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A surface seismic approach to liquefaction

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ABSTRACT: The liquefaction potential of soils is traditionally assessed through geotechnical approaches based on the calculation of the cyclical stress ratio (CSR) induced by the expected earthquake and the 'resistance' provided by the soil, which is quantified through standard penetration (SPT), cone penetration (CPT), or similar tests. In more recent years, attempts to assess the liquefaction potential have also been made through measurement of shear wave velocity (V_S) in boreholes or from the surface. The latter approach has the advantage of being non-invasive and low cost and of surveying lines rather than single points. However, the resolution of seismic surface techniques is lower than that of borehole techniques and it is still debated whether it is sufficient to assess the liquefaction potential. In this paper we focus our attention on surface seismic techniques (specifically the popular passive and active seismic techniques based on the correlation of surface waves such as ReMi^{TM}, MASW, ESAC, SSAP, etc.) and explore their performance in assessing the liquefaction susceptibility of soils. The experimental dataset is provided by the two main seismic events of M_L = 5.9 and 5.8 (M_W = 6.1, M_W = 6.0) that struck the Emilia-Romagna region (Northern Italy) on May 20 and 29, 2012, after which extensive liquefaction phenomena were documented in an area of 1200 km^2. We found that they appear not to have sufficient resolution to address the seismic liquefaction issue. However, it also emerged that the pure observation of the surface wave dispersion curves at their simplest level (i.e. in the frequency domain, with no inversion) is still potentially informative and can be used to identify the sites where more detailed surveys to assess the liquefaction potential are recommended.

1 INTRODUCTION

Assessing the liquefaction potential at a site is a goal traditionally achieved through geotechnical approaches based on the grain size distribution or on CPT and SPT (cone penetration and standard penetration tests. These methods are based on the calculation of the cyclical stress ratio (CSR) induced by the expected earthquake at the depth of the potentially liquefiable deposit and the 'resistance' provided by the deposit, quantified through the CPT or SPT. The geotechnical approaches are certainly the most explored, used, and reliable ones since they provide direct quantitative information about some mechanical properties of the soil column. However, they have the disadvantage of providing only point information and of being invasive and inapplicable to gravelly soils, where liquefaction has sometimes been documented. Parallel to the geotechnical ones, geophysical approaches have also developed and traditionally exploited the measurement of shear wave velocity V_S (because V_S is linked to the shear modulus of the soil, $\mu = \rho V_S^2$, where ρ is the density) in boreholes or in laboratory samples but at the expense of having the same limitations as CPT and SPT, that is, providing just point information, and being more expensive.

Surface multichannel geophysical methods like those relying on the dispersion of surface waves to retrieve V_S profiles would be ideal in principle, since they are spatially distributed and not invasive and can be used on any soil type. Seismic surface methods are however much less sensitive to the stiffness variation of soil with depth compared to the classical geotechnical methods for physical reasons: first, the depth of investigation is proportional to the 'exploring' wavelength but large wavelengths (i.e. large depths of investigation) are sensitive only to reflectors of comparable size; second, while the penetration parameters (sleeve friction or tip resistance) are directly proportional to the shear modulus G, V_S is proportional to the square root of G. Additionally, deriving a V_S profile from the dispersion curve of surface waves is not an easy task and, as the method is indirect and the problem underdetermined, it does not have a unique solution.

The results of an 11-year international project to gather new V_S data and develop state-of-the-art probabilistic CSR-V_S correlations for the occurrence of seismic soil liquefaction were presented by Kayen et al. (2013). The new V_S soil profiles, mostly derived from the SASW (Spectral Analysis of Surface Waves) method (Nazarian and Stokoe, 1984), were collected mainly in Japan (213), with a minority being collected in California (39), China (24), Taiwan (14), Alaska (9), and Greece (2).

In this paper we focus on the ‘descendants’ of the SASW technique, exploring their applicability within the method proposed by Kayen et al. (2013) to the Italian case and examining whether different geophysical approaches are possible to assess the liquefaction susceptibility of a soil.

Our dataset is provided by the May 20 and 29, 2012 earthquakes ($M_L = 5.9$ and $M_L = 5.8$, respectively) that occurred in the Po Plain area (Northern Italy), which caused a large number of liquefaction phenomena over an area extending up to 30 km from the epicenters.

2 DATA COLLECTION

2.1 *Site selection*

In the area struck by the aforementioned seismic events, we focus on 84 sites, which we grouped into four classes (in all cases the depth of the water table was within 3 m; in the majority of cases, within 1.5 m) representative of different depositional environments. Class A and B sites include shallow (< 8 m) sandy soil with liquefaction potential. At sites labeled A, liquefaction occurred during the 2012 events while at sites labeled B there was no surface evidence of liquefaction. Class C sites are those where sand is present at large depth (> 8 m) and did not exhibit liquefaction. Class D sites are composed of clay and silt, with no liquefaction potential. A closer look to the tip resistance q_C and the sleeve friction f_S of the single penetration tests four classes (Figure 1) reveals that a geotechnical difference exists between soils A and B: in the first case a higher sand content is present between 5 and 7 m depth (which is the level that underwent liquefaction), while in the second case sand is dominant in the upper 4 m.

2.2 *Site survey*

At the 84 sites we combine the active seismic exploration approach of MASW (Multichannel Analysis of Surface Waves, Park et al., 1999) and the passive approach of ReMi^{TM}-ESAC-SSAP (Refraction Microtemor^{TM}, Louie, 2001; Extended Spatial Autocorrelation Method, Ohori, 2002; Statistical Self-Alignment Property, Mulargia and Castellaro, 2013).

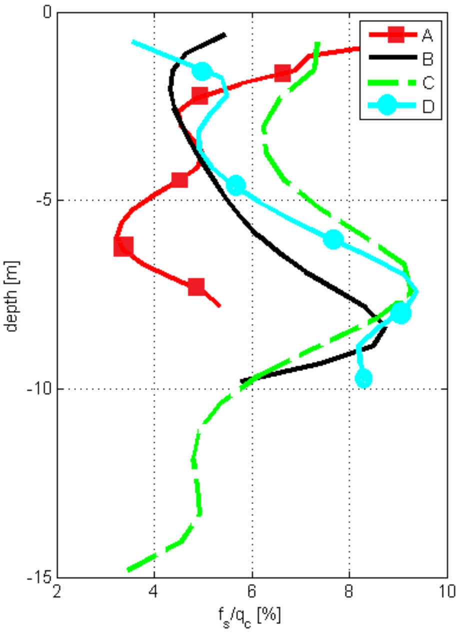

Figure 1. Average friction ratio (i.e. sleeve friction, f_S, versus tip resistance, q_C) for the four soil classes. Lower f_S/q_C ratios indicate sandy soils while ratios indicate silty-clayey soils.

This kind of survey exploits the fact that surface waves of different wavelengths, like those produced by common sources, excite the soil at different depths and travel with the specific velocity that characterizes the soil at the different depths: short wavelengths normally propagate slower (due to the low velocity of the shallow layers) while long wavelengths propagate faster. This property, called dispersion, is a phenomenon strictly related to surface waves. From the seismic signal recorded at different positions (a minimum of two) over time, slant-stack and FFT procedures produce the so-called phase/group velocity spectra, which indicate the most probable velocity of surface waves at each frequency. From this, a forward or inverse modeling procedure makes it possible to reconstruct a possible V_S model for the surveyed soil.

The 84 surveys performed in this study were conducted by using twelve 4.5 Hz, vertically polarized geophones (Geospace lp), set at intervals of 2.5 m each, connected to a SoilSpy Rosina acquisition system (MoHo srl), and data were processed by using the software Grilla, written by one of the authors (S.C.). Working with vertically polarized geophones implies that we deal with Rayleigh wave phase velocities, which are approximately 10–15% lower than V_S, depending on the Poisson’s ratio of the materials.

Recalling that a Rayleigh wave induces the maximum displacement at a depth equal to 1/3 to 1/2 of its wavelength λ (e.g. Chapter 4 in Lay and Wallace, 1995), and considering that our surveys show phase velocities V_R ranging between 150 and 250 m/s at $f = 4$ Hz (Figure 2), we get an average wavelength of $\lambda = V_R/f = (150–250)/4 = 37–62$ m, which stands for a depth of investigation $z_{max} \approx [\lambda/3, \lambda/2] \approx [12, 32]$

m, which is adequate for our task, since liquefaction generally occurs at depths shallower than 15 m and in the present case study it was documented at a depth shallower than 8 m.

This is not always the case. We pick the dispersion curves of the fundamental mode from the phase velocity spectra at the 84 inspected sites, grouping them as per the four soil classes defined before. The average dispersion curve plus or minus the standard deviation of each group is shown in Figure 2. We immediately observe that the geophysical approach is not capable of separating the four soil classes. Class A and B sites, characterized by liquefied and non-liquefied sandy soils, have exactly the same phase velocity distributions, while the CPTs (Figure 1) suggest that some difference exists between these two classes: class A soils are richer in sand between 5 and 7 m depth. This limitation of the adopted seismic surface methods is discussed in the next section.

Class D soils, which are characterized by clay and silt in the first 10 m depth, show significantly lower phase velocity distributions compared to class A and B soils in almost the whole frequency interval considered. Class C soils, characterized by sands at depths larger than 8 m, show phase velocity distributions comparable to class D soils in the high frequency part of the spectra, increasing up to or higher than the distribution of class A and B soils in the low frequency part. This trend is somewhat expected: V_R (and V_S) normally increases from clays to silt to sand in this type of depositional environment. However, this is probably the first time that this has been well documented in this part of the Po Plain, to the point that the phase velocity distribution in this geographic area could be used as a proxy for the shallow stratigraphy.

We note that the difference in the V_S values among classes (a few tens of meters per second) appears low compared to the difference in the CPT parameters. This is not surprising if one recalls that the shear modulus G is proportional to V_S^2 (and the same relation involving an exponent 2 exists between V_P and other elastic constants and V_R is a function of both V_S and V_P).

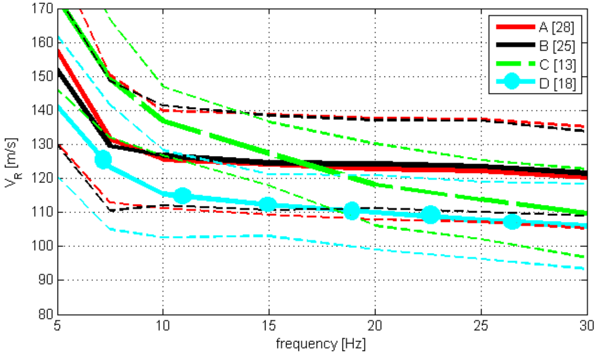

Figure 2. Dispersion curves (average ± standard deviation) grouped into the four soil classes. The number of curves used to assess the distribution of each soil group is indicated in square brackets in the legend.

3 RESULTS

The first relations between V_S values and liquefaction potential described in the literature were based on laboratory or direct (in hole) measurements. More recent attempts (Kayen et al., 2013) introduced, together with direct measurements, a number of V_S estimated from Spectral Analysis of Surface Waves (SASW), which is an ancestor of MASW. These methods consist in the calculation of the corrected seismic demand (cyclic stress ratio, CSR*) and the corrected soil capacity (V_{S1}) to be used as entry values in plots where the liquefaction and non-liquefaction areas are divided by curves representing different probability levels (Figure 3).

The critical stress ratio (CSR) is the ratio between the average shear and vertical stresses, τ_{avg}/σ_{avg}. This can be rewritten as CSR = $0.65\ a_{max}/g\ \sigma_V/\sigma'_V\ r_d$, where a_{max} is the peak ground acceleration at the surface, σ_V is the total overburden stress, σ'_V is the effective vertical overburden stress, and r_d is a non-linear mass participation factor, which depends on a number of factors including the soil depth, the average V_S of soil, the peak ground acceleration, and the earthquake magnitude. We use Eq. 4 in Kayen et al. (2013) to calculate r_d, by setting $a_{max} = 0.31$ g and $M_W = 6.1$, which are the values of the 2012 mainshock. The other parameters (depth of the sand layer on which to perform the calculations and depth of the water, average V_s of the overlying soil) are known at all sites from the penetration test, drillings, water wells, and the geophysical surveys performed *ad hoc*.

The adjustment of CSR to CSR* is done by scaling the computed CSR to compensate for the duration of shaking (duration weighting factor, DWF) relative to an equivalent $M_W = 7.5$ event, so that CSR* = CSR/(DWF K_σ), where $K_\sigma = 1$, following the recommendations in Kayen et al. (2013) and DWF = $15\ M_W^{-1.342}$ (Eq. 17 in *ibid.*).

The results are plotted in Figure 3 and show that our class A and B data (liquefied and non-liquefied sandy soils) are randomly distributed around the P_L = 15% line (this value is recommended in Kayen et al., 2013, and corresponds to a safety factor of 1.2), while the class C data (deep sands) are well separated and fall in the non-liquefaction zone.

We also note that if we wish to include both the A and B sites in the liquefaction area, we need to operate according to $P_L = 10^{-5}$, which represents a huge factor of safety (dashed line in Figure 3).

We observe that the phase velocity spectra/dispersion curves (Figure 2) are just experimental data with little subjective interpretation. Transforming these data into V_S profiles and calculating the CSR*-V_{S1} values requires a large number of assumptions and corrections (earthquake DWFs, adjustment for the influence of fines, calculation of effective stress, etc.) and is not a unique process (inversion of the data to get V_S profiles). All this effort does not seem to be warranted in the case of the present study and, besides the points above, there can be two further reasons for such a failure: 1) surface wave methods do not have sufficient sensitivity to characterize appropriately the V_S of the 2–4 m thick sandy layers potentially involved in the liquefaction phenomenon, and/or 2) the sandy deposits in this part of the Po Plain area have features that make them different from the sands studied worldwide by Kayen et al. (2013).

In order to better discriminate between the last two hypotheses, we calculated the liquefaction potential of the same sand layers through the fines-modified CPT tip resistance approach, $q_{c,1,mod}$ (Moss et al., 2006). Results in terms of CSR*-$q_{c,1,mod}$ are shown in Figure 4 and suggest that the geotechnical method provides a better prediction of the liquefaction potential (a failure rate of less than 20% is achieved by adopting the 20% liquefaction probability curve) compared to the seismic-surface wave based method, thus making the first hypothesis more credible.

We observe that the surface wave dispersion curves alone (Figure 2), prior to any inversion, can still be very informative. On the basis of the 84 surveys, for this area of the Po Plain we propose a soil classification scheme based on the Rayleigh wave dispersion curves (Figure 5), which indicates the degree (high, intermediate, or low) of caution recommended in assessing the liquefaction potential of the soil under the typical design earthquake ($M_W \approx 6.1$) imposed by the national building code (NTC, 2008) in this part of Italy for standard constructions. The class boundaries – high, intermediate, and low – mean that 50, 30, and <5%, respectively, of the sites presenting a dispersion curve completely falling within them experienced liquefaction during the 2012 $M_W \approx 6.1$ events (near field condition).

Generally speaking, low V_R values in this plot correspond to clays, while sand content increases the V_R values. A dispersion curve falling completely within the gray area of Figure 5 indicates with high probability a site with clays followed by sand at a depth greater than approximately 8 m. This configuration represents a low liquefaction susceptibility under a typical $M_W \approx 6.1$ earthquake.

A curve falling completely within the magenta area indicates a site with sand which can potentially undergo liquefaction. Further investigations are recommended at these sites, for example, by using CPT-STP, to better assess the liquefaction potential.

A curve falling completely within the lower yellow area (V_R < 110 m/s in the 10–30 Hz interval) indicates with high probability a clayey soil with low liquefaction potential. A curve falling completely within the upper yellow area (V_R > 150 m/s in the 10–30 Hz interval) indicates a site with dense sand in the upper 15 m, which would be less prone to liquefaction under the reference earthquake.

The above discussion applies also to the case of sites with a stiff crust, such as a dessicated clay layer or manmade fill, overlying a loose saturated sand. In these cases there would be a 'kink' in the dispersion curve (not normally dispersive) which would not closely match the dispersion curve shapes discussed above but would still represent a potentially liquefiable soil. The most part of the dispersion curve is however expected to lay within the boundaries of Figure 5, excluding the high frequency part which might lay above these limits.

Such a scheme appears to be more effective (and less demanding) in identifying the soils where further study is recommended compared to the CSR*-V_{S1} approach, in which V_{S1} is computed from surface-wave based seismic approaches. We emphasize that even though the V_R-frequency plot of Figure

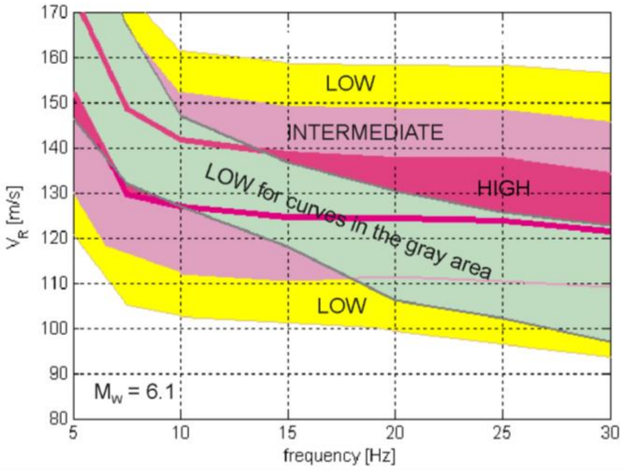

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Figure 5. represents the result of this study, before applying it to different geographical and geological settings, specific tuning and verification are needed.

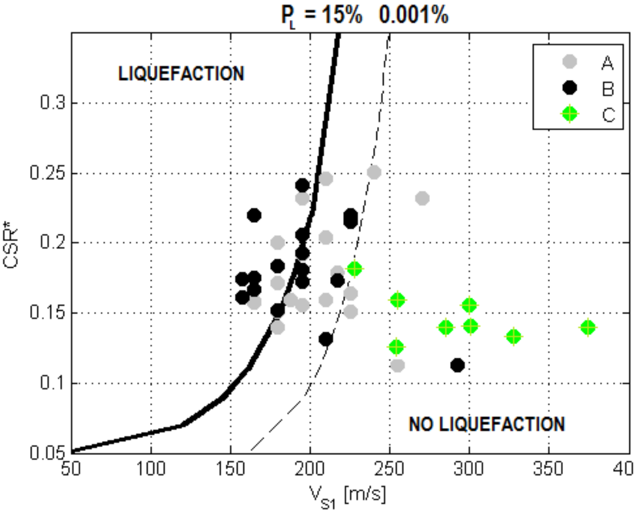

Figure 3. Corrected cyclic stress ratio (CSR*) versus corrected shear wave velocity (V_{S1}) for the sand layer at the inspected sites. The thick black line corresponds to the 15% liquefaction probability level proposed by Kayen et al. (2013).

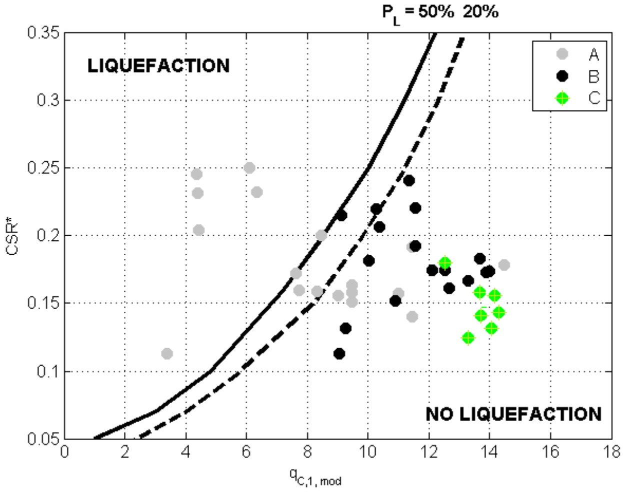

Figure 4. Corrected cyclic stress ratio (CSR*) versus corrected and fines-modified CPT tip resistance ($q_{c,1,mod}$) for the sand layer at the inspected sites. The black lines represent the contours of 50 and 20% probability of liquefaction (Moss et al., 2006). Data are normalized with respect to M_W = 7.5 and σ'_V = 1 atm.

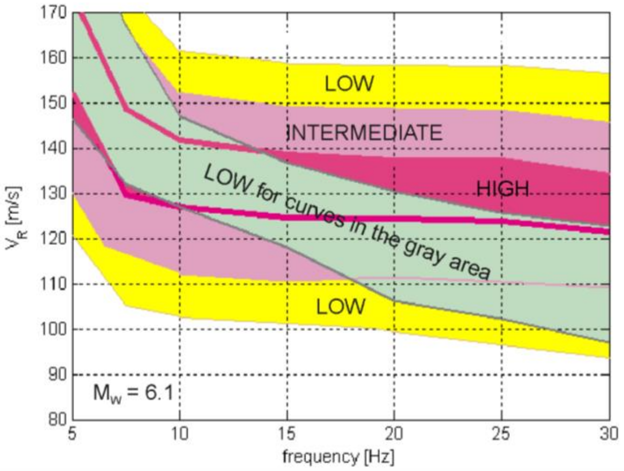

Figure 5. Soil classification scheme based on the Rayleigh wave dispersion curves for the surveyed area. The adjectives “high”, “intermediate”, and “low” indicate the degree of caution recommended in assessing the liquefaction potential of the soil. In general, low V_R values in this plot indicate clays, while the sand content increases the V_R values. A dispersion curve falling completely within the gray area indicates with high probability a site with clay at shallow depth and sand at large depth (> 8 m); this configuration represents a low liquefaction disposition under the typical $M_W \approx 6.1$ earthquakes used as design earthquakes in this area (NTC, 2008).

A curve falling completely within the magenta area indicates with high probability a site with sand which could undergo liquefaction. Further investigations are recommended at these sites, for example by using CPT-STP, to assess the liquefaction potential.

A curve falling completely within the lower yellow area indicates with high probability a clayey soil with low liquefaction potential. A curve falling completely within the upper yellow area indicates a site with dense sand in the upper 15 m, which would be less prone to liquefaction under the reference earthquake.

4 DISCUSSION AND CONCLUSIONS

The liquefaction potential of soils is commonly assessed through geotechnical methods (CPT, SPT, etc.) but some attempts to also estimate it through geophysical parameters, such as the shear wave velocity, V_S, of soils, have also been developed. Measuring V_S in boreholes or in the laboratory (when the collection of undisturbed samples is possible) has the advantage of providing more accurate values at the specific depth of interest but at the expense of higher costs and invasiveness compared to the geotechnical methods and of the same point validity. Being able to measure V_S from the surface and over wider areas therefore appears to be a desirable solution. In 2013, Kayen et al. proposed a probabilistic and deterministic method to assess the liquefaction potential of sands through V_S measurements. The dataset used also included a number of V_S estimates from surface-wave based methods, specifically SASW.

In this work we verified the applicability of seismic active and passive multichannel modern surface wave techniques in the prediction of liquefaction potential. The opportunity was provided by the two earthquakes that occurred in the Po Plain (Northern Italy) in 2012, causing extensive liquefaction. Using the abovementioned seismic surface techniques, we surveyed 84 sites where geological information was available from direct geotechnical methods (penetration test, drilling, etc.).

Based on the geotechnical information, the sites were grouped into four classes: A) liquefied sandy soils; B) non-liquefied sandy soils; C) deep sands; D) clayey-silty soils. The penetration tests suggested that on average in class A soils, sand was dominant at 5–7 m depth (and was in practice the liquefied layer) while in class B soils, sand was dominant at shallower depths. However, the geophysical surveys showed that the Rayleigh wave phase velocity spectra were clusterized into three groups only: classes A and B were found to be indistinguishable from a seismic point of view. Through a set of theoretical models, we showed that this is due to the resolution of the adopted seismic methods, which is a function of the ‘exploring wavelength’, and which makes seismic layers such as the sands under investigation – which are just 2–4 m thick and have V_S just a few ten of meters higher than the surrounding clay-silt – practically invisible at depths greater than 4–5 m.

We then applied the probabilistic and deterministic methods to assess the liquefaction potential of sands through the V_S measurement proposed by Kayen et al. (2013), but we found that this approach failed in the case of the present study since class A and B soils were found to be randomly distributed between the liquefaction and non-liquefaction zones, while predictive power exists for class C soils, which, as they represent deep sands, fall in the non-liquefaction zone.

The geotechnical approach based on the tip resistance in the CPT to assess the liquefaction potential was found to be more successful.

The reason for the failure of the surface geophysical method seems to be linked, therefore, not to the specific features of the sands in this area but to the insensitivity of the seismic surface-wave based methods used to the details of stratigraphy for this specific goal.

In conclusion, based on this study (i.e. in the region of V_{S1} = [150, 250] m/s), it seems that surface-wave methods (MASW, ReMi, ESAC, SPAC, and many others), which are extremely useful in a wide range of applications, do not have sufficient sensitivity to be used as predictors of liquefaction in the classic frame of seismic demand versus soil capacity scheme.

However, at least in this specific depositional environment, it also seems that the simple analysis of the Rayleigh wave phase velocity spectra – before any inversion procedure (Figure 2) – can be used since it suggests the presence of sand or clay. On the basis of the experimental results we built the 'caution against liquefaction' graph shown in Figure 5, which can however only be used in the studied area. Nonetheless, the procedure – after specific tuning for different geological settings – could probably also be applied at different sites.

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