability. Five waves were recorded for stresses below 10 kPa, as a higher variability was
240 observed in this stress range. In contrast, three measurements were deemed sufficient at 15 kPa
241 and above (the number of repetitions was chosen after interpreting the results of the initial tests).

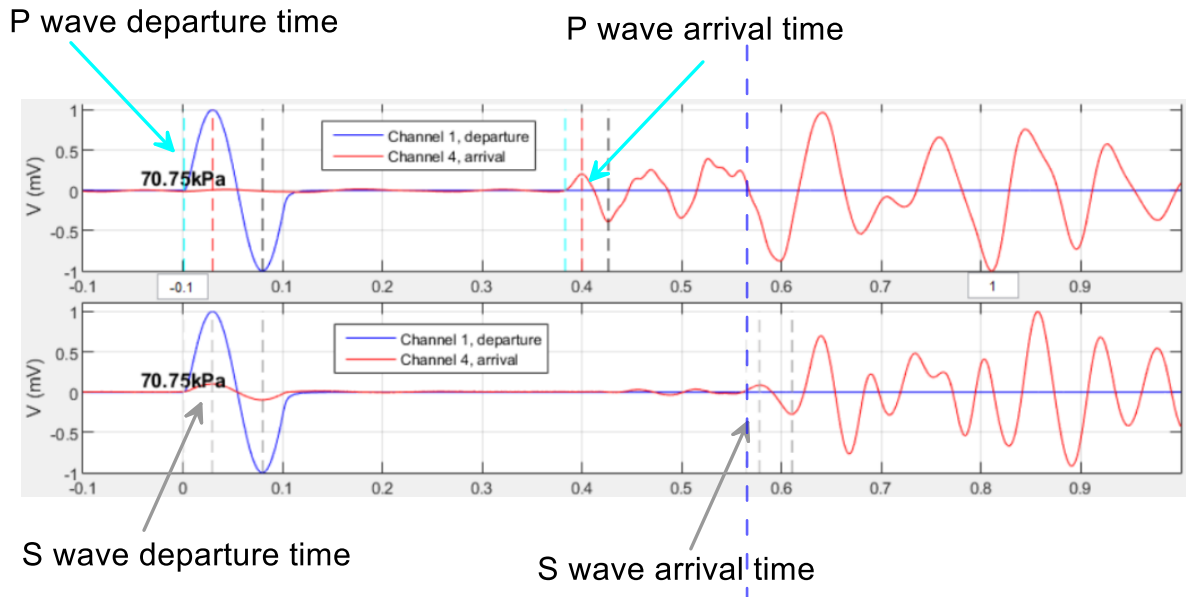
242 **3 Experimental results**

243 The tests were carried out on 4 pluviated samples (EP 1 to 4), with the following measured
244 densities: EP1=1.443 Mg/m³, EP2=1.443 Mg/m³, EP3=1.447 Mg/m³ and EP4=1.452 Mg/m³.

245 Determining the accurate travel time of the waves is crucial in bender element tests, and
246 various methods have been used in the literature. They include the first inversion of the output
247 signal and the first zero value immediately after the signal inversion (Shirley & Hampton, 1978;
248 Dyvik & Madshus, 1985; Jamiolkowski et al., 1995; Jovičić et al., 1996; Jovičić & Vilhar, 2009),
249 the peak-to-peak-method (Viggiani & Atkinson, 1995a), the cross-correlation frequency-domain
250 method (Viggiani & Atkinson, 1995b; Arulnathan et al., 1998; Boulanger et al., 1998; Mohsin &
251 Airey, 2003; Murillo et al., 2009; Murillo et al., 2011) and some methods simultaneously analysing
252 the travel time of both P and S waves (Lee & Santamarina, 2005; Wang et al., 2017).

253 As seen in Figure 6, which presents the data for 70.75 kPa, an accurate determination of
254 the travel time could be made by considering, for both P and S waves, the starting point of the
255 sinusoidal emitted signal and that of the received P and S signals. Interestingly, there is a clear

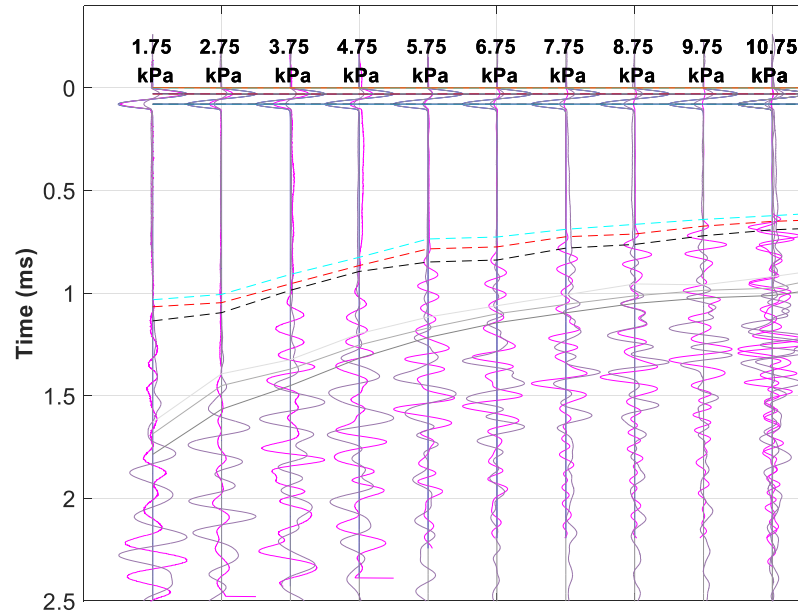
256 coupling between the reception of both waves. The S wave arrival could be detected in the received
 257 P wave signal (at 0.57 ms), as commented by Wang et al. (2017). Note also that some slight
 258 oscillations due to the P wave arrival (after 0.4 ms) are detected in the S wave signal, whereas a
 259 clear increase in amplitude in the P wave signal is observed when the S wave arrives after 0.57
 260 ms.



261
 262 Figure 6. P and S waves under 70.75 kPa, with good correspondence between both: the S wave
 263 arrival can also be detected in the P wave signal; the arrival of the P wave creates some slight
 264 perturbations in the S wave signal (time is in milliseconds).

265
 266 As seen in Figure 7, that presents both P (pink) and S (grey) signals under lower stresses
 267 (< 10 kPa), the signals become less clear at small stresses, particularly below 2.75 kPa. Besides
 268 carefully examining both signals and their coupling, the arrival time was also determined by
 269 extrapolating the trend resulting from larger stresses. The data show that bender elements can be
 270 used in (loose) sands, even under low stresses, smaller than those currently investigated in
 271 terrestrial geotechnical engineering.

272



273

274 Figure 7. P (pink) and S (grey) waves detected under smaller stresses below 10 kPa.

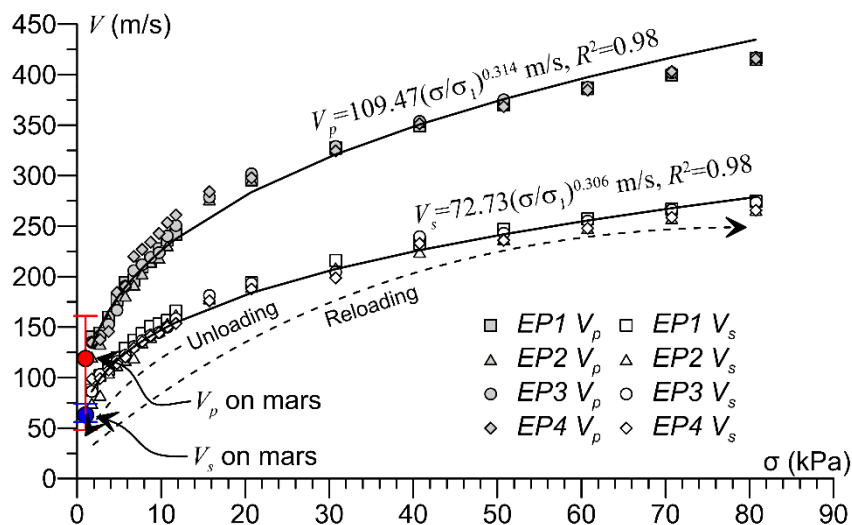
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276 Good agreement was also found with peak-to-peak data (calculating velocity with the tip-
 277 tip distance between bender elements, Lee & Santamarina 2005). A software (Appendix A) was
 278 implemented to interpret arrival times, visualise all P/S waves of each experimental program in a
 group and suggest the departing and arriving points.

279

280 Figure 8 shows the change in wave velocities with stress in the tests on samples EP1 to
 281 EP4. The shape of the curves is comparable to other data on sands (e.g. Bachrach et al. 2000,
 282 Zimmer et al. 2002, Delage et al. 2017). As indicated in the Figure, the stress path followed first
 decreases from 10.75 kPa to 0.75 kPa, before increasing to 10.75 kPa up to 80.75 kPa.

283



284

285 Figure 8. Measured wave velocities obtained using bender elements compared with those
 286 measured by Brinkman et al. (2022) on Mars (red and blue points).

287 Inspection of data along the unloading-reloading path indicates no significant hysteresis
 288 effect in both V_p and V_s curves, showing satisfactory reversibility in the response, in conjunction
 289 with slight changes in the grain assembly. Also, the variability of the measured wave velocities
 290 between the different samples is low, demonstrating good repeatability and providing confidence
 291 in the results.

292 As expected, the velocities decrease with decreased applied stress, according to the
 293 following equations:

$$294 \quad V_p = 109.47 \left(\frac{\sigma}{\sigma_1} \right)^{0.314} \quad R^2=0.98 \quad (4)$$

$$295 \quad V_s = 72.73 \left(\frac{\sigma}{\sigma_1} \right)^{0.306} \quad R^2=0.98 \quad (5)$$

296 where $\sigma_1 = 1$ kPa is a reference stress.

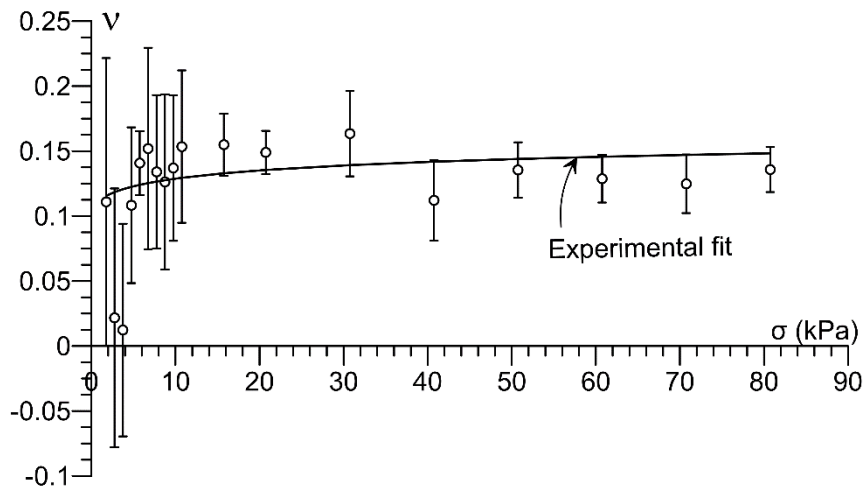
297 **4 Discussion**

298 The exponents derived from Figure 8 (Eqs 4 and 5) are slightly different for V_p and V_s ,
 299 showing that our experimental data are not fully in agreement with the elasticity theory. When
 300 trying to fit V_p and V_s with the same exponent, one gets a value of 0.31, with no dependency of
 301 the Poisson ratio with respect to the confining stress. This leads however to a Poisson ratio of
 302 0.105, in disagreement with our experimental results. The exponents values derived from Figure
 303 13 are higher than those measured (0.22) at higher stresses between 25 and 450 kPa by Delage et
 304 al. (2017) on three other Martian simulants (Mojave Mars simulant, MSS-D and Eifel sand).

305 Interestingly, these data agree reasonably well with the in-situ measurements performed on
 306 Mars during the hammering campaign of the HP³ self-penetrating dynamic probe (see Figure 1),
 307 during which emitted waves were detected by SEIS. The V_p/V_s values determined by Brinkman et
 308 al. (2022) are reported in the figure, considering that they correspond to a vertical stress of 0.9 kPa,
 309 resulting from an average depth of 0.2 m at a density of 1.2 Mg/m³ (Grott et al. 2022) under a
 310 gravity of 3.721 m/s².

311 Figure 9, that presents the Poisson ratios computed using Eq. 1 from $V_p - V_s$ measurements
 312 at each point, exhibits more variability below 5 kPa. This is probably related to the difficulty of

313 properly measuring travel times at low stresses (see Figure 12), in a stress range for which the use
 314 of bender elements becomes more tricky.



315

316

317 Figure 9. Changes in Poisson ratio with respect to confining stress determined from bender element
 318 measurements (points) and from the fitted curves of Figure 8 (curve).

319

320 Since the values of the exponents of Eqs 4 and 5 are close, the relationship V_p/V_s is slightly
 321 dependent on stress, with $V_p/V_s = (\sigma/\sigma_1)^{0.008}$. Therefore, from Eq. 1, the fitting equation for the
 322 Poisson ratio becomes:

$$323 \quad \nu = 0.5 \frac{2.265 \left(\frac{\sigma}{\sigma_1} \right)^{0.016} - 2}{2.265 \left(\frac{\sigma}{\sigma_1} \right)^{0.016} - 1} \quad (6)$$

324

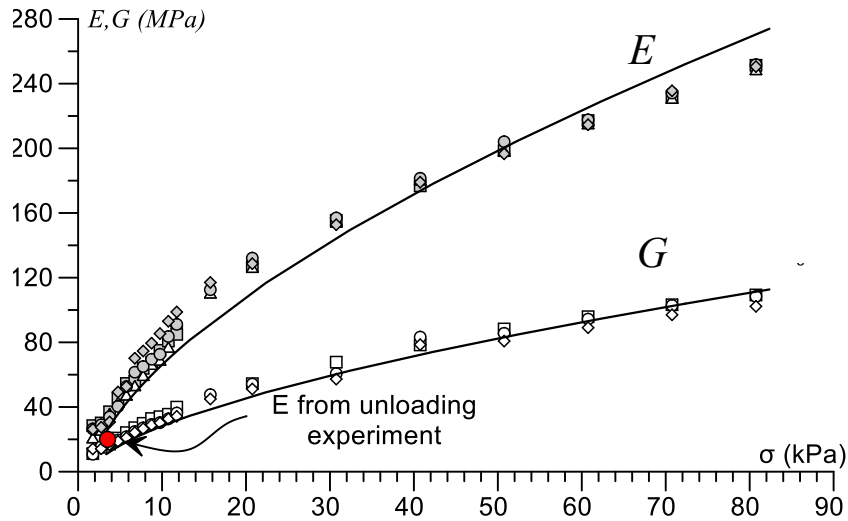
325 This low dependency of the Poisson ratio with respect to stress is illustrated in the curve
 326 of Figure 9 that indicates a slight decreasing trend below 10kPa, derived from both individual
 327 points and fitted curves.

328 The larger dispersion of our experimental data below 5 kPa indicates that bender elements
 329 are less efficient in this area. Inspection of the data of Figure 9 also shows that the changes in V_p/V_s
 330 with stress seems to somewhat differ below 10 kPa, with a less regular curvature of the data. The
 331 changes in Poisson ratio below 5 kPa would certainly deserve more investigation, in an area where
 332 the efficiency of bender elements is perhaps limited.

333 The velocities may be used to calculate the elastic shear modulus G (from Eq. 2) and the
 334 Young modulus $E = 2G(1 + \nu)$. The results, presented in Figure 10, show how the moduli

335 decrease with decreased stress. Interestingly, the data at low stress are not far from the measured
 336 value of E from interaction tests carried out with the SEIS foot on Fontainebleau sand (20 MPa at
 337 3.5 kPa, Delage et. al 2022b).

338



339

340 Figure 10. Changes in shear and Young modulus with respect to confining stress determined from
 341 model predictions. The results from an interaction with the SEIS foot (red point) is in good
 342 agreement (Delage et al. 2022b).

343 5 Conclusions

344 Wave measurements were performed under low stresses by using bender elements on loose
 345 samples of Fontainebleau sand used as a Martian regolith simulant. This was made to better
 346 constrain the elastic properties of the regolith at the surface of the InSight landing site and to help
 347 interpreting in-situ elastic data obtained at surface through wave measurements (Brinkman et al.
 348 2022) of indentation experiment carried out with the IDA (Delage et al. 2023). Current knowledge
 349 on wave transfer in sands was extended to low stresses (< 10 kPa) by using a horizontal cylindrical
 350 sample submitted to changes in vacuum (between 2 and 80 kPa). Additional stresses due to gravity
 351 and to the confining membrane were carefully calibrated and accounted for. Uncertainty in wave
 352 velocity determination was reduced by performing 3 to 5 measurements at each stress, and tests
 353 were carried out on 4 different samples. Bender elements were able to provide wave velocity
 354 measurements at stresses as low as 1.75 kPa, with however greater variability below 5 kPa. The
 355 change in V_p and V_s with respect to stress followed a power law, with however two slightly
 356 different exponent values, indicating that elastic hypotheses were not fully respected within the

357 sand sample. The calculation of the Poisson ratio ν from wave velocities measurements confirmed
358 that ν was reasonably constant above 10 kPa. Conclusions are less clear below 5 kPa, where the
359 bender elements measurements are less accurate. The possibility of having a decreasing Poisson
360 ratio in this area seems still worth of investigation, to be conducted through other experimental
361 techniques.

362 This study enlarged the knowledge of the elastic behaviour of sands under low-stress and
363 low strain, a novel topic in wave velocities investigations, that was useful to interpret local wave
364 velocity measurements carried out at the InSight landing site (Brinkman et al. 2022). Further
365 information was also gained about the Poisson ratio under low stress, another important parameter
366 to estimate the surface elastic response of the surface.

367 However, the comparison of our laboratory data on a Martian simulant with what could be
368 the response of a true Martian regolith is not straightforward. First, one have to consider possible
369 differences in the grain package, that is known to have significant effects on seismic wave travel.
370 It is very probable that the packing resulting from our pluviation method on a vertical sample, that
371 has been put horizontally afterwards, differs from the packing of surface regolith grains on Mars,
372 that results from very long term wind saltation (through many repetitive small lateral jumps of
373 sand grains along the wind direction). It could be that the post convenient way to mimic the
374 resulting packing would be by trying to reproduce the saltation process on a (subrounded) sand
375 field submitted to constant wind. Then, the best would probably to run in situ wave determination
376 by using a line of geophones aimed at detecting an impact made on the ground, as done by
377 Bachrach et al. 2000 on a beach in California.

378 Note also that direct observations and measurements made on the InSight landing site
379 showed that the soil profile was not only made up of a sandy material. The true profile is composed
380 of a surface 1 cm thick sand/dust layer, overlaying an around 20 cm thick loose duricrust made up
381 of a cohesive matrix containing some pebbles, located above a 12 cm layer of sand overlaying a
382 gravel/sand deposit (Golombek et a. 2020, Warner et al. 2022, Delage et al. 2022, Spohn et al.
383 2022). However, in-situ wave velocity measurements carried out during the hammering session of
384 the HP³ self-penetrating gauge (Brinkman et al. 2022) provided values of velocity and Poisson
385 ratio close to those found in this work. Also, our investigation may be useful, as a first step, for
386 other areas of Mars, where thicker deposits of sand, with dunes and ripples, have been observed
387 (e.g., Ehlmann et al. 2017). This can also be the case for future Mars missions.

388 Some of the questions raised in this experimental investigation are further considered in a
389 companion paper (Caicedo et al. 2023) in which data at small stress are analysed through a contact
390 mechanics theory derived from Bachrach et al. (2000).

391 **Acknowledgments**

392 These results are part of the PhD thesis of Juan-Pablo Castillo Betancourt, financially supported
393 by Universidad de los Andes (Colombia) and École des Ponts ParisTech (France). The authors are
394 also grateful to NASA, CNES, their partner agencies and Institutions (UKSA, SSO, DLR, JPL,
395 IPGP-CNRS, ETHZ, IC, MPS-MPG). The authors want to thank the contributions made by the
396 Ecole des Ponts ParisTech Navier-CERMES technical team for setting up the experimental device,
397 especially Loic Lesueur, Marine Lemaire, Emmanuel De Laure, Baptiste Chabot and Xavier
398 Boulay. This paper is Insight contribution N° ICN 327.

399

400 **References**

- 401 Andria-Ntoanina, I. (2011). Caractérisation dynamique de sables de référence en laboratoire - Application
402 à la réponse sismique de massifs sableux en centrifugeuse. PhD thesis, Ecole des Ponts ParisTech (in
403 French).
- 404 Arulnathan, R., Boulanger, R. W. and Riemer, M. F. (1998). Analysis of Bender Element Tests. In
405 *Geotechnical Testing Journal*, GTJODJ, 21(2).
- 406 Bachrach, R., Dvorkin, J. and Nur, A. M. (2000). Seismic velocities and Poisson's ratio of shallow
407 unconsolidated sands. *Geophysics*, 65(2), 559–564. <https://doi.org/10.1190/1.1444751>.
- 408 Bachrach, R., and Avseth, P. (2008). Rock physics modeling of unconsolidated sands: Accounting for
409 nonuniform contacts and heterogeneous stress fields in the effective media approximation with
410 applications to hydrocarbon exploration. *Geophysics*, 73(6). <https://doi.org/10.1190/1.2985821>
- 411 Bahrami, M., Yovanovich, M. M. and Culham, J. R. (2005). A compact model for spherical rough contacts.
412 *J. Tribol.* Oct 2005, 127(4): 884-889, <https://doi.org/10.1115/1.2000982>
- 413 Banin, A. et al. 1992. in *MARS* (eds Kieffer, H. H., Jakosky, B. M., Snyder, C. W. & Matthews, M. S.)
414 594–625 (University of Arizona Press, Tucson, 1992).
- 415 Banerdt, W. B., Smrekar, S. E., Banfield, D., Giardini, D., Golombek, M., Johnson et al. (2018). Initial
416 results from the InSight mission on Mars. *Nature Geosciences* (13) 183 – 189.
- 417 Bates, C. R. (1989). Dynamic soil property measurements during triaxial testing. *Géotechnique*, 39(4), 721-
418 726.

- 419 Benahmed, N. (2001). Comportement mécanique d'un sable sous cisaillement monotone et cyclique :
 420 application aux phénomènes de liquéfaction et de mobilité cyclique. PhD thesis, Ecole des Ponts
 421 ParisTech (in French).
- 422 Boulanger, RW, Arulnathan, R., Harder, LF, Torres, R., and Driller, M. (1998): Dynamic Properties of
 423 Sherman Island Peat, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 124, (1), 12-
 424 23.
- 425 Brinkman, N., Schmelzbach, C., Sollberger, D., Pierick, J. T., Edme, P., Haag, T. et al. (2022). In situ
 426 regolith seismic velocity measurement at the InSight landing site on Mars. *Journal of Geophysical*
 427 *Research: Planets*, 127(10), e2022JE007229.
- 428 Butt, S. U., Antoine, J. F. and Martin, P. (2015). Simplified stiffness model for spherical rough contacts.
 429 *Tribology-Materials, Surfaces & Interfaces* 9(2), 63-70.
- 430 Caicedo B., Castillo Betancourt J. P., Delage P., Lognonné Ph., Banerdt W.B. (2023). Waves velocities and
 431 Poisson ratio in a loose sandy martian regolith simulant under low stresses. Part 2: theoretical analysis
 432 Castillo-Betancourt Juan Pablo. (2023). juan9715/MRA-Bender-Element-data: Bender data public
 433 repository release (Release) [Data set]. Zenodo. <https://doi.org/10.5281/zenodo.8161970>
- 434 Cresswell, A., Barton, M. E. and Brown, R. (1999). Determining the maximum density of sands by
 435 pluviation. *Geotechnical Testing Journal*, 22(4), 324–328. <https://doi.org/10.1520/gtj11245j>
- 436 Delage, P., Karakostas, F., Dhemaied, A., Belmokhtar, M., Lognonné, P., Golombek, M. et al. (2017). An
 437 Investigation of the Mechanical Properties of Some Martian Regolith Simulants with Respect to the
 438 Surface Properties at the InSight Mission Landing Site. *Space Science Reviews*, 211(1–4), 191–213.
 439 <https://doi.org/10.1007/s11214-017-0339-7>
- 440 Delage, P., Marteau, E., Vrettos, C., Golombek, M., Ansan, V., Banerdt, W. B. et al. (2022a). The
 441 mechanical properties of the Martian soil at the InSight landing site. In *Proceedings 20th International*
 442 *Conference on Soil Mechanics and Geotechnical Engineering*, Sydney. [https://hal.science/hal-](https://hal.science/hal-03706564)
 443 [03706564](https://hal.science/hal-03706564).
- 444 Delage, P., Castillo-Betancourt, J. P., Caicedo Hormaza, B., Karakostas, F., De Laure, E., Lognonné, P. et
 445 al. (2022b). The interaction between the SEIS seismometer of the InSight Martian mission and a
 446 regolith simulant. *Géotechnique*, 1-12.
- 447 Delage P., B. Caicedo, M. P. Golombek, T. Spohn, C. Schmelzbach, N. Brinkman, et al. (2023).
 448 Investigating the Martian soil at the InSight landing site. Keynote Lecture, International Symposium IS
 449 Porto 2023, submitted to *Soils and Rocks*.
- 450 Dyvik, R. and Madshus, C. (1985): Laboratory measurement of Gmax using bender elements, *Proc. ASCE*
 451 *Annual Convention, Advances in the art of testing soils under cyclic conditions*, Detroit, 186-196.

- 452 Ehlmann B.L. et al. 2017. Chemistry, mineralogy, and grain properties at Namib and High dunes, Bagnold
453 dune field, Gale crater, Mars: a synthesis of Curiosity rover observations. *Journal of Geophysical*
454 *Research, Planets* 122: 2510–2543. <https://doi.org/10.1002/2017JE005267>
- 455 Garcia, R. F., Daubar, I. J., Beucler, É., Posiolova, L. V., Collins, G. S., Lognonné, P. et al. (2022). Newly
456 formed craters on Mars located using seismic and acoustic wave data from InSight. *Nature Geoscience*,
457 15(10), 774-780.
- 458 Giardini D., Lognonné P., Banerdt W.P., Pike W.T., Christensen U., Ceylan S. et al. (2020). The seismicity
459 of Mars. *Nature Geosciences* 13: 205 – 212.
- 460 Goetz, W., Pike, W. T., Hviid, S. F., Madsen, M. B., Morris, R. V., Hecht, M. H. et al., (2010). Microscopy
461 analysis of soils at the Phoenix landing site, Mars: Classification of soil particles and description of
462 their optical and magnetic properties. *Journal of Geophysical Research E: Planets*, 115(8), 1–23.
463 <https://doi.org/10.1029/2009JE003437>
- 464 Golombek, M., Kipp D., Warner I.J., Daubar I.J., Ferguson R.L., Kirk R.L. et al. (2017). Selection of the
465 InSight landing site. *Space Science Review* 211, 5–95.
- 466 Golombek M, Warner NH, Grant JA, Hauber E, Ansan V, Weitz CM et al (2020). Geology of the InSight
467 landing site on Mars. *Nat Commun* 11(1):1014. <https://doi.org/10.1038/s41467-020-14679-1>
- 468 Golombek M., T. Hudson, P. Bailey, N. Balabanska, E. Marteau, C. Charalambous et al. (2023). Results
469 from InSight Robotic Arm Activities. *Space Science Review*, 219:20 doi:10.1007/s11214-023-00964-
470 0
- 471 Grott M., T. Spohn, J. Knollenberg, C. Krause, T.L. Hudson, S. Piqueux et al., (2021). Thermal
472 Conductivity of the Martian Soil at the InSight Landing site from HP3 Active Heating Experiments.
473 *Journal of Geophysical Research - Planets*, doi 10.1002/essoar.10506340.1.
- 474 Hariprasad, C., Rajashekhar, M. & Umashankar, B. Preparation of Uniform Sand Specimens Using
475 Stationary Pluviation and Vibratory Methods (2016). *Geotechnical and Geological Engineering* 34,
476 1909–1922. <https://doi.org/10.1007/s10706-016-0064-0>
- 477 Haskin, L. A. et al. Water alteration of rocks and soils from the Spirit rover site, Gusev crater, Mars. *Nature*
478 436, 66–69 (2005).
- 479 Henkel, D. J. and Gilbert, G. D. (1952). The effect measured of the rubber membrane on the triaxial
480 compression strength of clay samples. *Géotechnique*, 3(1), 20–29.
- 481 Hobiger, M., Hallo, M., Schmelzbach, C., Stähler, S. C., Fäh, D., Giardini, D. et al. (2021). The shallow
482 structure of Mars at the InSight landing site from inversion of ambient vibrations. *Nature*
483 *communications*, 12(1), 1-13.
- 484 Hurowitz, J. A. et al. In situ and experimental evidence for acidic weathering of rocks and soils on Mars. *J.*
485 *Geophys. Res.* 111, E02S19 (2006).

- 486 Jamiolkowski, M., Lancellotta, R. and Lo Presti D.C.F. (1995). Remarks on the stiffness at small strains of
487 six Italian clays. Proc. Symposium on Pre-failure Deformation Behaviour of Geomaterials, 817 – 836,
488 Balkema. <https://www.researchgate.net/publication/306157192>
- 489 Jovičić, V., Coop, M. and. Simic. M. (1996): Objective criteria for determining Gmax from bender element
490 tests, *Géotechnique*, 46(2), 357-362.
- 491 Kolbuszewski J.J. (1948). An empirical study of maximum and minimum porosities of sand. In:
492 Proceedings of Second International Conference on Soil Mechanics and Foundation Engineering,
493 Rotterdam, Netherland: ISSMGE, vol 1, pp 158–165
- 494 Kumar, J. and Madhusudhan, B. N. (2010). Effect of relative density and confining pressure on Poisson
495 ratio from bender and extender elements tests. *Géotechnique*, 60(7), 561-567.
- 496 Lee, J.-S. and Santamarina, J. C. (2005). Bender Elements: Performance and Signal Interpretation. *Journal*
497 *of geotechnical and geoenvironmental engineering*. 131(9), 1063-1070.
498 <https://doi.org/10.1061/ASCE1090-02412005131:91063>
- 499 Lognonné, P., Banerdt, W. B., Giardini, D., Pike, W. T., Christensen, U., Laudet, P. et al. (2019). SEIS:
500 Insight's seismic experiment for internal structure of Mars. *Space Science Reviews*, 215(1), 1-170.
- 501 Lognonné P., Banerdt W. B., Pike W. T., Giardini D., Christensen U., Garcia R. F. et al., (2020). Constraints
502 on the shallow elastic and anelastic structure of Mars from InSight seismic data. *Nature Geoscience*,
503 <https://doi.org/10.1038/s41561-020-0536-y>.
- 504 Marteau E, Golombek M, Vrettos C, Garvin JB, Williams NR (2021). Soil mechanical properties at the
505 InSight landing site, Mars. In: 52nd Lunar and Planetary Science Conference, abstract #2067, Houston.
- 506 Marteau E, Golombek M, Vrettos C, Delage P, Williams NR, Ansan V (2022). Soil strength properties
507 derived from scraping and dumping activities at the InSight landing site on Mars. In: 53rd Lunar and
508 Planetary Science Conference. Abstract #1523, Houston.
- 509 Marteau E, Golombek M, Delage P, Vrettos C, Hurst K, Gomez A et al. (2023). Initial results from the
510 Insight lander robotic arm soil mechanics experiments on Mars. 54th Lunar and Planetary Science
511 Conference. Abstract #1597, Houston.
- 512 Morgan, P., Grott, M., Knapmeyer-Endrun, B., Golombek, M., Delage, P., Lognonné, P. et al. (2018). A
513 pre-landing assessment of regolith properties at the InSight landing site. *Space Science Reviews*,
514 214(6), 1-47.
- 515 Mohsin, A. K. M. and Airey D. W. (2003): Automating Gmax measurement in triaxial test. Deformation
516 characteristics of Geomaterials, Proceedings 3rd International Symposium IS Lyon. Balkema, Lyon,
517 73-80.

- 518 Murillo, C. A., Thorel, L. and Caicedo, B. (2009). Spectral analysis of surface waves method to assess shear
 519 wave velocity within centrifuge models. *Journal of Applied Geophysics*, 68(2), 135–145.
 520 <https://doi.org/10.1016/j.jappgeo.2008.10.007>
- 521 Murillo, C., Sharifipour, M., Caicedo, B., Thorel, L. and Dano, C. (2011). Elastic parameters of
 522 intermediate soils based on bender-extender elements pulse tests. *Soils and Foundations*, 51(4), 637-
 523 649.
- 524 Nakagawa, K., Soga, K. & Mitchell, J. K. (1996). Pulse transmission system for measuring wave
 525 propagation in soils. *J. Geotech. Engng Div., ASCE* 122(4), 302–308.
- 526 Newland, P. L. and Allely, B. H. (1959). Volume changes during undrained triaxial tests on saturated
 527 dilatant granular materials. *Géotechnique*, 9(4), 174–182.
- 528 Prasad, M. (2002). Acoustic measurements in unconsolidated sands at low effective pressure and
 529 overpressure detection. *Geophysics*, 67(2), 405–412. <https://doi.org/10.1190/1.1468600>
- 530 Posiolova, L. V., Lognonné, P., Banerdt, W. B., Clinton, J., Collins, G. S., Kawamura, T. et al. (2022).
 531 Largest recent impact craters on Mars: Orbital imaging and surface seismic co-investigation. *Science*,
 532 378(6618), 412-417.
- 533 Seiferlin K., Ehrenfreund P., Garry J., Gunderson K., Hütter E., Karg G. et al. (2008). Simulating Martian
 534 regolith in the laboratory. *Planetary and Space Science* 56: 2009 – 2025
- 535 Shirley, D. J. and Hampton, L. D. (1978). Shear-wave measurements in laboratory sediments. *The Journal*
 536 *of the Acoustical Society of America*, 63(2), 607-613. <http://acousticalsociety.org/content/terms>.
- 537 Spohn, T., Grott, M., Smrekar, S. E., Knollenberg, J., Hudson, T. L., Krause, C. et al. (2018). The Heat
 538 Flow and Physical Properties Package (HP3) for the InSight Mission. In *Space Science Reviews* (Vol.
 539 214, Issue 5). The Author(s). <https://doi.org/10.1007/s11214-018-0531-4>
- 540 Spohn, T., Hudson, T. L., Marteau, E., Golombek, M., Grott, M., Wippermann, T. et al. (2022a). The
 541 InSight HP3 Penetrator (Mole) on Mars: Soil Properties Derived From the Penetration Attempts and
 542 Related Activities. *Space Science Reviews* (2022) 218:72, [https://doi.org/10.1007/s11214-022-00941-](https://doi.org/10.1007/s11214-022-00941-z)
 543 [z](https://doi.org/10.1007/s11214-022-00941-z)
- 544 Spohn, T., Hudson, T. L., Witte, L., Wippermann, T., Wisniewski, L., Kedziora, B. et al. (2022b). The
 545 InSight-HP³ mole on Mars: Lessons learned from attempts to penetrate to depth in the Martian soil.
 546 *Advances in Space Research*, 69(8), 3140-3163, doi :10.1007/s11214-022-00941-z.
- 547 Suwal, L. P. and Kuwano, R. (2013). Statically and dynamically measured Poisson's ratio of granular soils
 548 on triaxial laboratory specimens. *Geotechnical Testing Journal*, 36(4), 493-505.
- 549 Verdier N., Ansan V., Delage P., Ali K.S., Beucler E., Charalambous C. et al. (2023). Using wind dispersion
 550 effects during the InSight tether burial activities to better constrain the regolith grain size distribution.
 551 Revised version submitted, *Journal of Geophysical Research – Planets*.

- 552 Viggiani, G. and Atkinson, J. H. (1995a). Stiffness of fine-grained soil at very small strains. *Géotechnique*,
553 45(2), 249–265.
- 554 Viggiani, G. and Atkinson, J. H. (1995b). Interpretation of bender element tests. *Géotechnique*, 45(1), 149–
555 154.
- 556 Vilhar, G. & Jovičić, V., (2009). Measurement And Interpretation Of The Small Strain Stiffness Of Boštanj
557 Silty San. *Acta Geotechnica Slovenica*. 6(2), 57-75
- 558 Wang, Y., Benahmed, N., Cui, Y. J. and Tang, A. M. (2017). A novel method for determining the small-
559 strain shear modulus of soil using the bender elements technique. *Canadian Geotechnical Journal*,
560 54(2), 280–289. <https://doi.org/10.1139/cgj-2016-0341>
- 561 Warner N. H., M. P. Golombek , V. Ansan, E. Marteau , N. Williams , J. A. Grant et al. (2022). In Situ and
562 Orbital Stratigraphic Characterization of the InSight Landing Site—A Type Example of a Regolith-
563 Covered Lava Plain on Mars. *Journal of Geophysical Research – Planets*, doi 10.1029/2022JE007232
- 564 Zimmer, M., Prasad, M., & Mavko, G. (2002). Pressure and porosity influences on V_P - V_S ratio in unconsolidated
565 sands. *The Leading Edge*, 21(2):178-183, <https://doi.org/10.1190/1.1452609>.

566

567 **Open Research**

568 All the Waveform data csv files from the Bender Element measurements performed on the four
569 samples, used for wave velocity calculations in the study are available at the public MRA-
570 Bender-element-repository repository (Castillo-Betancourt Juan Pablo. (2023)). Instructions may
571 be found on the “README” file of the repository.

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Appendix A: Methodology for travel time determination

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A Matlab script was developed to enable accurate and quick identification of the departing and arrival times on a considerable amount of data within a reasonable timeframe (about 150 waves were acquired in each of the four experimental programs, with a total of 1200 wave measures to analyse).

The MATLAB script allows to simultaneously consider up to three methodologies for identifying the departing and arrival times. The procedure identifies local maximum, minimum and zero values, that make up the potential points of interest of the signal (shown in Figure A1). This identification is an automatic initialisation method of suggested arrival and departure points. To achieve this, the following procedure was implemented.

- Initially, a set of candidates for local maximums and minimums is established after evaluating the sign function of numerically calculated derivatives between every point in the signal and its surrounding neighbours. This procedure is a recursive method based on a parameter selected to determine an adequate number of points (seeking to not saturate the visual interface with too many choices of potential candidate points).

- After that, the search is widened from each candidate point by following the curve up to the previous existing inflection point (or the beginning of the signal, should it be the case). A new candidate point is then proposed.

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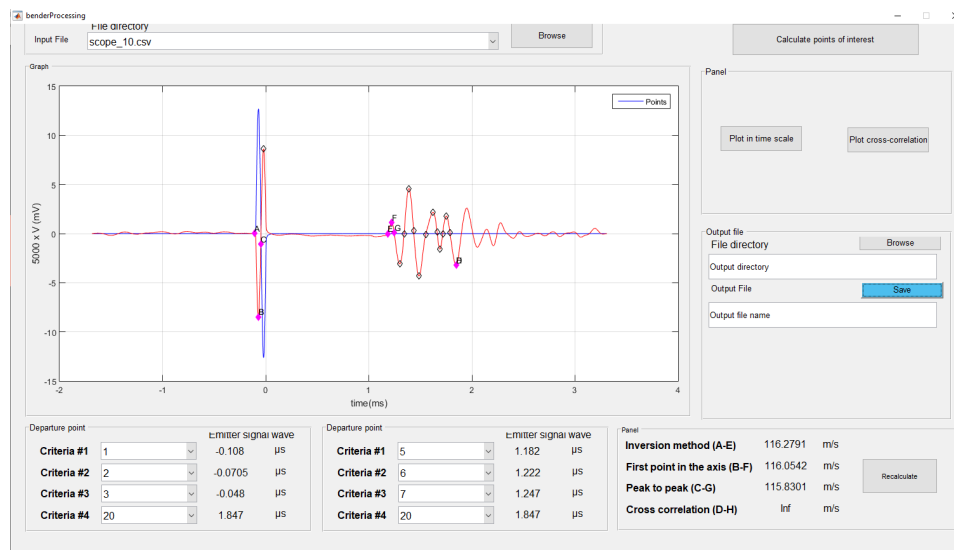
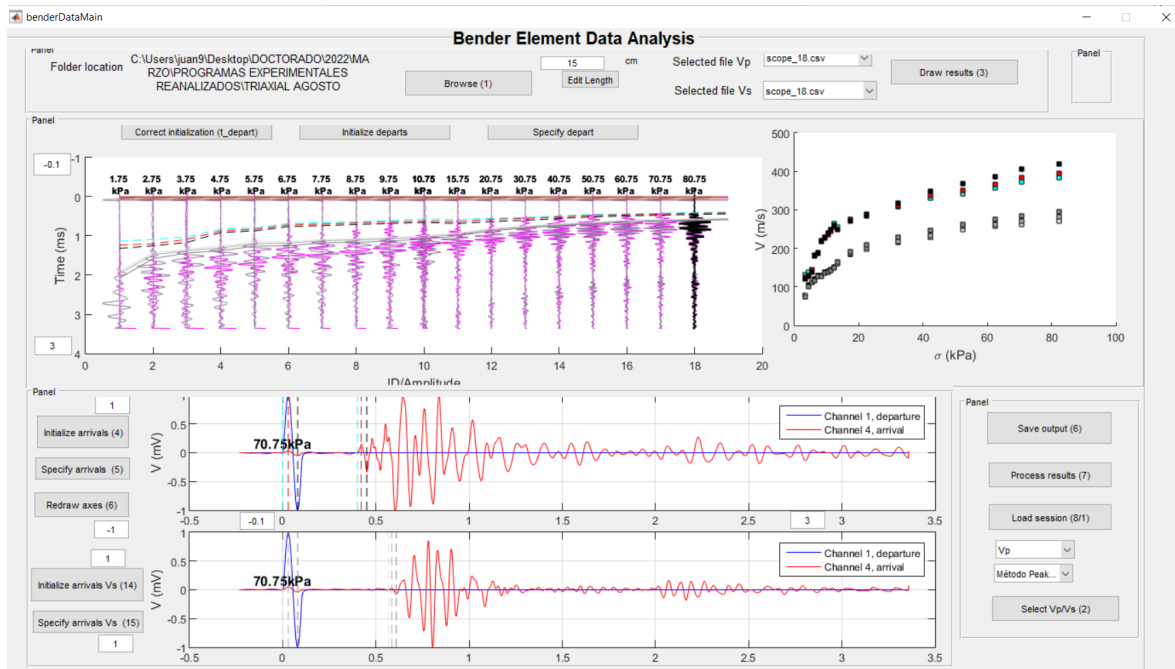


Figure A1. The interface of the Matlab script for single wave data analysis.

596 The script also allows simultaneous visualisation of the waves under various confining stresses, as
 597 seen in Figure A2. All the signals acquired at the same stress value are averaged to account for
 598 variability and repeatability. By observing all the measures, the user can choose the time arrival
 599 points by clicking on a visual interface.



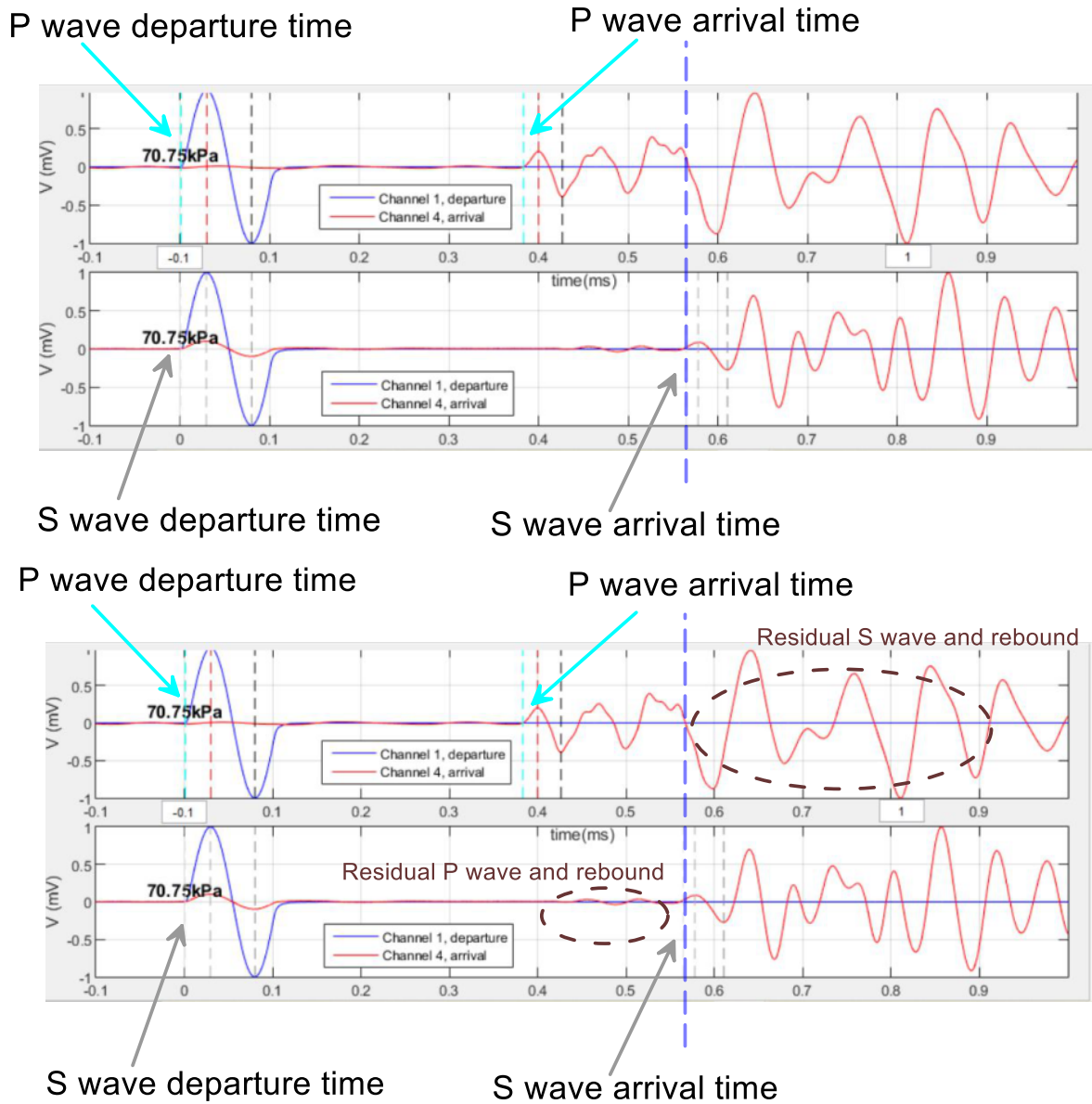
600

601 Figure A2. Interpretation script showing all waves measured at different stresses.

602 Proper signal visualisation is critical when using Wang's arrival time approach, because it requires
 603 viewing P and S waves simultaneously on the same timescale, as seen in Figure A2. In contrast to
 604 usual methods like peak-to-peak or arrival-to-arrival, a matching of P and S wave signals are
 605 compared. While determining the P wave arrival time is relatively simple (the choice is given by
 606 the first departure of the signal from the zero axis in the P signal), Wang's criterion indicates that
 607 the location of the S wave arrival time correspond to the peak of the "initial main excursion in the
 608 opposite direction of movement compared to that of the S-wave received signal". This means that
 609 the first sizeable negative peak in S wave will characterise the S wave arrival time. Choosing this
 610 last peak can often be a challenge and the associated P wave hence allows an objective and
 611 repeatable measurement. The chosen point for the S wave arrival time is to be found at the exact
 612 location when the first negative peak with considerable amplitude appears in the P wave signal,
 613 indicating the arrival of the S components produced by this P wave signal. This also implies that
 614 the motion registered in the S wave signal before the chosen time of arrival corresponds to the

615 faster P wave produced by the action of the bender that emitted the S wave and its rebounds on the
 616 sample walls.

617 Figure A3 shows an example of the waveforms acquired during one of the four experimental
 618 programs, along with lines marking the identified locations of the departure and arrival of the
 619 waves for the three utilised criteria.



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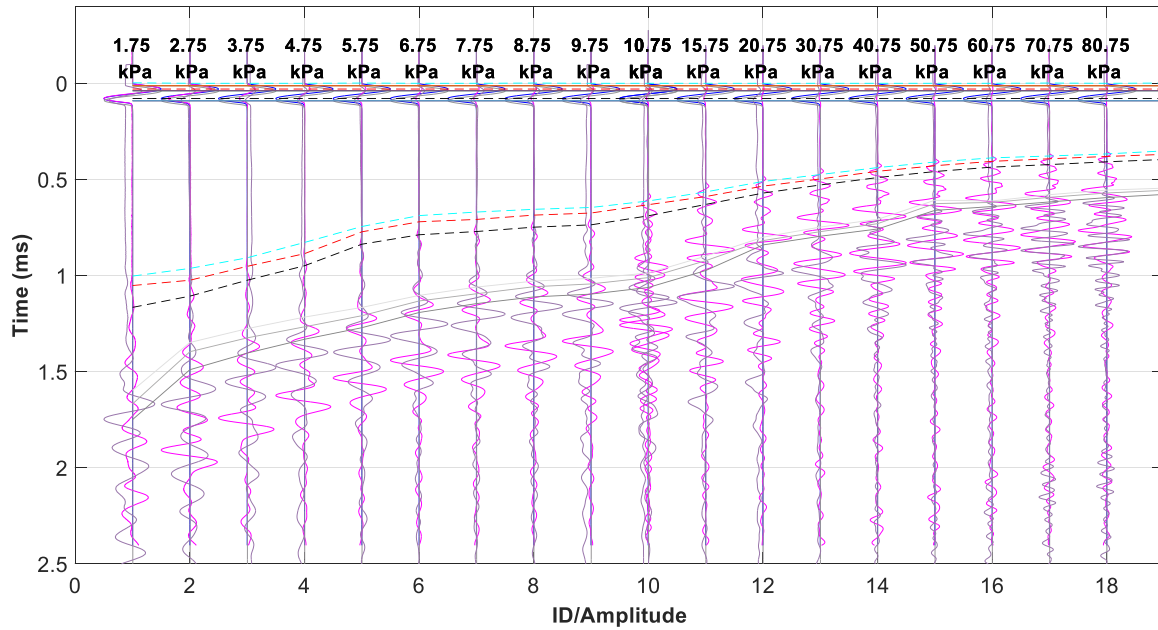
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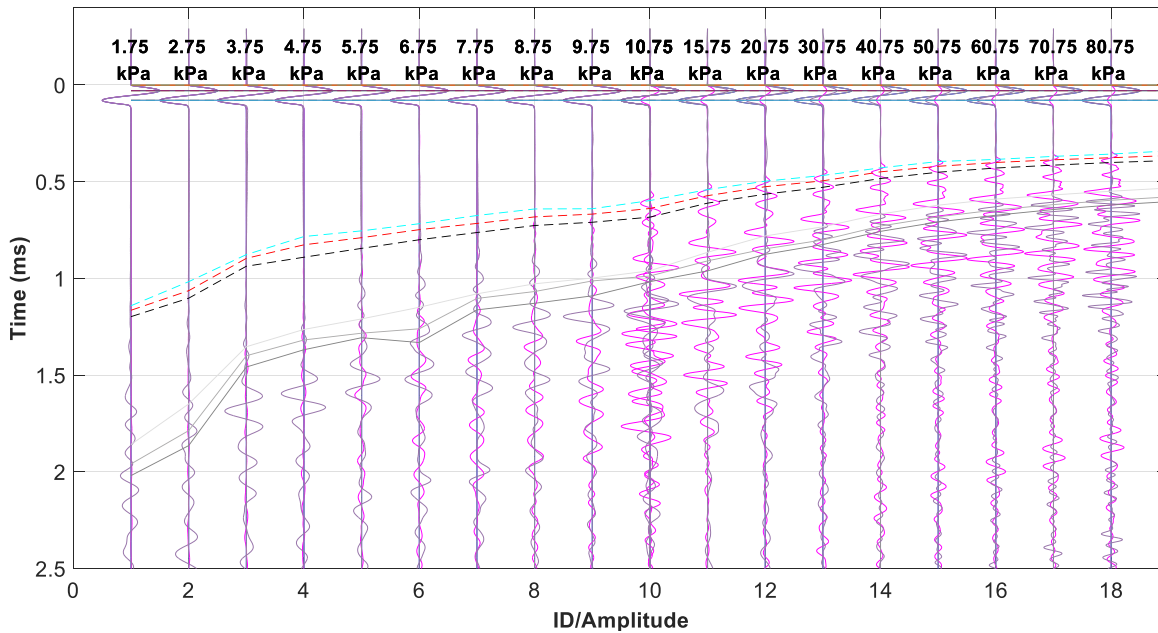
Figure A3. Simultaneous visualisation of the P and S waves following Wang’s method.

624 The following figures present the waves acquired during the other three experimental programs,
 625 along with the lines identifying the departure and arrival times for both P and S waves. The figures
 626 are shown as generated in the data processing tool built for data interpretation.



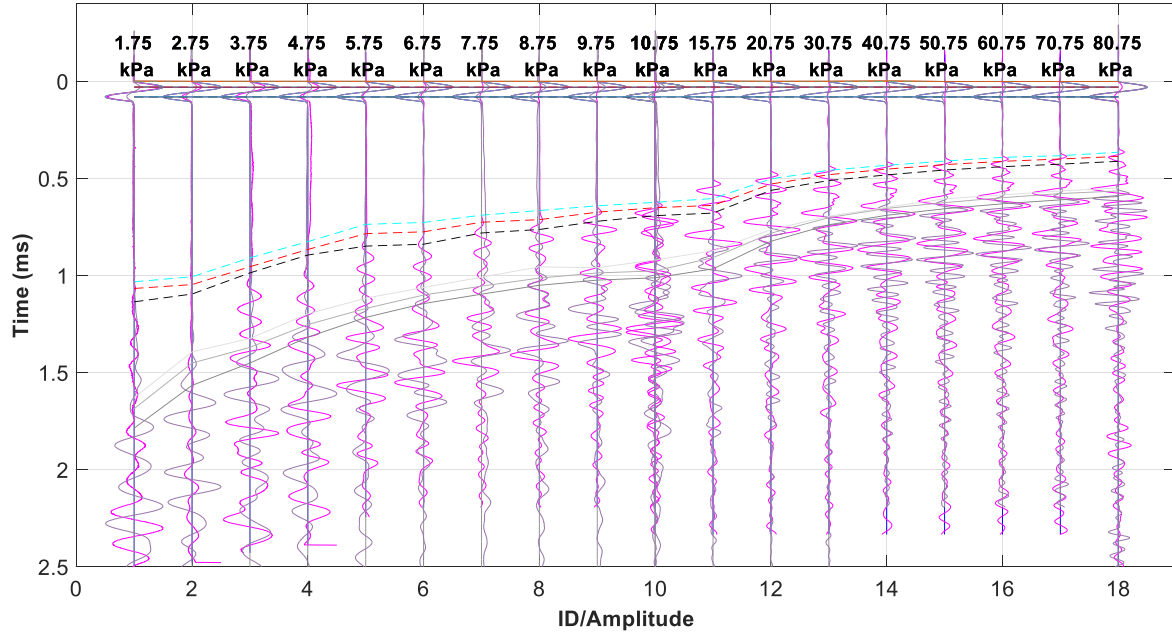
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Figure A4. Waves acquired on sample EP1. Depart and arrival times are indicated both for P and S waves.



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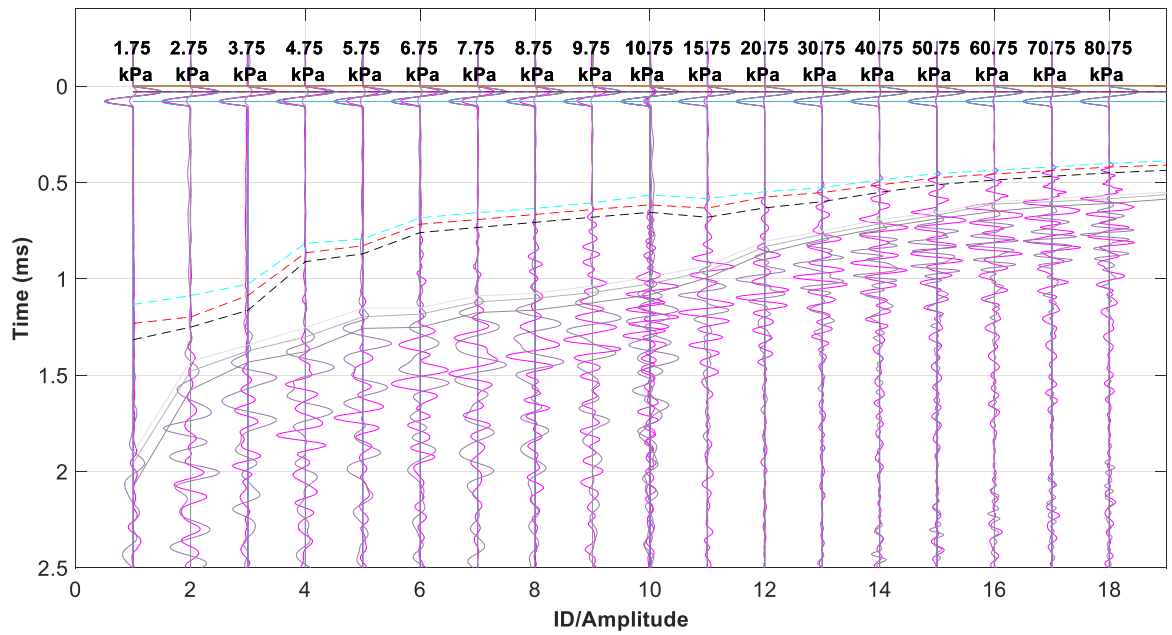
Figure A5. Waves acquired on sample EP2. Depart and arrival times are indicated both for P and S waves.



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634 Figure A6. Waves acquired on sample EP3. Depart and arrival times are indicated both for P and S waves.

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637 Figure A7. Waves acquired during on sample EP4. Depart and arrival times are indicated both for P and S
638 waves.