International Workshop on Advances in Laboratory Testing of Liquefiable Soils
Sıvılaşan Zeminlerde Laboratuvar Uygulamaları Uluslararası Çalıştayı
17 Eylül 2022
17 September 2022

Soil liquefaction assessment in undisturbed and reconstituted conditions: challenges and opportunities

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17 September 2022

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Outline

- Motivation
- Pilot site: location and geological setting
- Site investigation
- Advanced sampling techniques
- Laboratory test results
- Conclusions

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Motivation: Historical evidence of Earthquake-induced Liquefaction Damages (Lisbon, 1755)

Archiv für Kunst und Geschichte, Berlin

"Water bubbles burst in many places, it seemed that these come from the center of the Earth, because it brought black earth, white and black sand (...) only during the time that lasted the earthquake"

Main features:

- Strongly affected by the **1755** Lisbon earthquake

"Allegory to the 1755 Earthquake", by João Glama Stroberle

Motivation: Historical evidence of Earthquake-induced Liquefaction Damages (Benavente, Lisbon region, 1909)

“The water ejected through these openings came flooding certain areas and women raised their skirts because of the height of water”
(Tagus Valley, earthquake April 23, 1909)

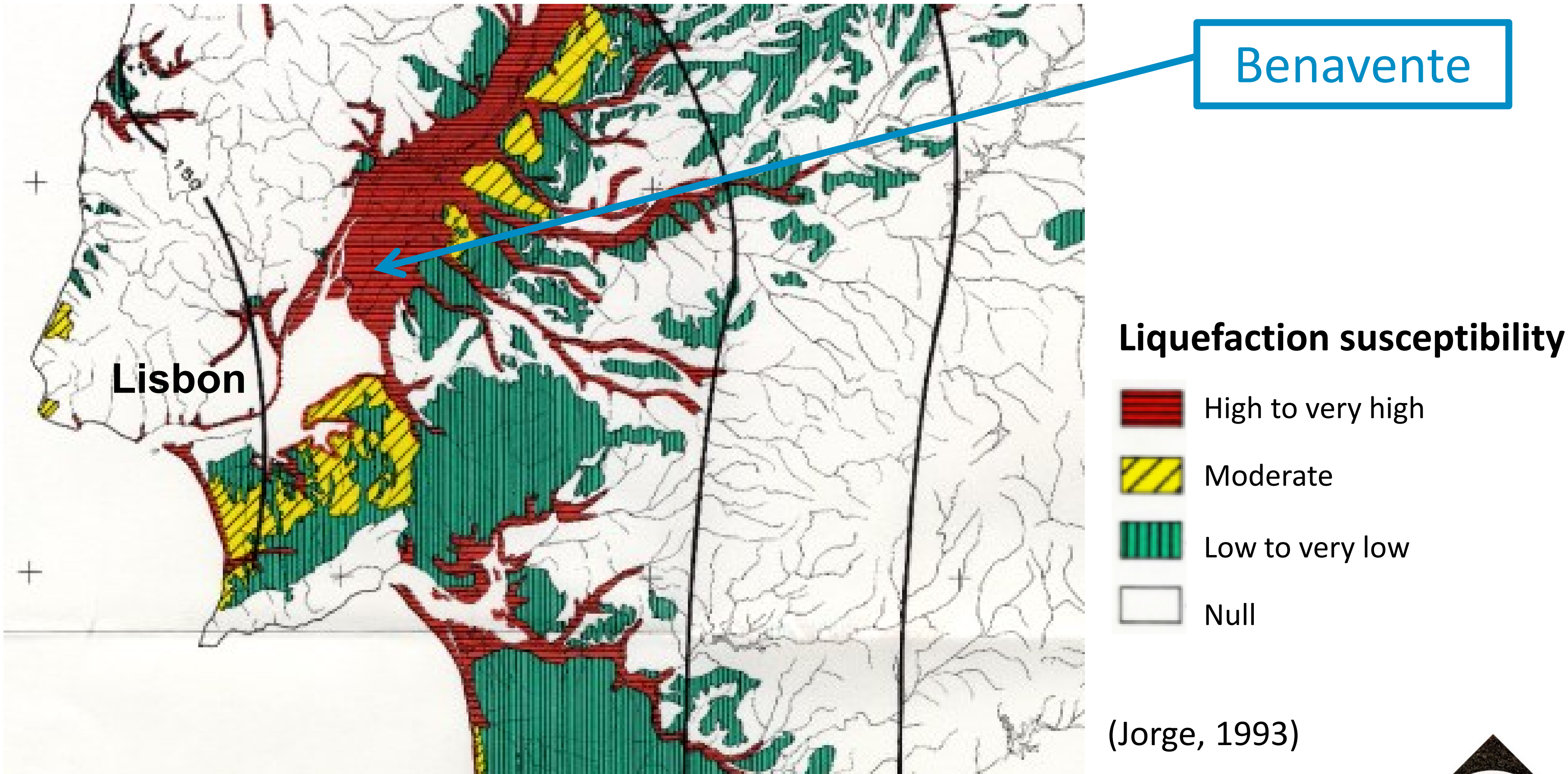
Main features:

- Epicentre of the 1909 earthquake
- **Evidence of liquefaction** in the 1909 earthquake

Sand boils

Evidence of liquefaction (Choffat & Bensaude, 1912)

Motivation: Liquefaction susceptibility in Portugal



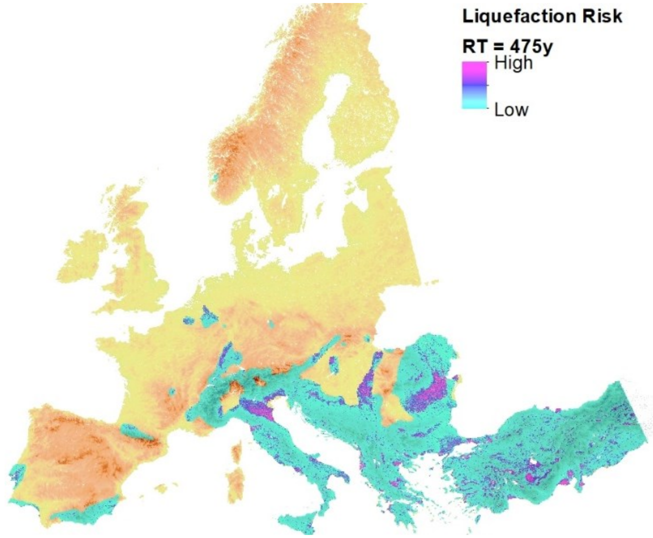
(Jorge, 1993)

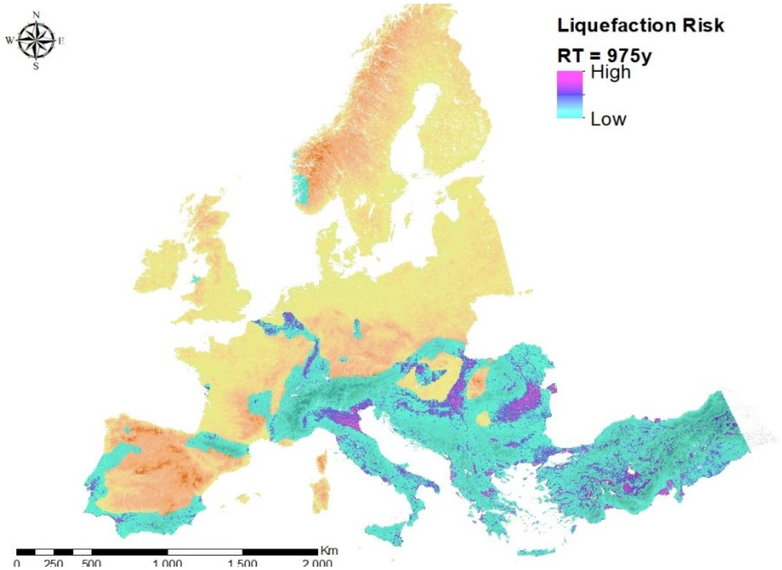
LIQUEFACT pilot sites

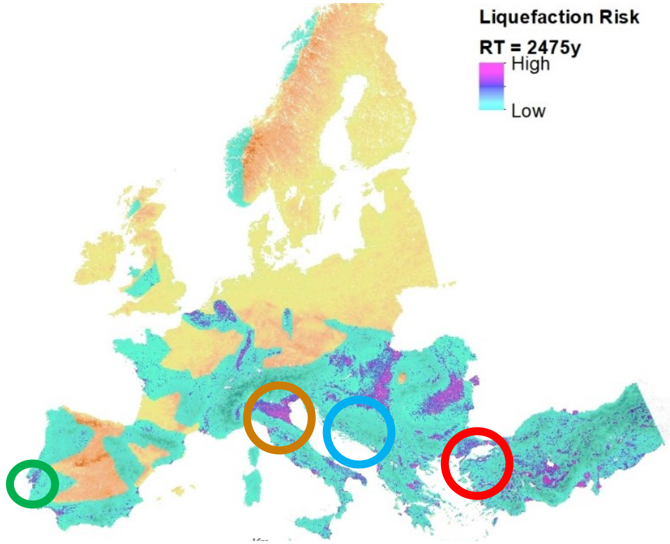
Macrozonation: Development of a European liquefaction hazard map

European Commission | Horizon 2020 European Union funding for Research & Innovation

liquefACT







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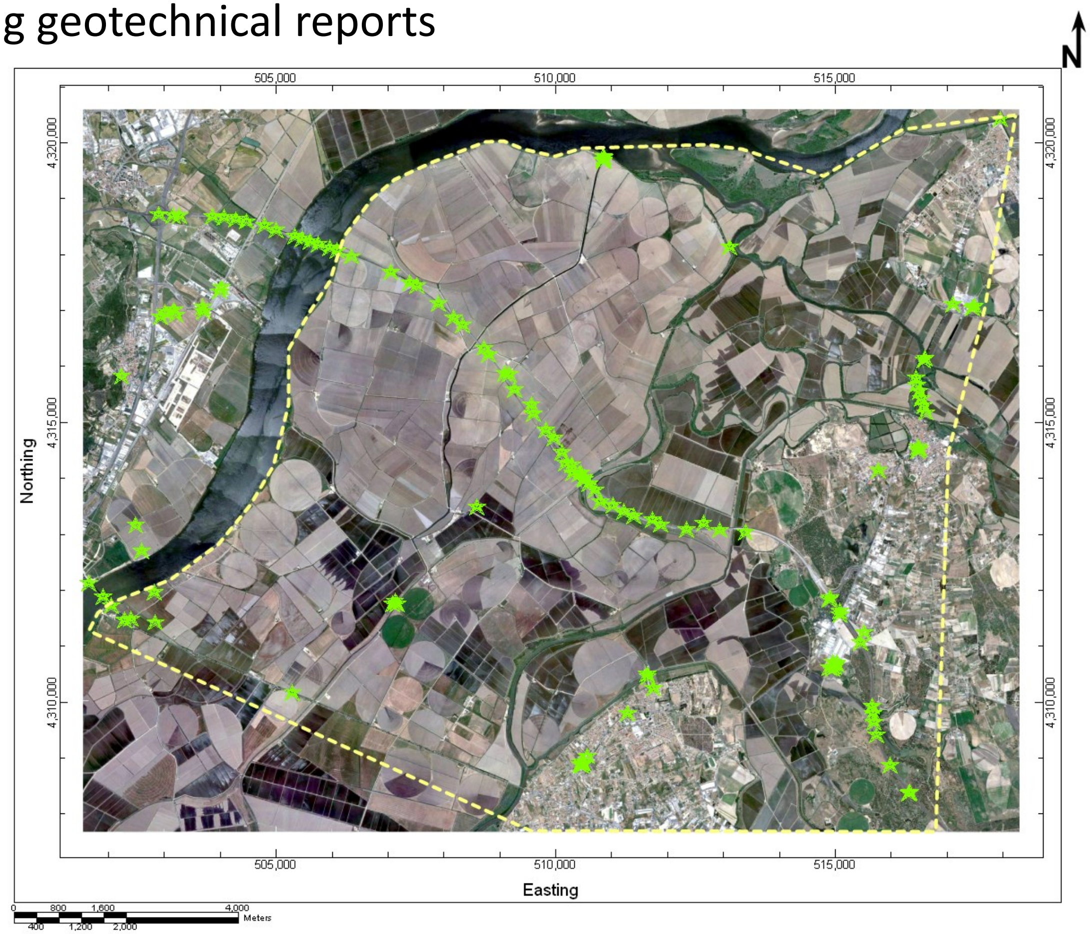
Pilot site: location

Lezíria Grande: farming region and mid-sized cities of Vila Franca de Xira & Benavente

Pilot site: existing data

Collection of existing geotechnical reports

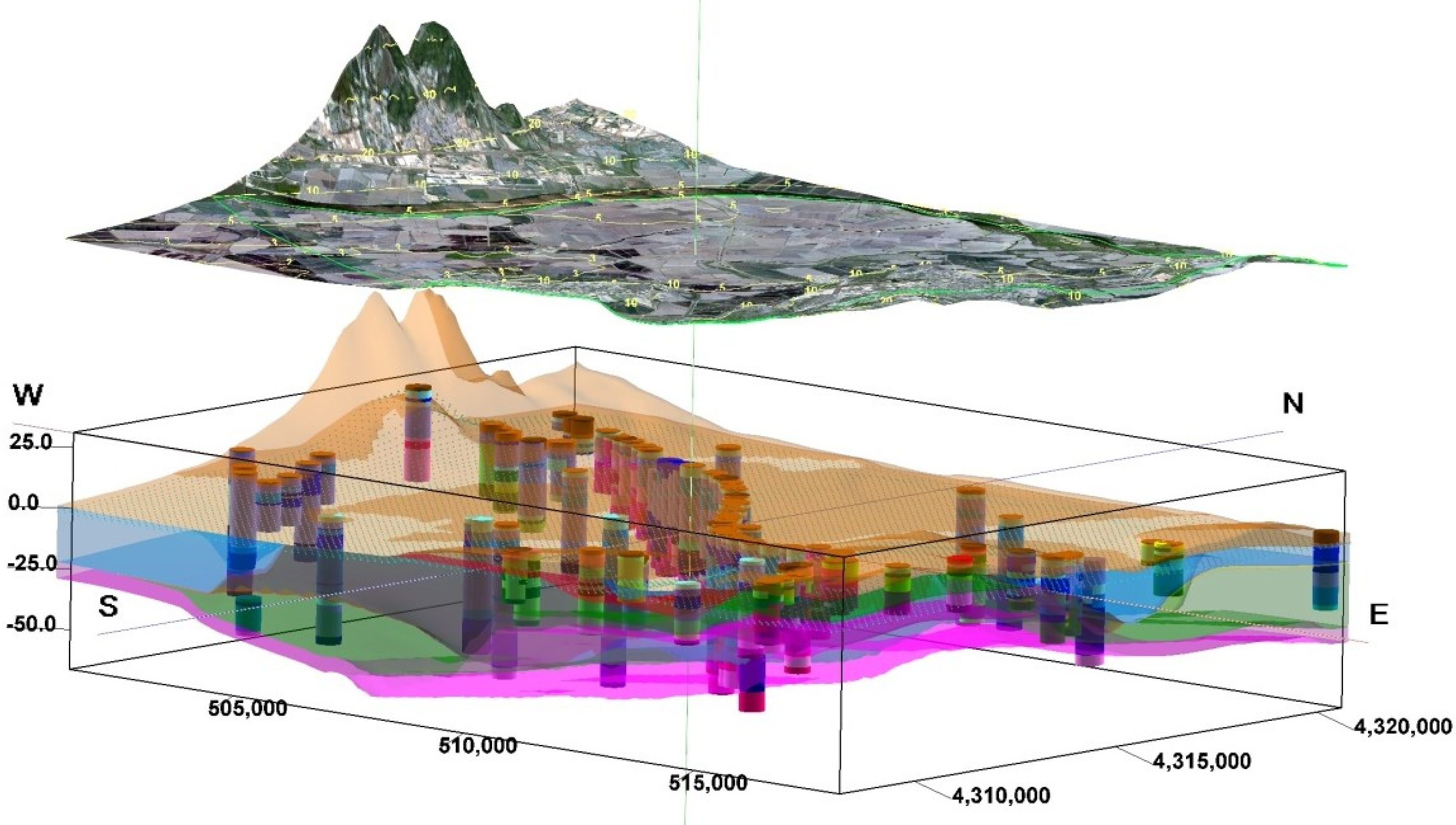


Pilot site: geological model

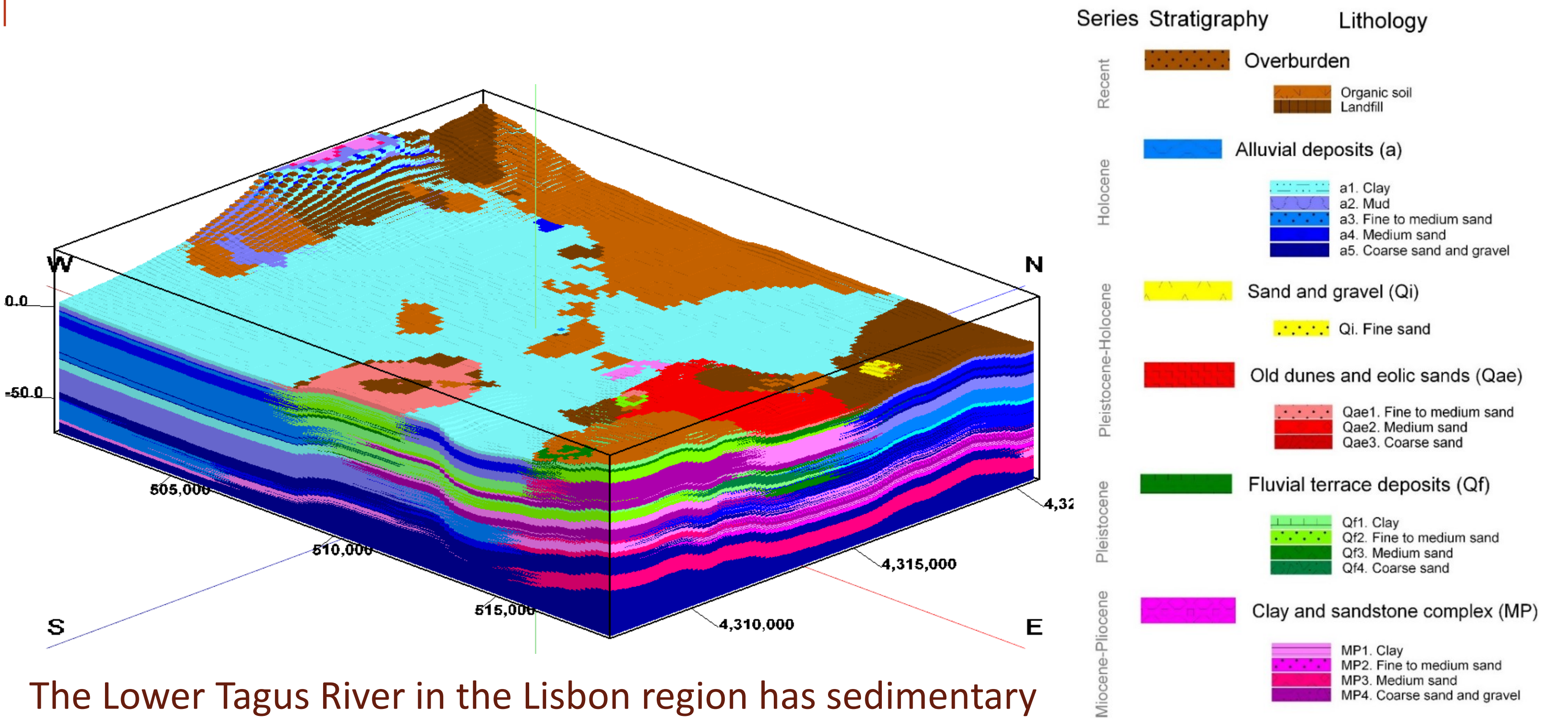
- The final Portuguese pilot site area for liquefaction microzonation studies has been defined.
- The polygon covers an area of 146.9 km^2.
- All available geological and geotechnical information has been georeferenced and integrated into a SQLite database using **Rockworks17®** application.
- The final database integrates 125 boreholes, 92 SPT, 53 CPT, 14 Cross-Hole, 9 SDMT, 13 SR, 1 SASW, 3 MASW and 52 HVSR.

Rockworks17®

Pilot site: topographic and geological model



Pilot site: geological setting



The Lower Tagus River in the Lisbon region has sedimentary deposits with high incidence of loose to medium sandy and silty-sandy soils, interbedded by soft fine soils

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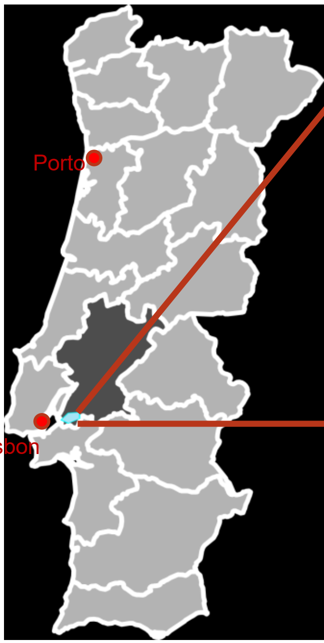
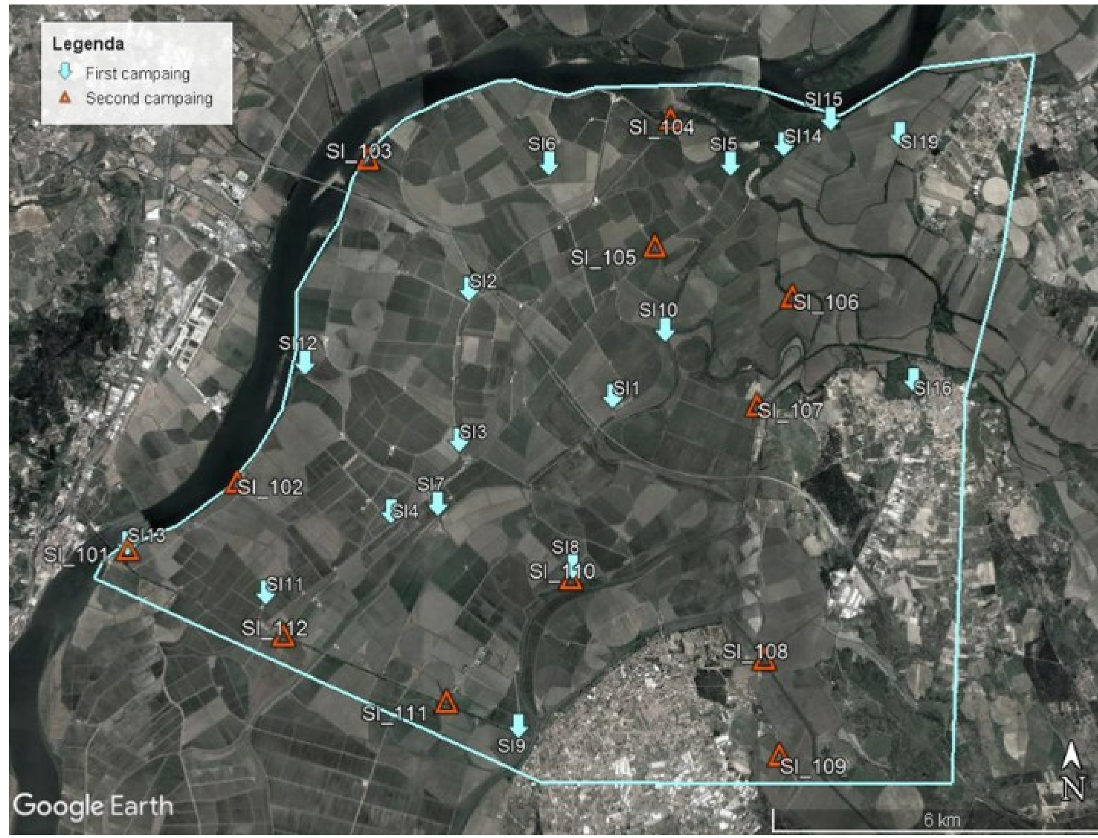
Pilot site: site investigation locations



Area: 14683 ha
Perimeter: 50.8 km
Site Investigation: 29

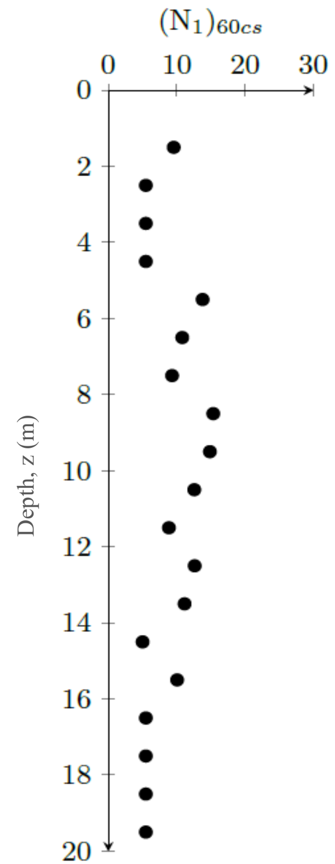


Pilot site: site investigation

Type		Number of tests	Location
Geotechnical tests	SPT	2	SI1; SI7
	CPTu	25	SI1, SI2, SI3, SI4, SI5, SI6, SI7, SI10 SI12, SI13, SI14, SI15, SI19, SI101, SI102, SI103, SI104, SI105, SI106, SI107, SI108, SI109, SI110, SI111, SI112
	DMT	10	SI1, SI7, SI8, SI9, SI15, SI16, SI17, SI106, SI109, SI111
Geophysical tests	SCPTu / SDMT	7	SI1, SI7, SI14, SI15, SI106, SI109, SI111
	SASW	1	SI5
	Cross-Hole	2	SI1; SI7
	Seismic Refraction	8	SI1, SI5, SI6, SI7, SI9, SI11, SI12, SI13
Sampling collection	Mazier	2 (24 samples)	SI1, SI7
	Dames & Moore	2 (32 samples)	SI14, SI15
	Gel-Push	6 (29 samples)	SI14, SI15

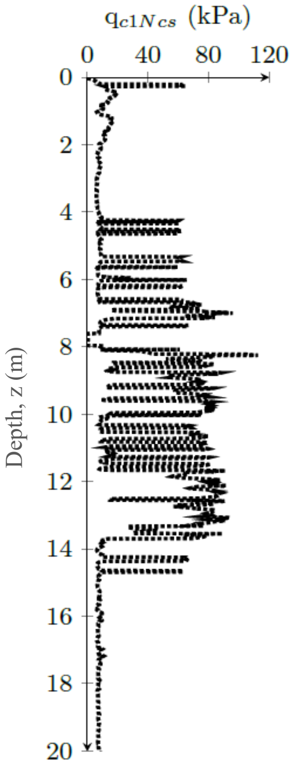
Site investigation results

In situ testing: SPT



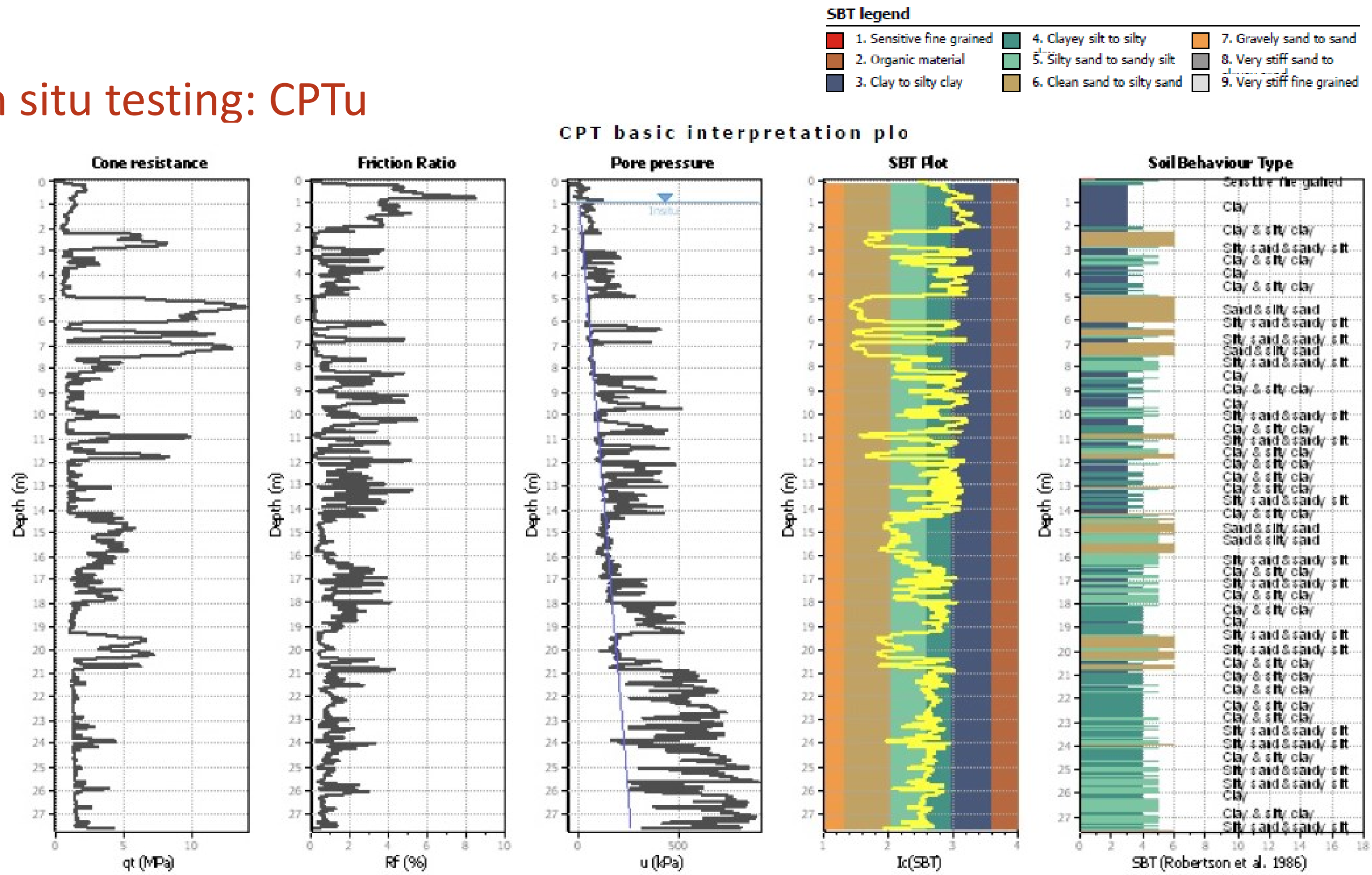
Site investigation results

In situ testing: CPTu



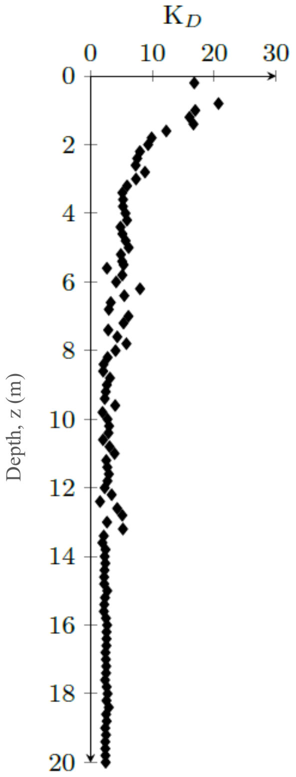
Site investigation results

In situ testing: CPTu



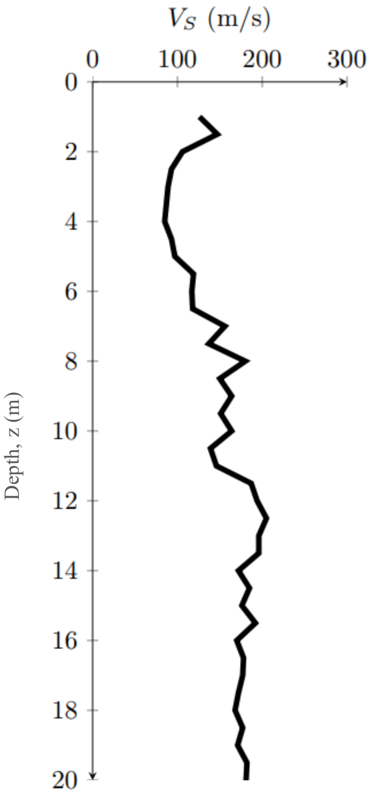
Site investigation results

In situ testing: DMT



Site investigation results

In situ testing: Geophysical tests (CH, SCPTu & SDMT)



Site investigation results

In situ testing allowed the identification of:

- Soil lithology (visual description and results variation)
- Strain-strength properties (correlations)
- Soil behaviour type (Robertson, 2009)
- Soil stiffness before sampling
- Liquefaction susceptibility (different methods)

Site investigation results

In situ testing: liquefaction assessment

$$FS_{liq} = \frac{CRR}{CSR}$$

CRR → Soil resistance → Different methods → Test results

CSR → Seismic action → $CSR = 0.65 \cdot \left(\frac{a_{max}}{g}\right) \cdot \left(\frac{\sigma_v}{\sigma'_v}\right) \cdot r_d$

Seed & Idriss (1971)

Seismic action → Parameters from Eurocode 8

Site investigation results

In situ testing: liquefaction assessment

CRR computation from in situ test data using the most recent methods

In situ test	Equation for $CRR_{7.5}$	Reference
SPT	$\exp\left[\left(\frac{(N_1)_{60cs}}{14.1}\right)+\left(\frac{(N_1)_{60cs}}{126}\right)^2-\left(\frac{(N_1)_{60cs}}{23.6}\right)^3+\left(\frac{(N_1)_{60cs}}{25.4}\right)^4-2.8\right]$	Boulanger and Idriss (2014)
CPTu	$\exp\left[\left(\frac{q_{c1Ncs}}{113}\right)+\left(\frac{q_{c1Ncs}}{1000}\right)^2-\left(\frac{q_{c1Ncs}}{140}\right)^3+\left(\frac{q_{c1Ncs}}{137}\right)^4-2.8\right]$	Boulanger and Idriss (2014)
DMT	$\exp\left[\left(\frac{5}{108}K_D\right)+\left(\frac{25}{67}K_D\right)^2-\left(\frac{5}{16}K_D\right)^3+\left(\frac{25}{114}K_D\right)^4-3\right]$	Robertson (2009)

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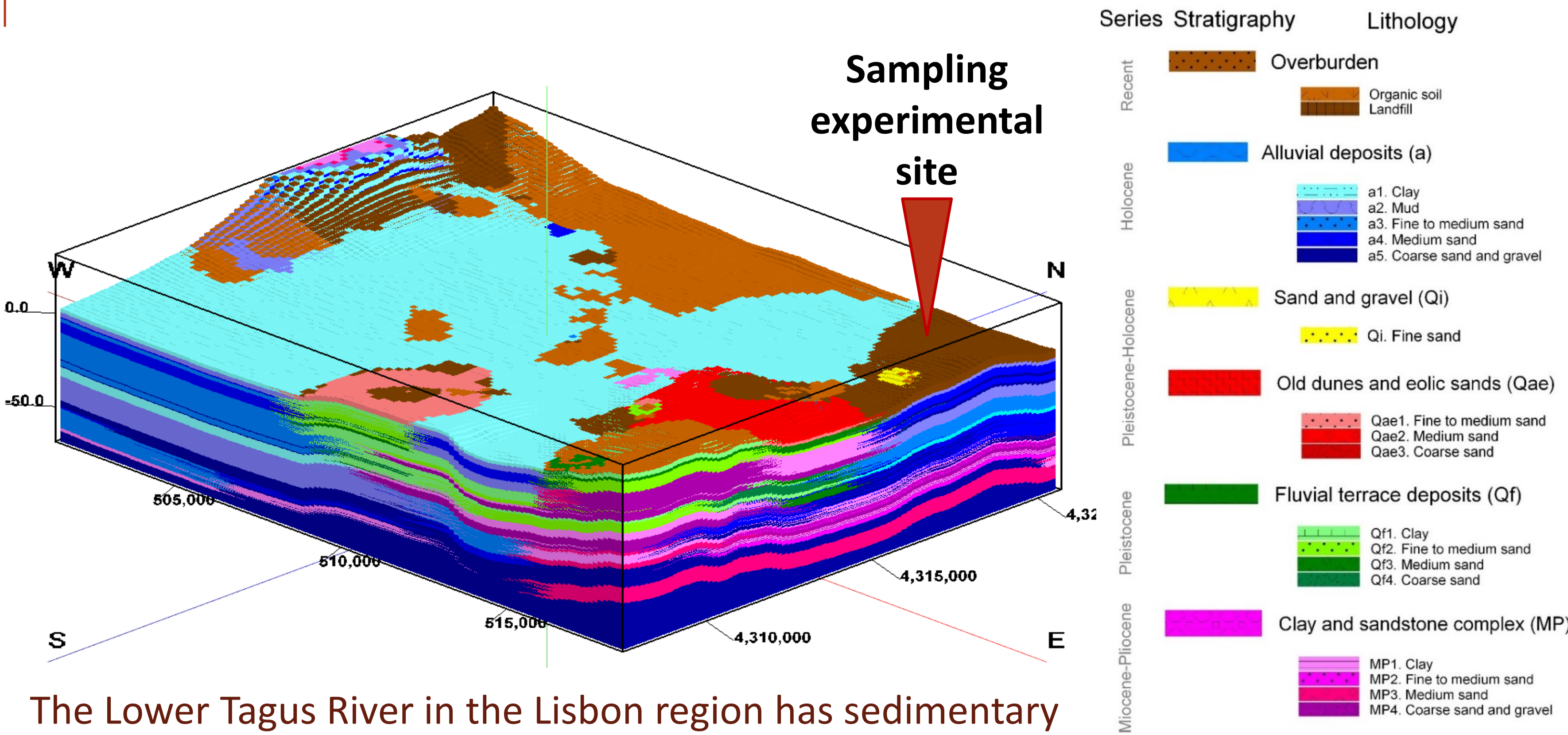
Sampling experimental site
Advanced sampling for undisturbed samples



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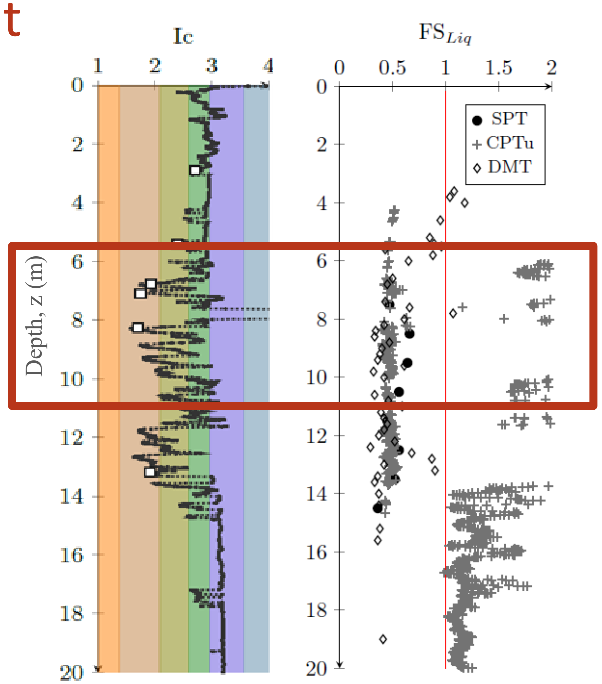
Site investigation results

In situ testing: liquefaction assessment

Interlayering
A correction for the presence of fines is required



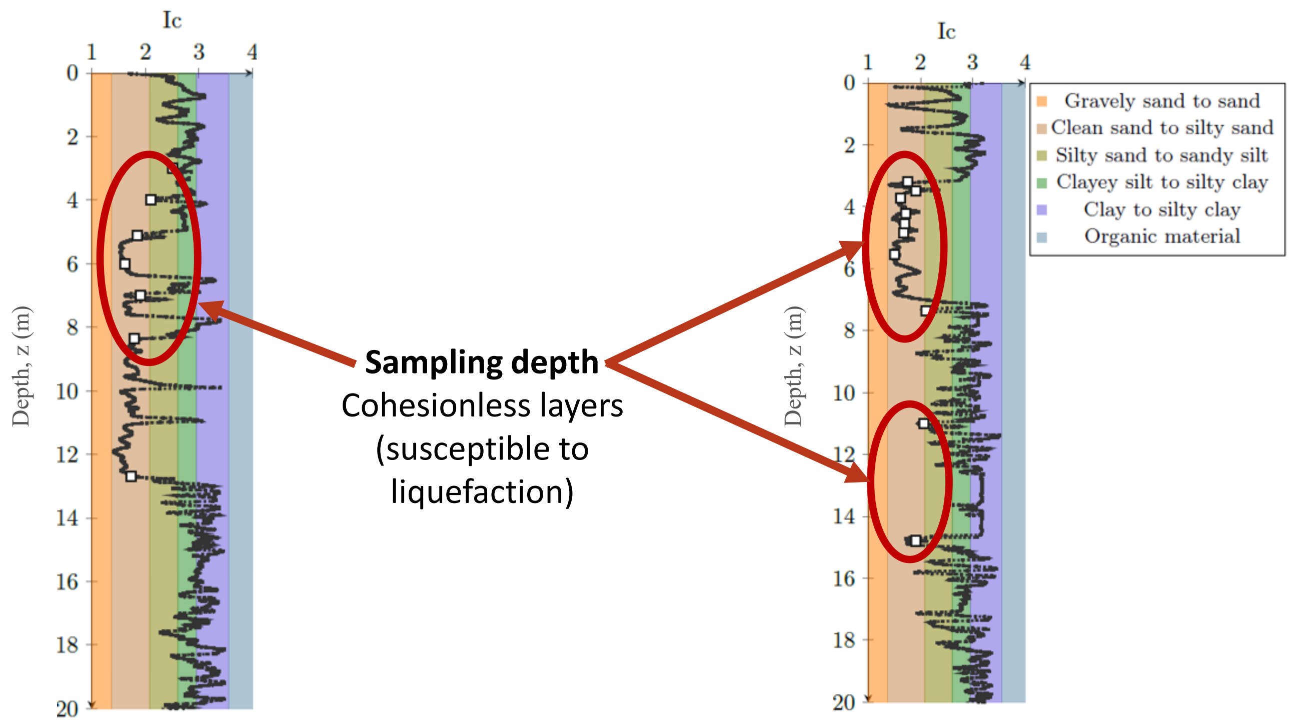
FINES CONTENT

- **SPT**: lab results
- **CPTu:** correlation
- **DMT:** correlation

Site investigation results

In situ testing: identification of liquefiable layers for sampling

Sampling at selected depths, considering the most susceptible to liquefaction triggering



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Advanced sampling techniques
Three different samplers

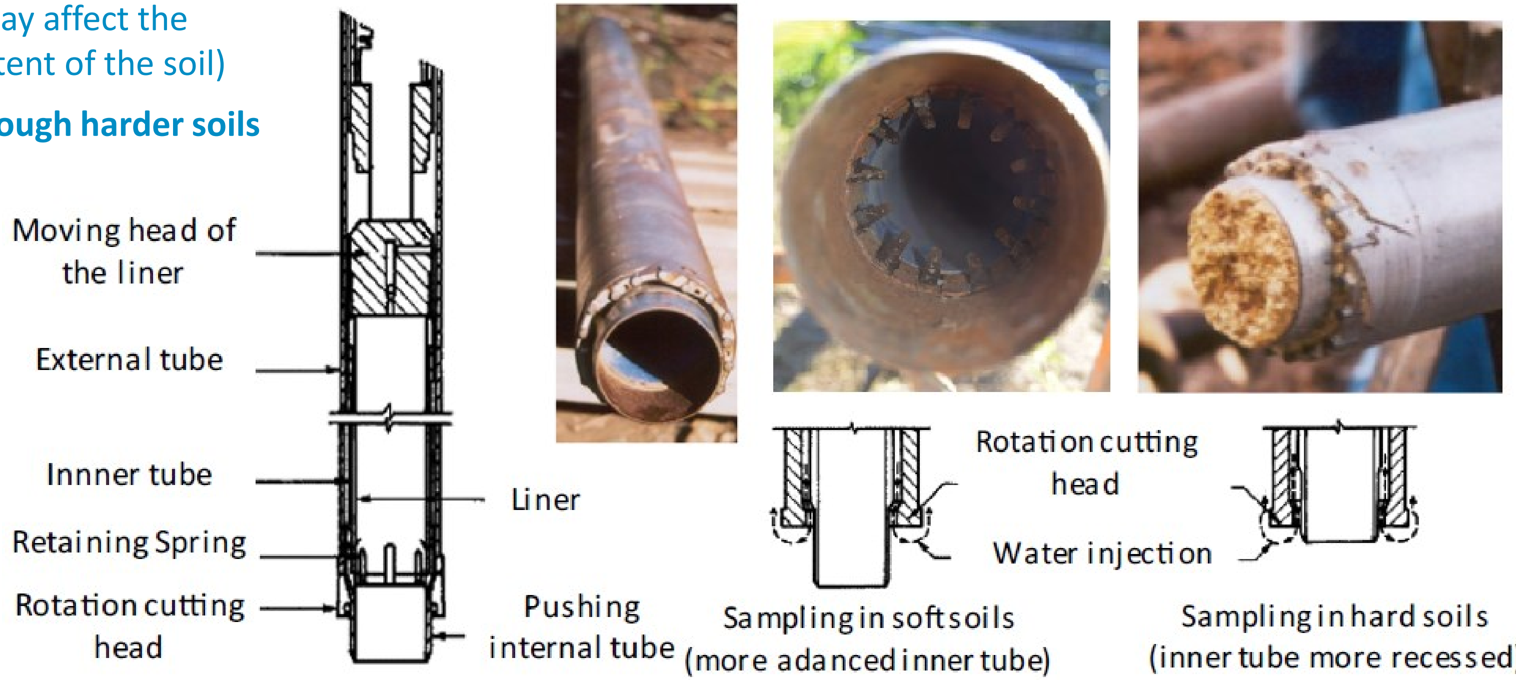
Mazier

Dames & Moore

Gel-Push

Advanced sampling techniques
Mazier sampler

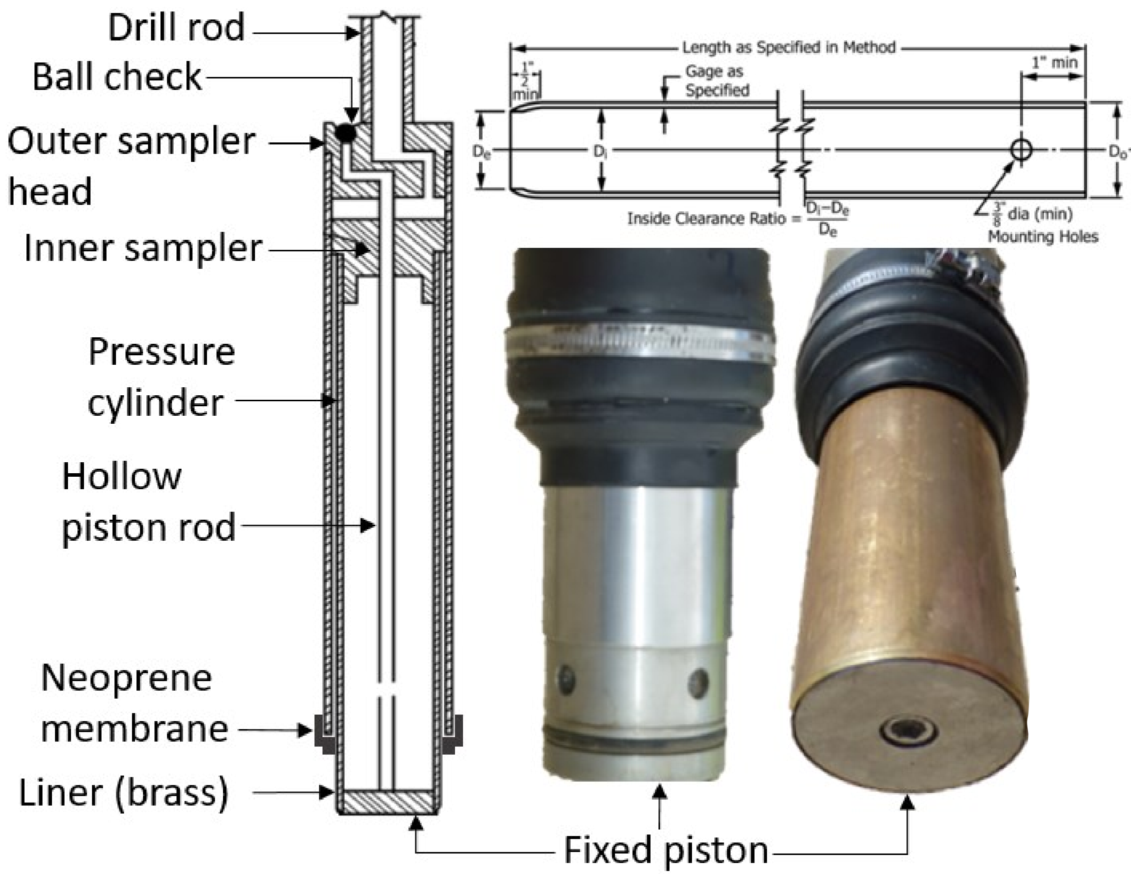
- **Rotary triple tube with a PVC liner**
- **Uses pumped water for drilling** (may affect the water content of the soil)
- **Drives through harder soils**



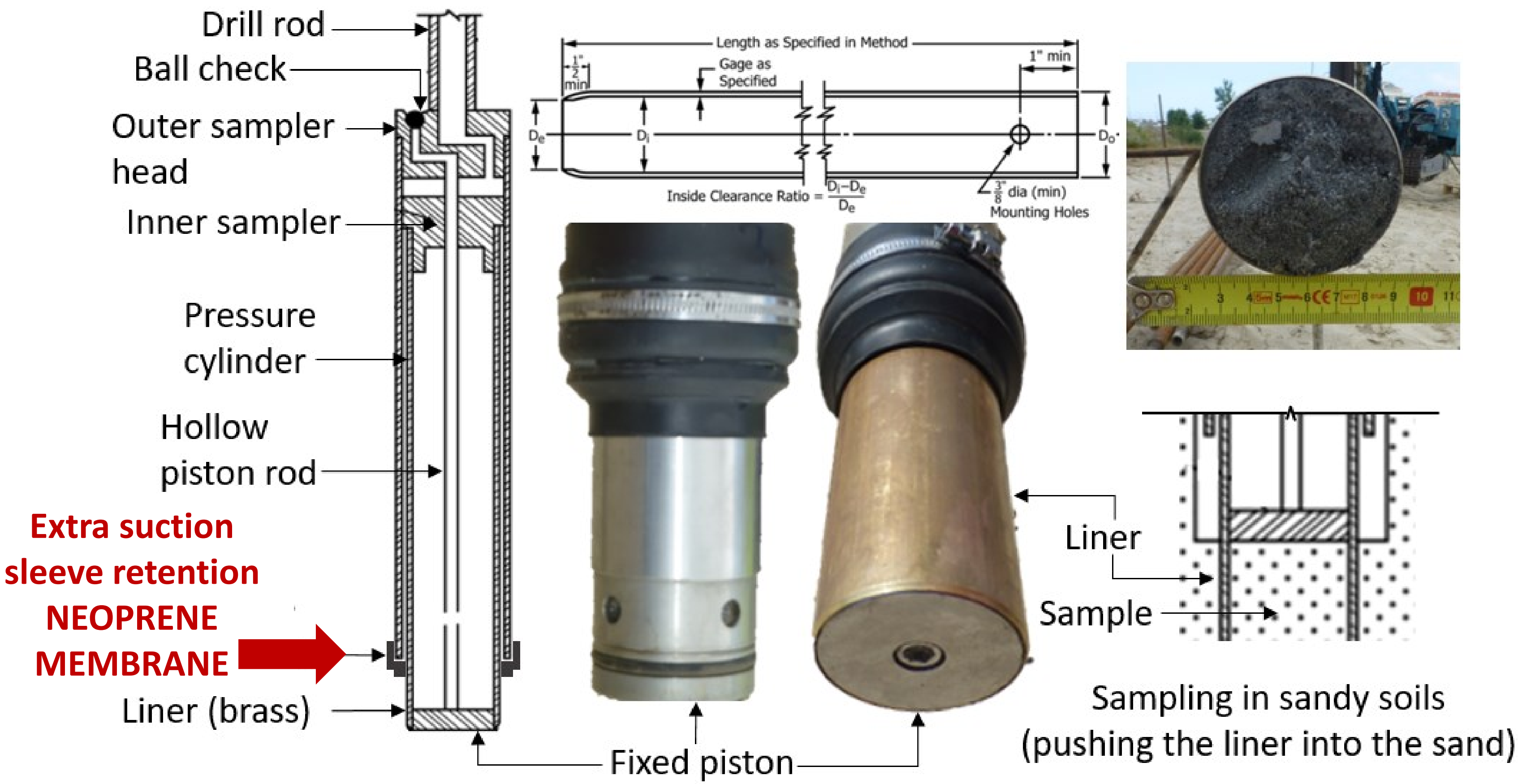
Advanced sampling techniques

Dames & Moore: an enhanced Osterberg sampler

- **Hydraulic activated fixed-piston** (Osterberg-type)
- **Smooth brass liner** (less friction between soil-liner)
- **Neoprene skirt seal to create vacuum during sampling** (lower risk of sample falling)

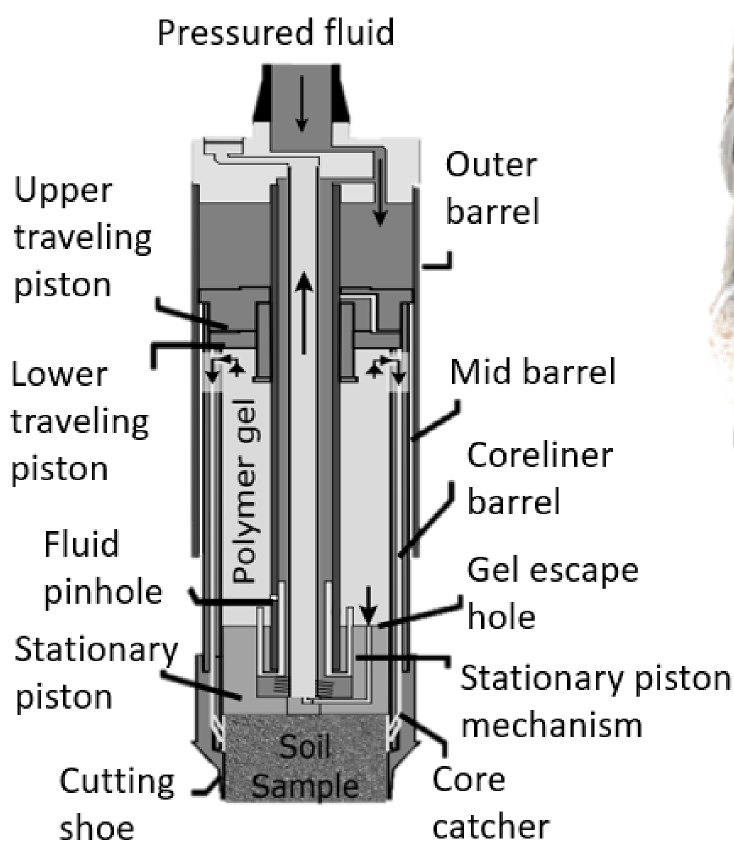


Advanced sampling techniques
Dames & Moore: an enhanced Osterberg sampler

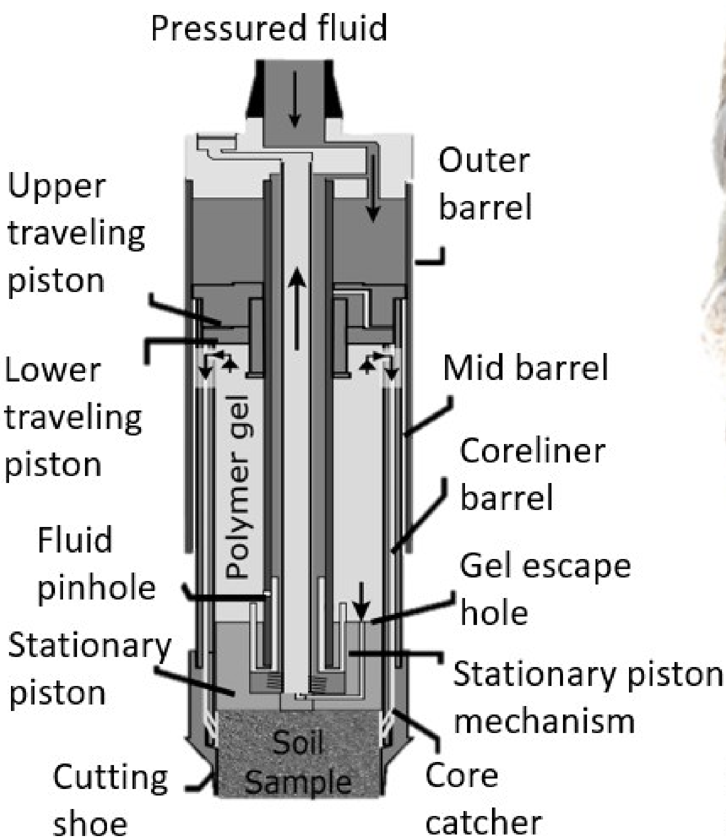


Advanced sampling techniques
Gel-push: a “step beyond” on push-in sampling

- **Uses a viscous polymer gel** (significant friction reduction between soil-liner)
- **Hydraulic activated fixed-piston**
- **Core catcher** (keeps the sample inside the liner)
- **Most advanced technique**



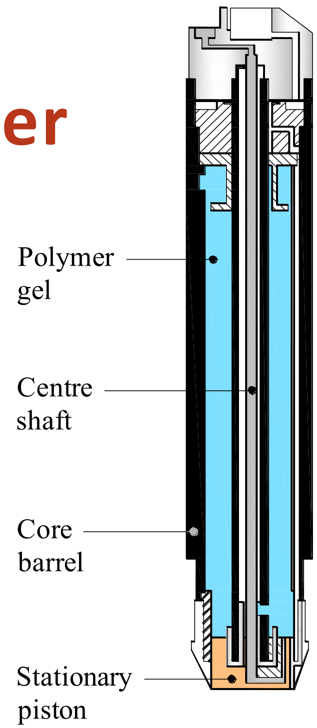
Advanced sampling techniques
Gel-push: a “step beyond” on push-in sampling

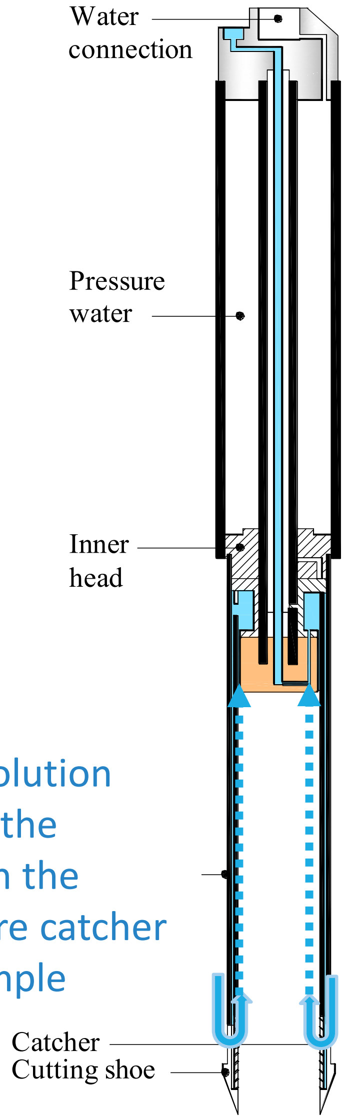


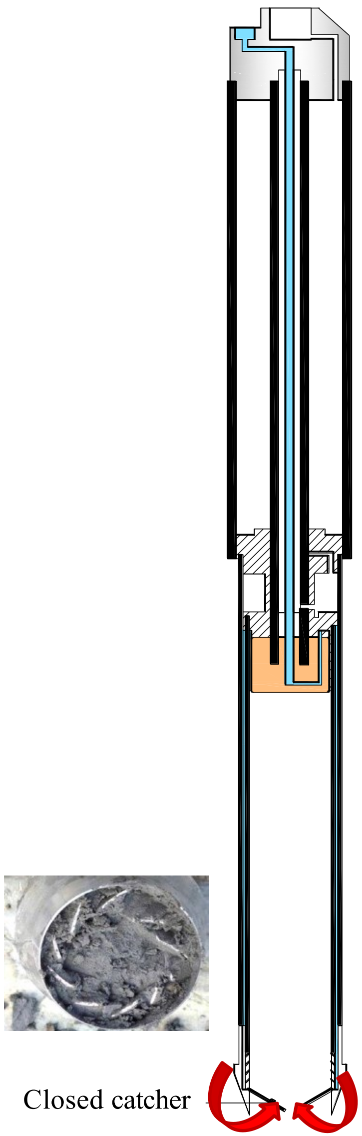
Polymer fall down after sampling

Gel-push sampler

Its success resides on the use of a polymer solution of extremely low viscosity

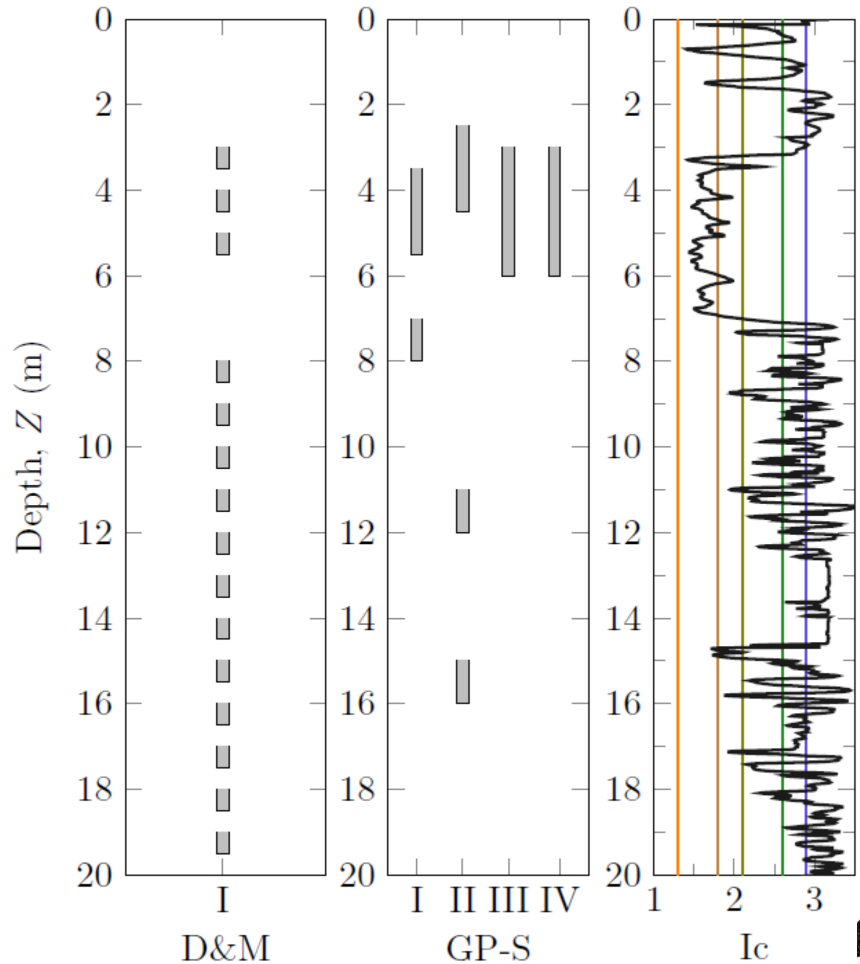




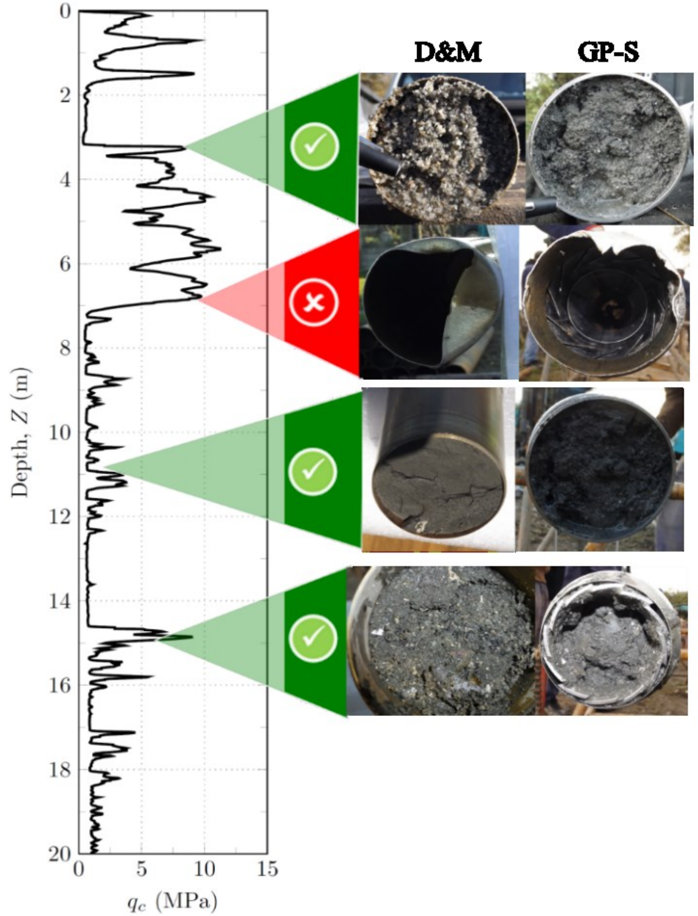


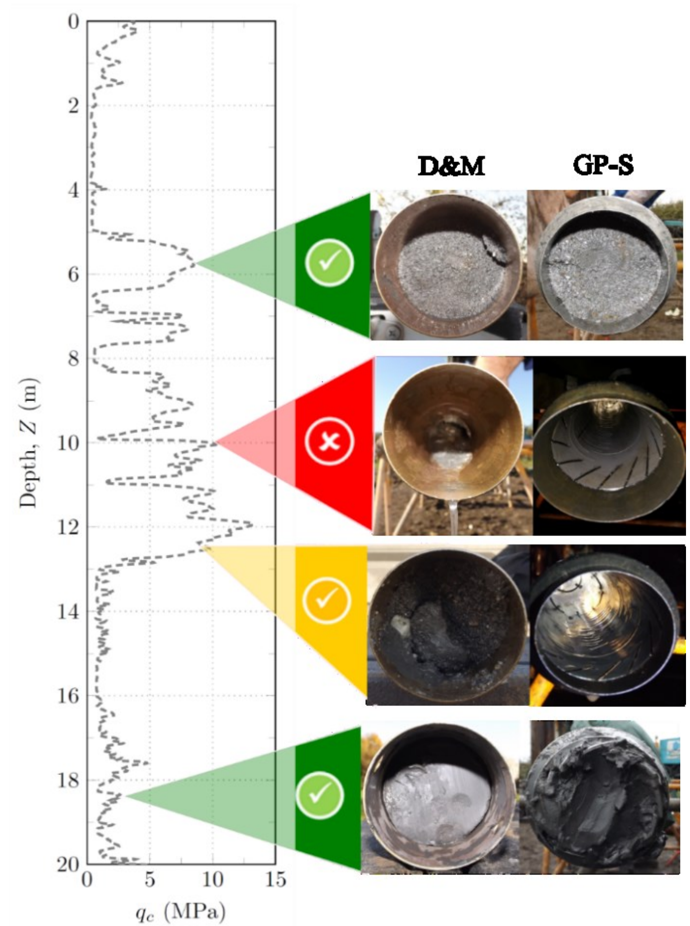
The polymer solution seeps through the narrow gaps on the sides of the core catcher to coat the sample

Sampling: Operation and recovery profile



Performance of sampling techniques



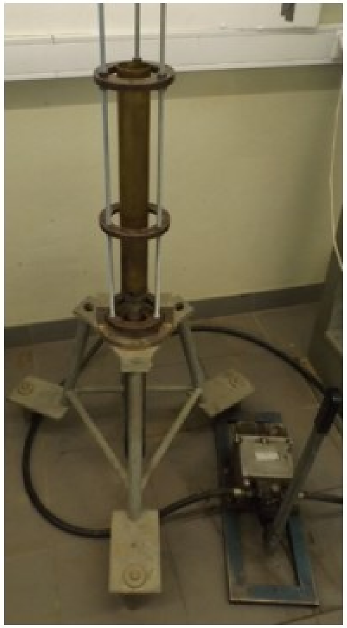


The recovery ratio of D&M ranged between 80% and 94%, whereas the recovery of GP-S ranged between 43% and 88%.

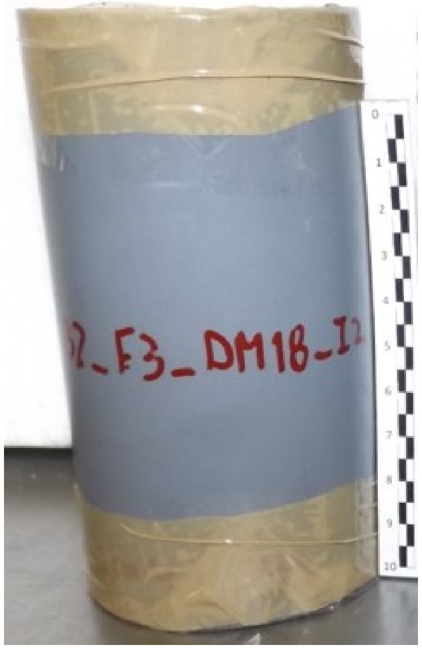
Site investigation results

After in situ testing: transport, extrusion and storage

Transport in a specifically designed wooden box

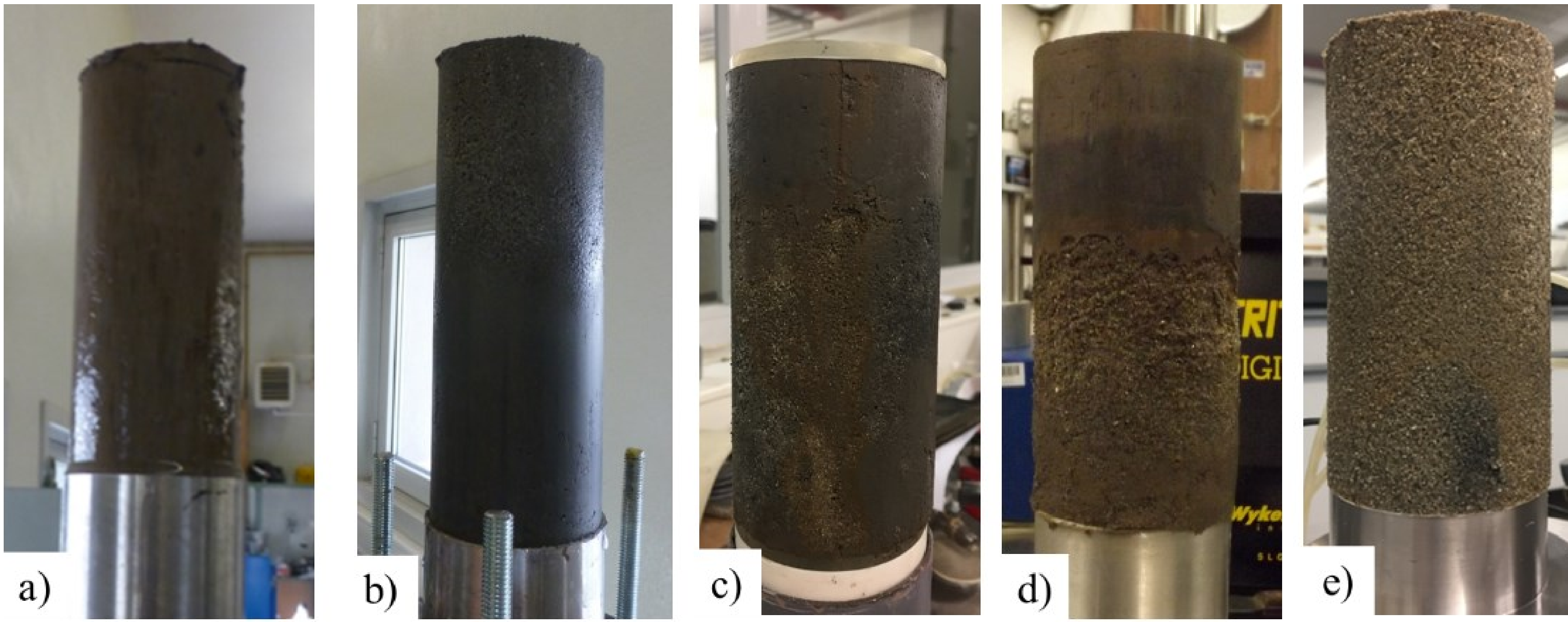


Extrusion in the vertical direction



Storage in PVC tubes under temperature and humidity controlled conditions

High quality samples: laboratory preparation



Sampling in liquefiable layers	Gel-Push	28 samples
	Dames & Moore	27 samples

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Laboratory testing: undisturbed samples

Sample preparation, storage and handling

Sample handling before element testing

Handling is as important as **advanced sampling** in obtaining representative and reliable test results!

Video of setting up an undisturbed soil sample for cyclic triaxial testing

Laboratory testing: undisturbed samples

Sampling quality assessment

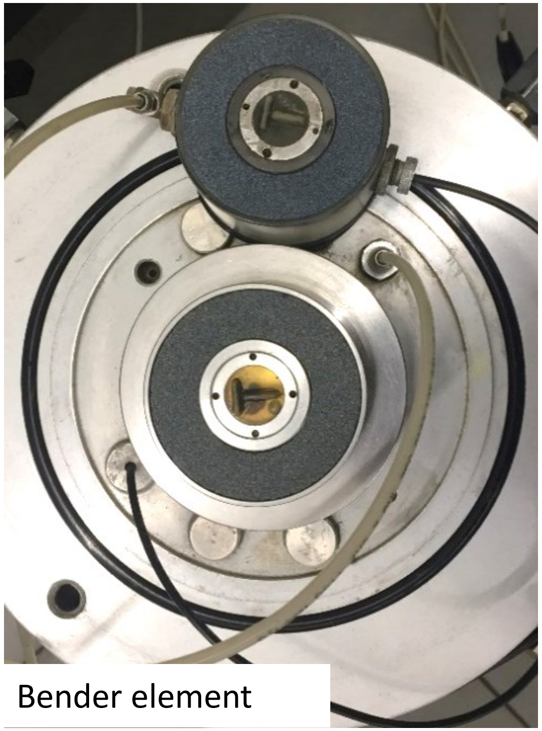
Sample quality classification based on V_S normalised ratio (Ferreira *et al*., 2011)

Quality zone	V_S* ratio	Sample quality	Sample condition
A	≥ 85%	Excellent	Perfect
B	85% - 70%	Very good	Undisturbed
C	70% - 60%	Good	Fairly undisturbed
D	60% - 50%	Fair	Fairly disturbed
E	< 50%	Poor	Disturbed

Laboratory testing: undisturbed samples

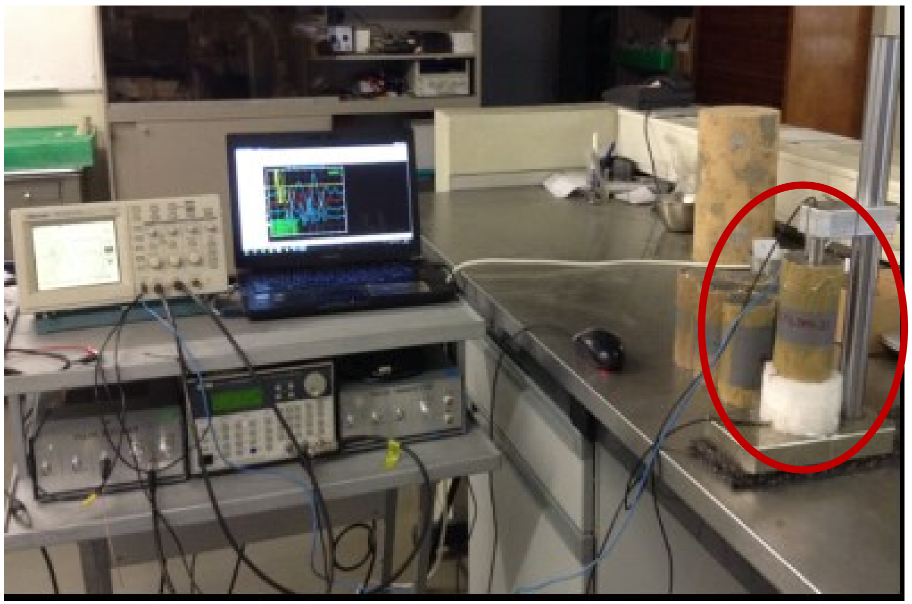
Sampling campaign: sampling quality assessment


Geophysical in situ results


Bender element

Laboratory testing: undisturbed samples

Sampling campaign: immediate measurement of Vs in the laboratory using BE



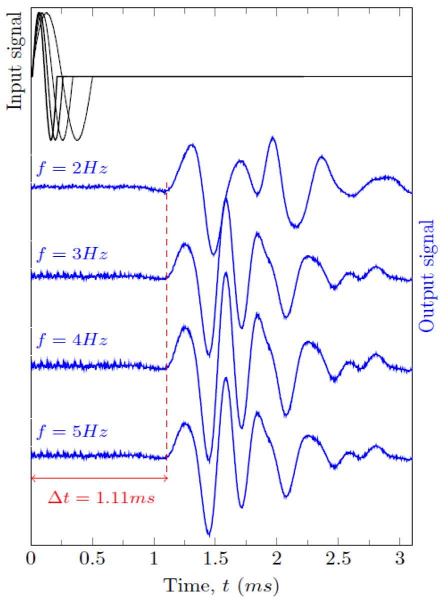
Bender element bench tests

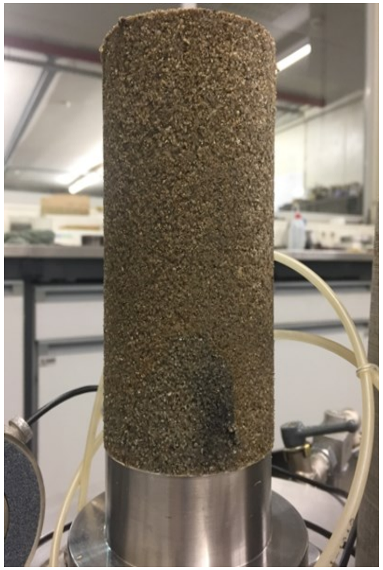
(p´ = atmosphere)

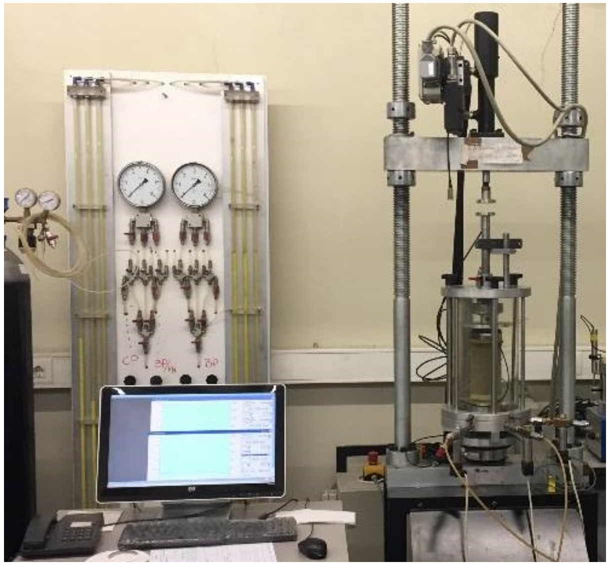
Laboratory testing: undisturbed samples

Sampling campaign: measurement of Vs in the laboratory using BE

Bender element in cyclic triaxial tests







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Laboratory testing: undisturbed samples

Sampling campaign: normalisation of *Vs*

Void ratio effect

BE Bench

BE CTx

$$V_S^* = \frac{V_S}{\sqrt{F(e)}}$$

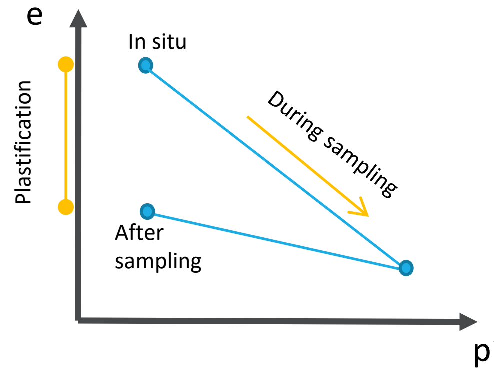
$$F(e) = e^{-1.3}$$

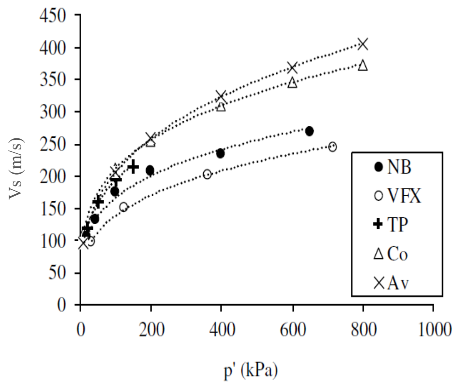
Lo Presti *et al*. (1993)

Overburden effect

BE Bench

$$V_S^{**} = V_S^* \left(\frac{p_0'}{p'}\right)^{0.25}$$

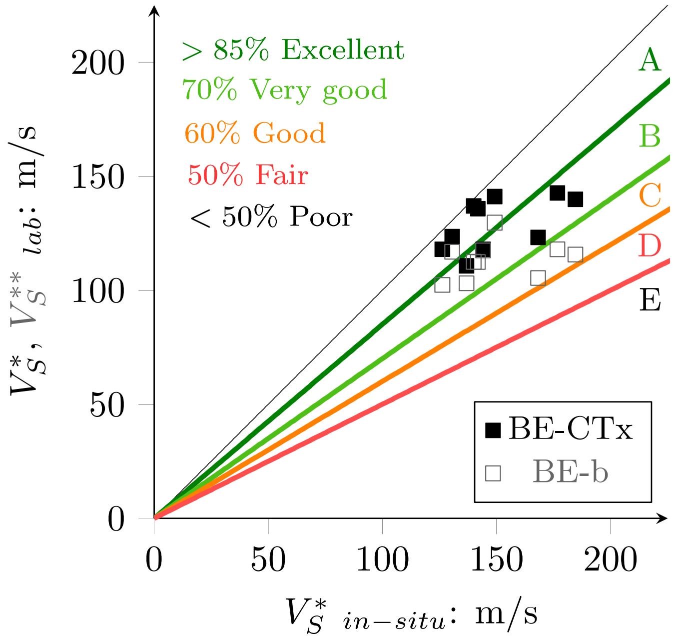




Ramos et al. (2019)

Laboratory testing: undisturbed samples

Sampling campaign: sample quality of GP-S



Molina-Gómez *et al*. (2019)

More consistent results in the triaxial measurements because:

- **BE-b**. Lack of confining pressure, affecting the coupling between the BE and the soil sample. Weaker signals and poorer resolution.
- **BE-CTx.** Reestablishment of the in situ conditions (stress-state and full saturation).

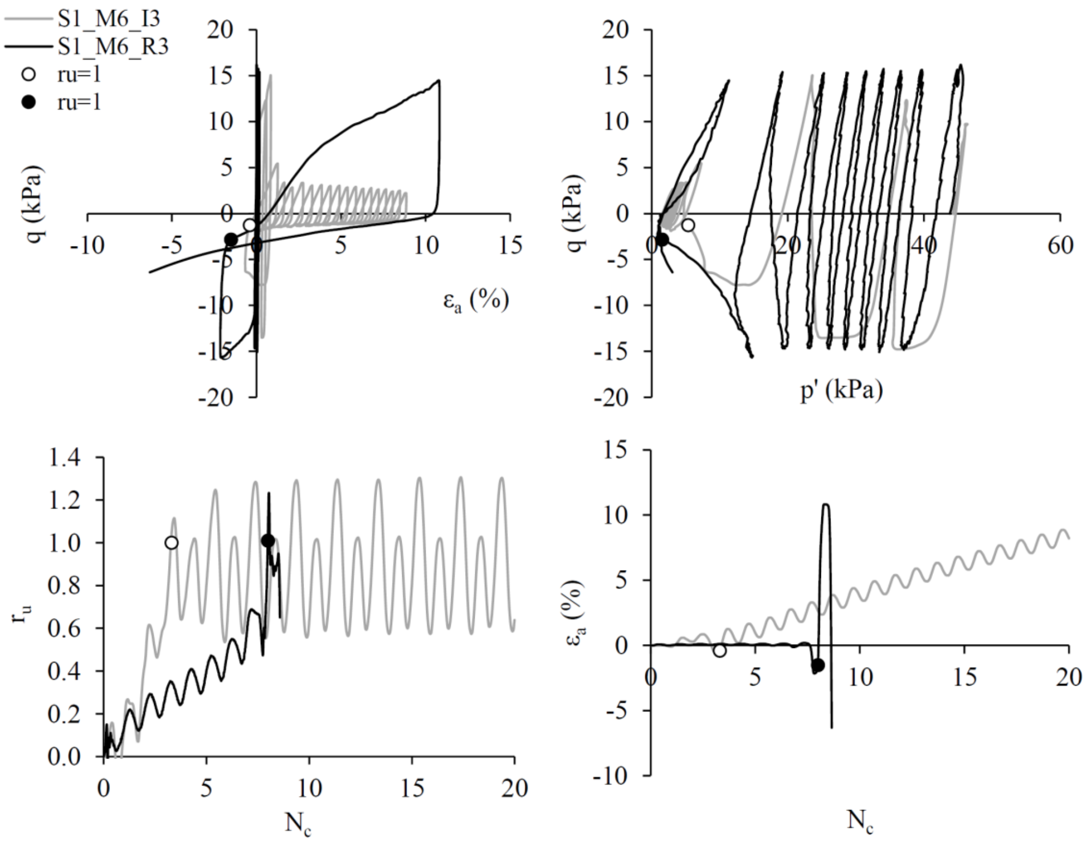
Note that full saturation corresponds to B > 0.98 and Vp ~ 1500 m/s.

Laboratory testing: reconstituted samples

To study the effect of fabric, and since the materials from undisturbed specimens were all different, reconstituted specimens were prepared after testing each undisturbed sample, in order to directly compare the cyclic behaviour results.

- preparation by moist tamping and air pluviation
- same relative density of the undisturbed sample (Dr)
- same effective stress conditions (p´)
- same cyclic loading conditions (CSR)

Laboratory testing:
undisturbed versus reconstituted samples



Comparison of undisturbed and reconstituted specimens (FC = 6%)

Ramos (2021)

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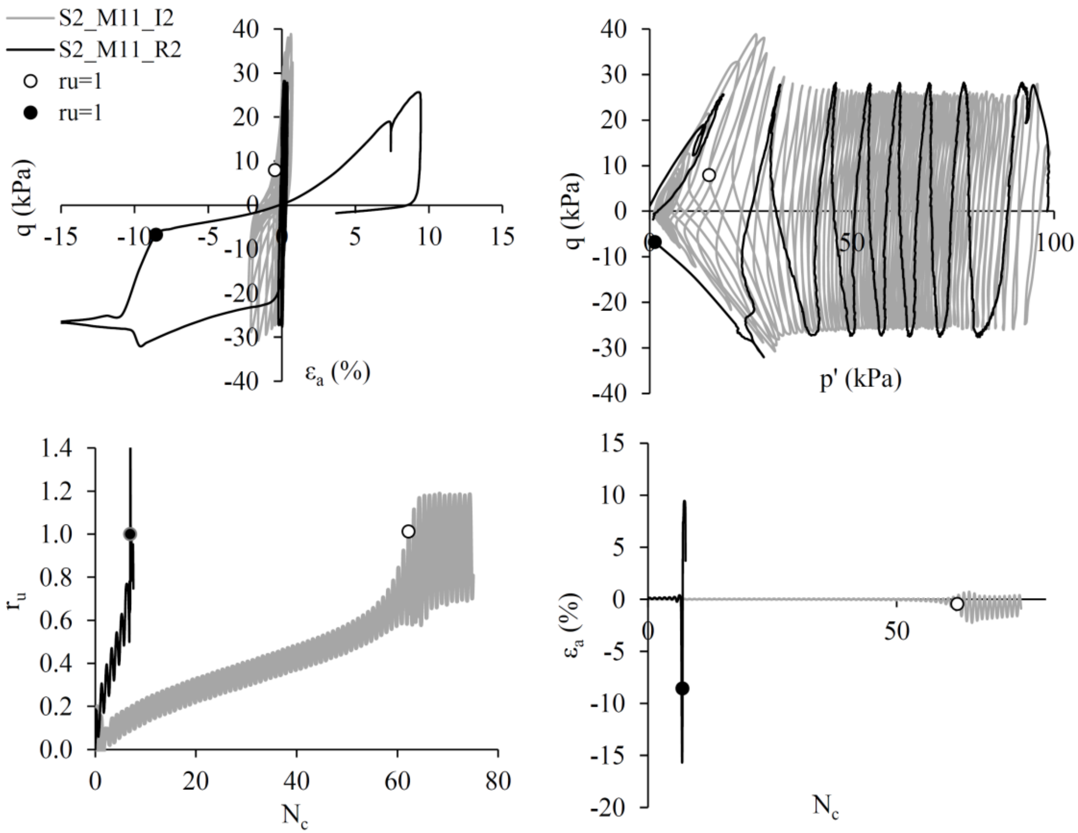
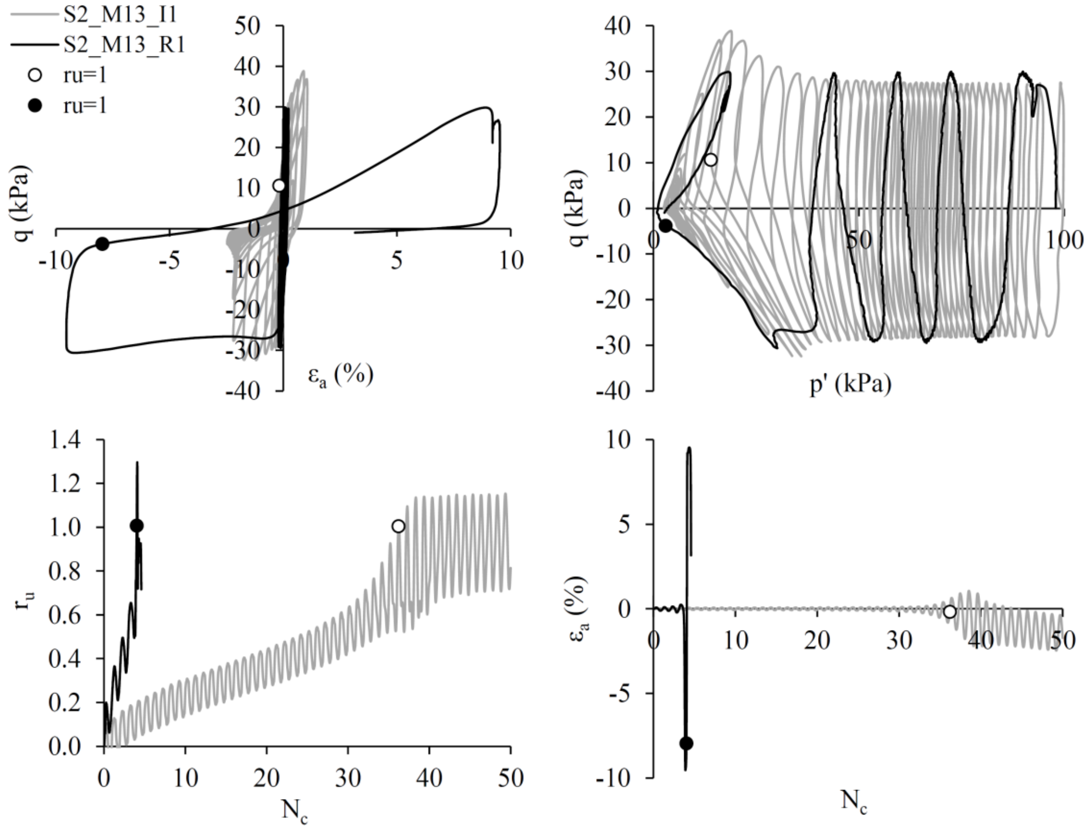
Laboratory testing:
undisturbed versus reconstituted samples



Comparison of undisturbed and reconstituted specimens (FC = 9%)

Ramos (2021)

Laboratory testing:
undisturbed versus reconstituted samples

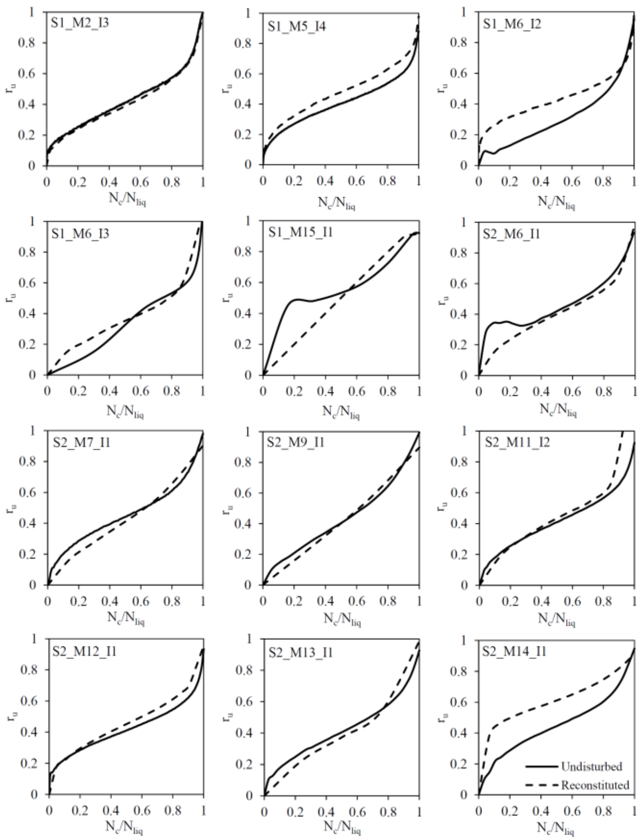


Comparison of undisturbed and reconstituted specimens (FC = 18%)

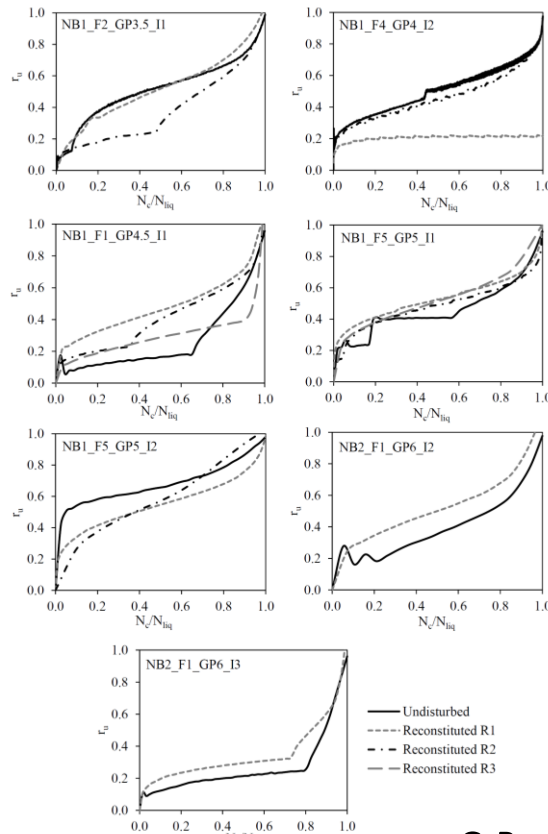
Ramos (2021)

Laboratory testing:
undisturbed versus reconstituted samples

Pore pressure ratio evolution



Mazier

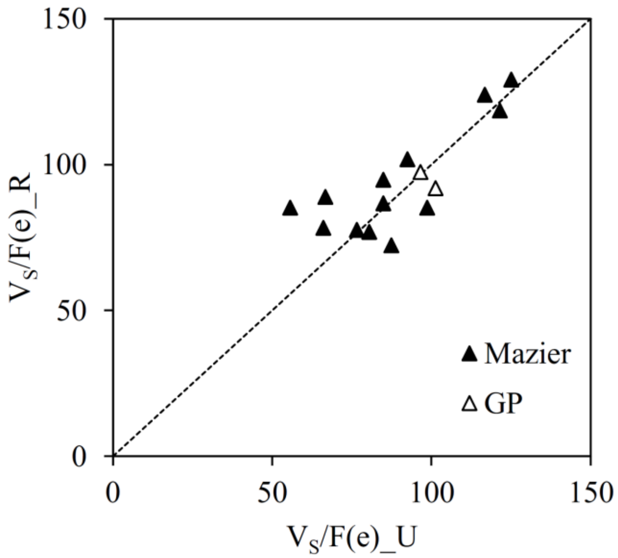


G-P

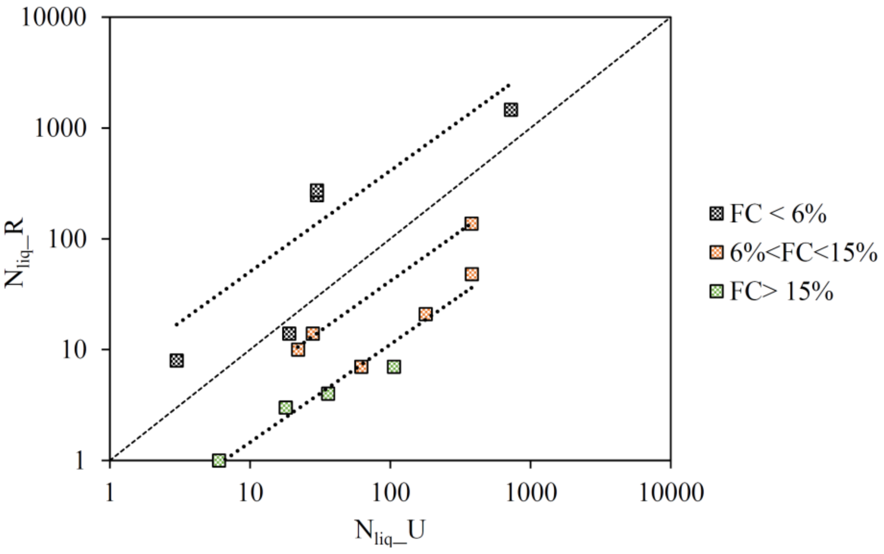
Comparison of undisturbed and reconstituted specimens

Ramos (2021)

Laboratory testing:
undisturbed versus reconstituted samples



Comparison between the shear wave velocity normalised by the void ratio function of undisturbed and reconstituted specimens



Comparison between N_{liq} of undisturbed and reconstituted specimens

Ramos (2021)

Outline

- Motivation
- Pilot site: location and geological setting
- Advanced sampling techniques
- Laboratory test results
- **Conclusions**

Conclusions: site investigation

This research addressed the geotechnical characterization of a geotechnical test site in liquefiable soils in the Lisbon area, by means of extensive in situ tests (SPT, CPTu, SDMT and geophysical borehole tests) and advanced sampling techniques (Mazier, Dames & Moore and Gel-Push).

Different locations were studied in detail, in order to estimate the liquefaction susceptibility of the test site and to identify liquefiable layers for collecting cohesionless samples.

In order to estimate the susceptibility to liquefaction from in situ tests, it was found necessary to combine field test results with the fines content of each soil layer measured in the laboratory.

Conclusions: sampling quality

The assessment of sample quality showed that the three samplers were capable of collecting high to good quality samples of different types of soils.

The Mazier sampler exhibited poorer performance than the other two samplers. GP-S and D&M samplers reduce sample disturbance during sampling and induce minimal damage in the fabric and structure. The low friction of each technique decrease the compression of the soil.

D&M has a better performance than the GP-S, mainly due to its shorter liner length and the generation of vacuum by the neoprene seal, which allowed obtaining a higher recovery ratio of 80%-94% and easier retrieval of the samples.

Immediate bench BE tests and cyclic triaxial tests were carried out. More consistent results were obtained in the triaxial measurements due to the reestablishment of the in situ conditions (stress-state and full saturation) and better BE signal quality.

Conclusions: liquefaction assessment

The undisturbed samples collected were tested for liquefaction assessment. A comparison with reconstituted specimens of the same soil, with similar relative density and applied cyclic loading was carried out, so the differences can be directly attributed to the fabric and structure of the specimens.

Given the alluvial nature of the soil deposit, undisturbed samples often evidence interbedded layering, typically varying between silty sands and silty clays. It was found that each undisturbed sample is essentially a unique soil, with different intrinsic properties.

Since natural interlayering cannot be adequately reproduced in reconstituted conditions, significant differences have been observed, in terms of cyclic resistance, cyclic strains and excess pore pressure build-up.

Conclusions: liquefaction assessment

The results show a marked influence of the fines content on the comparison of undisturbed and reconstituted cyclic resistance.

For FC below 6%, the reconstituted specimens exhibited slightly higher cyclic resistance; while at higher FC, higher resistance was observed for undisturbed samples. The response in terms of strains and excess pore pressure also differed.

On the other hand, the undisturbed specimens exhibited a more stable behaviour, with a steady strain increase. This behaviour has been attributed to the structure of the undisturbed specimens, which layering and lamination provided a more stable response even beyond liquefaction triggering.

While undisturbed samples are valuable for an accurate characterization of the soil profiles, representative constitutive parameters are more clearly defined based on reconstituted specimen testing.

Key publications

- Ramos, C., Molina-Gómez, F., Viana da Fonseca, A. & Ferreira, C. (2022). Earthquake-induced liquefaction assessment of undisturbed and reconstituted specimens from a natural alluvial deposit (upcoming Special Issue "Assessment of Earthquake-Induced Soil Liquefaction Hazard“ in *Geosciences*)

- Ramos, C., Viana da Fonseca, A. & Ferreira, C. (2021). CPTu-based approaches for cyclic liquefaction assessment of alluvial soil profiles. *Soils & Rocks*, Vol. 44(4): e2021070121. https://doi.org/10.28927/SR.2021.070121

- Lai, C. et al. (2021). Technical guidelines for the assessment of earthquake induced liquefaction hazard at urban scale. *Bulletin of Earthquake Engineering*, Vol. 19: 4013-4057 . https://doi.org/10.1007/s10518-020-00951-8

- Molina-Goméz, F., Ferreira, C., Ramos, C. & Viana da Fonseca, A. (2020) Performance of Gel-Push sampling in liquefiable soils. *Géotechnique Letters*, Vol. 10(2): 256-261, https://doi.org/10.1680/jgele.19.00073

- Ferreira, C., Viana da Fonseca, A., Ramos, C., Saldanha, A.S., Amoroso, S. & Rodrigues, C. (2020). Comparative analysis of liquefaction susceptibility assessment methods based on the investigation on a pilot site in the greater Lisbon area. *Bulletin of Earthquake Engineering*, 18(1): 109-138. https://doi.org/10.1007/s10518-019-00721-1

Key publications

- Molina-Gómez F., Viana da Fonseca A., Ferreira, C., Ramos C. & Cordeiro D. (2021). Novel sampling techniques for collecting high-quality samples: Portuguese experience in liquefiable soils. 6th International Conference on Geotechnical and Geophysical Site Characterization (paper 115). Budapest (Hungary).

- Ramos, C., Ferreira, C., Molina-Gómez, F., & Viana da Fonseca, A. (2021). Enhanced liquefaction susceptibility evaluation of Lisbon sands by CPTu and SPT tests with laboratory GSD and plasticity. 6th International Conference on Geotechnical and Geophysical Site Characterization (paper 178). Budapest (Hungary).

- Viana da Fonseca, A., Molina-Gómez, F., Ferreira, C. & Cordeiro, D. (2021). An integrated interpretation of SCPTu for liquefaction assessment in intermediate alluvial deposits in Portugal. 6th International Conference on Geotechnical and Geophysical Site Characterization (paper 141). Budapest (Hungary).

- Ramos, C., Ferreira, C., Molina-Gómez, F. & Viana da Fonseca, A. (2019). Critical state characterisation of Portuguese liquefiable sands. IS-Glasgow, 26-28 June 2019. DOI: 10.1051/e3sconf/20199206003

- Viana da Fonseca, A., Ferreira, C., Molina-Gómez, F. & Ramos, C. (2019). Collection of high-quality samples in liquefiable soils using new sampling techniques. Proceedings of the XVII ECSMGE-2019, Reykjavik, 1-6 September 2019 (doi: 10.32075/17ECSMGE-2019-0014).

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Thank you!

Obrigada!

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