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SEISMIC CHARACTERIZATION OF SHALLOW BEDROCK SITES WITH MULTI-MODAL MONTECARLO INVERSION OF SURFACE WAVE DATA

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KEY WORDS

Site characterization, Shallow bedrock, Seismic site response, Surface waves, Monte Carlo inversion, Geophysical methods.

ABSTRACT

Sites with a limited overburden over a stiff basement are of particular relevance for seismic site response. At the same time the characterization of such stratigraphies by means of surface wave methods poses some difficulties in the interpretation. Indeed the presence of sharp seismic contrasts between the sediments and the shallow bedrock is likely to cause a relevance of higher modes in the surface wave apparent dispersion curve, which must be properly taken into account in order to provide reliable results. In this study a Monte Carlo algorithm based on a multimodal misfit function has been used for the inversion of the experimental dispersion curves. Case histories related to the characterization of stations of the Italian Accelerometric Network are reported. Spectral ratios and amplification functions associated to each site, were moreover evaluated and compared to attain a complete characterization and an independent benchmark test. The results show the robustness of the inversion method in such non trivial conditions and the possibility of getting an estimate of uncertainty related to solution non-uniqueness.

INTRODUCTION

The relevance of stratigraphic conditions with shallow bedrock for seismic site response evaluation is well recognized in the literature. Contemporary seismic codes (IBC 2000, UBC97, EC8) consider the mean value of shear wave velocity over the shallowest 30 meters as the main parameter for soil classification. However many studies (see for instance [1], [2]) have proved that such approach can be misleading in many cases, such as sites with a shallow and abrupt stiffness change between the bedrock and the soft weathering layer. These sites are characterized by high values of

$V_{S,30}$ which lead to an underestimation of the site amplification in conventional approaches introduced by the codes. In this perspective, an in-depth knowledge of local soil conditions is an important factor for interpreting recorded earthquake ground motions, since different site conditions can induce amplifications in different period ranges and influence their peak values and response spectral ordinates. Moreover, an assessment of actual stratigraphic conditions is a requirement for the correct use of real accelerograms for earthquake resistant design of structural and geotechnical systems.

Surface wave tests are commonly used for seismic site characterization because they are both economically and time convenient when compared to other methods that can be adopted to infer the shear wave velocity profile (e.g. cross-hole and down-hole tests). Moreover it has been shown by several authors that the shear wave velocity profile extracted by this method is both reliable and accurate. If a single site response parameter concerning the average velocity of the first meters of profile is intended to be extracted (e.g. $V_{S,30}$) the results of surface wave tests have been demonstrated to be strictly comparable to the ones from invasive tests [3, 4, 5]. Possible uncertainty in the determination of the soil profile due to non-uniqueness of the inverse problem solution are of minor influence in the evaluation of site amplification parameters [6]. Moreover, the resolution provided by boreholes methods is not strictly necessary for the seismic characterization of a site.

However in non-trivial stratigraphic conditions, like shallow bedrock situations or inversely dispersive profiles, the interpretation of surface wave tests has to be performed with particular attention [7, 8]. Surface wave propagation is indeed a multimodal phenomenon, i.e. the dispersion curve is composed by several modal curves while in surface wave analysis it is often assumed that only the fundamental mode is excited. This assumption, which is reasonable for normally dispersive profiles, can lead to severe errors when the experimental dispersion curve is an apparent dispersion one, generated by mode superposition [9, 7]. The relevance of higher modes is a common feature both in presence of velocity inversions in the S-wave velocity profile [10] and in presence of a strong impedance contrast in the near surface [8]. Often it is not possible to identify the mode jump; indeed the transition can be continuous and smooth because of limited spatial resolution [11]. Inclusion of higher modes in the inversion process has several advantages: increases the penetration depth [12], stabilizes the inversion process [15], enhances the resolution in Vs of the inverted model [13] and generally increases the sensitivity on model parameters [16] providing more accurate results [17].

In this note some case studies of the application of a Monte Carlo inversion algorithm based on a multimodal misfit function are reported and discussed. The surveys are part of a project aimed at improving and updating the Italian strong motion database (ITACA; http://itaca.mi.ingv.it/ItacaNet/).

METHOD

In this paper an inversion based on a Haskell-Thomson matrix determinant misfit function proposed by Maraschini et al. [17] is applied. This function allows all the modes to be automatically taken into account avoiding mode misidentification. Moreover the reduced computational cost of the algorithm makes this approach very appealing for stochastic inversion.; in this respect his implementation in a Monte Carlo inversion scheme allows uncertainty caused by non-uniqueness to be quantified, while mitigating the risk of falling in local minima [25]. The results of the inversion is a set of profiles which are “equally good” with respect to available experimental information, accounting also for data uncertainty. In this respect the distribution of the experimental dispersion curve is assumed to be Gaussian, with a standard deviation of 5%, in line with previous experimental evidences [37]. For this reason the profiles selected can be considered an equally possible solution of the inverse problem. The results of the Monte Carlo inversion are reported in the following figures using a representation based on the relative misfit. The darkest colour always corresponds to the model having the lowest misfit with reference to the experimental dispersion curve. The same colour is used to represent each shear wave velocity model and its associated dispersion curve.

Four case histories are presented in this study. For all sites, shallow bedrock conditions or velocity inversions are expected., The sites are locations of permanent stations of the Italian accelerometric network. Details of the experimental setup for each site are given in Table 1; all datasets have been acquired by using a 5 kg sledge hammer as a source and a geophone array with an inline offset of 3 m. Dispersion curves have been obtained using fk analysis implemented in the package SWAT, which has been developed in Matlab® environment at Politecnico di Torino.

EXPERIMENTAL EXAMPLES

The first dataset has been collected in Sestri Levante (Liguria Region). The superficial layer at this site is constituted by an alluvial-colluvial heterometric deposit a few meters deep which lies over a weak torbiditic bedrock (interbedded silty and sands). Tests have been executed along an unpaved track used for the passage of trucks near the station. Observing the experimental dispersion curve (Figure 1b), a velocity increase with frequency is noted. In such situations the apparent dispersion curve follows higher modes in the high frequency range and the subsoil profile probably presents a velocity inversion [8]. The best profiles selected by the Monte Carlo algorithm are plotted in Figure 1a. The profiles are similar and consistently present a velocity inversion in the shallow layers. The fitting between the experimental dispersion curve and the dispersion curve of the best profiles is very good (Figure 1c). In Figure 1b, the experimental dispersion curve is superimposed on the colormap of the Haskell-Thomson matrix of the best fitting profile. This representation shows that the transition between different modes is associated to low values of the determinant misfit function, allowing several modes to be taken into account without a full dynamic simulation of wave propagation. This dataset is particularly challenging for a surface wave inversion algorithm. The apparent dispersion curve, which is composed by a single branch, follows higher modes both in the low and in the high frequency ranges with smooth transitions i.e. it is not possible to identify the mode number for the data points.

The second case history is related to the accelerometric station in Ispica (Sicilia Region). This site lies on a thin fill soil which leans on a very shallow limestone bedrock (outcrop evidences have been observed near the station). The dispersion curve (Figure 2b) is quite noisy because of the very strong velocity contrast between the two layers. Two main branches are retrieved (one between 30 and 100 Hz, the other between 240 and 350 Hz) with velocities ranging from 1000 to 1400 m/s and two small branches located around 200 Hz with velocities between 400 and 700 m/s. All of the profiles selected by the inversion code (Figure 2a) indicate a strong S-wave velocity contrast (from approximately 300 m/s to 1400 m/s) at about 0.8 m depth, so that the interface between the upper fill soil and the lower limestone bedrock is clearly determined. It is important to underline that with a mode numbering based algorithm it wouldn't be possible to attribute a priori any of the four branches of the experimental dispersion curve to a particular mode. Instead with the present approach the inversion result is reliable and in agreement with our a priori information on the site.

The Santa Croce site is located in southern Sicily as well: the superficial layer is an uncultivated soil with a substantial sand content laying over a shallow compacted limestone bedrock. The retrieved dispersion curve (Figure 3b) consists of three branches, all of them showing a phase velocity decrease with frequency. Figure 3a a reports the best fitting profiles from the Monte Carlo inversion. All profiles are similar and show an upper 1.5 m thick layer with a velocity of about 200 m/s then the S-wave velocity progressively increases with depth until the bedrock (with a S-wave velocity of about 1200 m/s) is reached. The dispersion curve corresponding to the best profile (Figure 3c) attribute the first branch of the experimental curve (with frequencies between 30 and 45 Hz , velocities from 500 to 1000 m/s) to the first higher mode and the second branch (with frequencies between 50 and 130 Hz and velocities from 150 to 350 m/s) to the fundamental mode.

The last case history is located in Varese Ligure (Liguria Region), in an uncultivated area on a hillside where the bedrock is expected to be quite shallow. Indeed, the site lies on a "flysch" formation mainly constituted by marbly limestones with outcrop evidences near the accelerometric station. However, where tests have been executed, a relevant soil coverage is present. The apparent dispersion curve coherently shows a decrease of the S-wave velocity as the frequency increases, but likely the curve follows the first higher mode at low frequencies, “jumping” to the fundamental mode from 40 Hz on (Figure 4b). The profiles which minimize the misfit function are represented in Figure 4a: a superficial 2 m thick layer with a velocity of 300 m/s lies upon an intermediate 4.5 m thick layer characterized by a S-wave velocity of approximately 600 m/s; the firm bedrock interface is at about 6.5 m depth and the formation has a velocity of 1100 m/s. For this site a P wave refraction survey is also available on the same array. The layering results compare well with surface wave inversion. The first interface under soil coverage can be attributed to altered “flysches”.

For each site we simulated the seismic site response for the best fitting velocity profiles using the code Shake91 [38]. The results of amplification functions obtained for each site are reported in Figure 5. Since in most of the soil profiles the stratigraphy can be easily modelled as shallow deposit over bedrock, comparison of the amplification functions is also performed with theoretical evaluation of the site resonance frequency and amplitude [39], also reported in Figure 5. In this computation the mean slowness has been used as an average parameter for the soil layers over the bedrock which is placed at the depth determined from the correspondent shear wave velocity soil profiles.

Amplification functions and site resonance frequency can be also experimentally extracted from the Horizontal to Vertical Spectral Ratio (H/V) method. This method, also termed Nakamura’s method [40], makes use of ambient vibration recording, for tens of minutes to over an hour depending on the expected site frequency, by means of a three-component station [41]. The spectra of the horizontal and vertical components of ambient vibrations are calculated and their ratio is evaluated. For sites conditions where there is a strong velocity contrast, a clear peak will occur in the H/V curve that closely corresponds to the fundamental frequency of the site. For two of the sites in the present study H/V spectral ratio curves have been evaluated and are reported for comparison in Figure 6. Data for H/V analyses have been acquired with 2 Hz triaxial geophones along 16 min ambient vibration records and processed by means of the open source code Geopsy (www.geopsy.org). The parameters used for window selection are in accordance with recommended values developed in the SESAME project [41]. Since high resonance frequency is expected at the sites, the use of relatively high frequency geophones and short recording windows is not a major concern. For the Sestri Levante site, comparison is also made with the H/V curve extracted, using a similar procedure, from a real earthquake record available at the accelerometric station (Figure 6). The seismic event (5.4 magnitude at about 90 km epicentral distance from the station) originated in the Parmesan Apennines.

DISCUSSION

The sites of the present study are characterized by dispersion curves whose inversion requires the necessity to take into account high propagation modes. In all four sites a shallow bedrock is expected and in one of them very probably a velocity inversion occurs. It is then very likely that the four apparent dispersion curves do not follow the fundamental mode but they may “jump” from one mode to another. As the applied inversion method does not require mode numbering, we can attribute every branch of the experimental dispersion curve to a particular propagation mode without any a priori assumptions. The present multimodal approach has proven to be suitable for this kind of sites because higher modes consideration increases penetration depth, as low frequency points belong to a higher mode, and avoids sound mistakes in the parameters of the deeper layer due to mode misidentification.

The results reported in terms of amplification functions leads to two main considerations. First, it is shown that the uncertainty in the inversion process (number of profiles selected by the Monte Carlo inversion) is of minor importance in the evaluation of the site response characteristics of the sites. Indeed the amplification functions of all of the profiles selected by the inversion procedure are very consistent and lead to the identification of very similar amplification functions and a clear resonance frequency (main peak of the amplification function). The only profile that seems critical at higher frequencies is the Varese Ligure one which however shows a very clear resonance peak (Figure 5d) despite the high uncertainty in the location of the second interface (Figure 4a). Secondly, if the soil profile is a simple two layer case (deposit over bedrock) there is clearly good correspondence between the theoretical resonance frequency and the one extracted from the simulations (Ispica site Figure 5b). On the contrary, when more than one layer is present, since the theoretical resonance frequency is based on the mean velocity of the shallower soils the obtained values underestimate the resonance in a normal dispersive condition (Figure 5c – d) and overestimate it in situations when a velocity inversion is present (Figure 5a). These aspects have to be evaluated when the mean velocity value of the sediments is intended to be extracted from peak resonance frequency only [42].

As far as the seismic classification of these types of sites is concerned, $V_{S,30}$ cannot be considered a representative parameter for shallow bedrock situations. In this respect the mean shear velocity of the soil deposits ($V_{S,h}$) and the fundamental frequency can be considered relevant parameters. To statistically evaluate the uncertainty in the profile parameters (velocities and thicknesses) and in the local site response characteristics ($V_{S,h}$ and fundamental frequency) resulting from the adopted Monte Carlo algorithm box plots of the distribution of each of the parameters are reported in Figure 7 for two sites. Values are normalized with respect to the median for a comparison of the different parameters. In both case histories it can be noted that the uncertainty in the site response parameters is lower than the uncertainty on single model parameters since average values along the soil profile are concerned. Moreover, it can be observed that the uncertainty in the fundamental frequency is always higher than the one on the average velocity. It must be remarked that in the Sestri Levante site (Figure 7a) this difference is particularly noticeable due to the increased uncertainty in layer thicknesses (box plots dimensions are however exaggerated in respect to velocities due to normalization) and that in the Varese Ligure site (Figure 7b) the higher uncertainty in the second interface position does not directly reflect on site response parameters.

In the same two sites, where a comparison is available with the H/V curve, a very good correspondence is obtained between the simulated amplification functions and the H/V curve. This is particularly true for the Sestri Levante site even if this site is characterized by non-trivial stratigraphic conditions (Figure 6a). The small difference with the earthquake resonance peak can be attributed to bedrock depth variations since our dataset has been acquired, due to logistic problems, a few tens of meters apart from the station. In the Varese Ligure site, on the contrary, a lower peak seems also to be present in the H/V curve but the main peak is well in accordance with simulated data

(Figure 6b). Moreover in this second situation the H/V curve is not characterized by a sharp resonance peak according to the definition introduced by Bard et al. [41] and again possible bedrock depth differences can be attributed to the shift of surveys in respect to the station.

CONCLUSIONS

In this work a Monte Carlo algorithm for surface wave inversion based on a multimodal misfit function is applied. The effectiveness of the algorithm is shown in real case histories. The algorithm is tested inverting dispersion curves which present difficulties, as passages of the apparent dispersion curve to higher modes both in the low and high frequency ranges. It has been shown that high quality profiles can be extracted with this procedure even in non trivial stratigraphic conditions. The robustness of the proposed approach has been moreover evaluated with comparisons with independent measurement (H/V) and with statistical analyses on the results.

ACKNOWLEDGEMENTS

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LIST OF TABLES

Table 1. Acquisition parameters for the case histories.

	No. of active channels	**Geophone spacing [m]**	**Sampling Rate [ms]**	**Time window [s]**	**Pre-trigger [s]**
Sestri Levante	48	0.7	0.25	0.512	0
Ispica	48	1	0.5	2.048	0.4
Santa Croce	48	1	0.5	2.048	0.3
Varese Ligure	48	0.9	0.25	0.512	0

LIST OF FIGURES

Figure 1 Sestri Levante Site: a)Best fitting profiles; b) Dispersion curves of soil profiles compared with the experimental dispersion curve; c) Absolute value of the Haskell-Thomson matrix determinant for the best fitting model compared to the experimental dispersion curve.

Figure 2 Ispica Site: a)Best fitting profiles; b) Dispersion curve of soil profiles compared with the experimental dispersion curve; c) Absolute value of the Haskell-Thomson matrix determinant for the best fitting model compared to the experimental dispersion curve.

Figure 3 Santa Croce Site: a)Best fitting profiles; b) Dispersion curve of soil profiles compared with the experimental dispersion curve; c) Absolute value of the Haskell-Thomson matrix determinant for the best fitting model compared to the experimental dispersion curve.

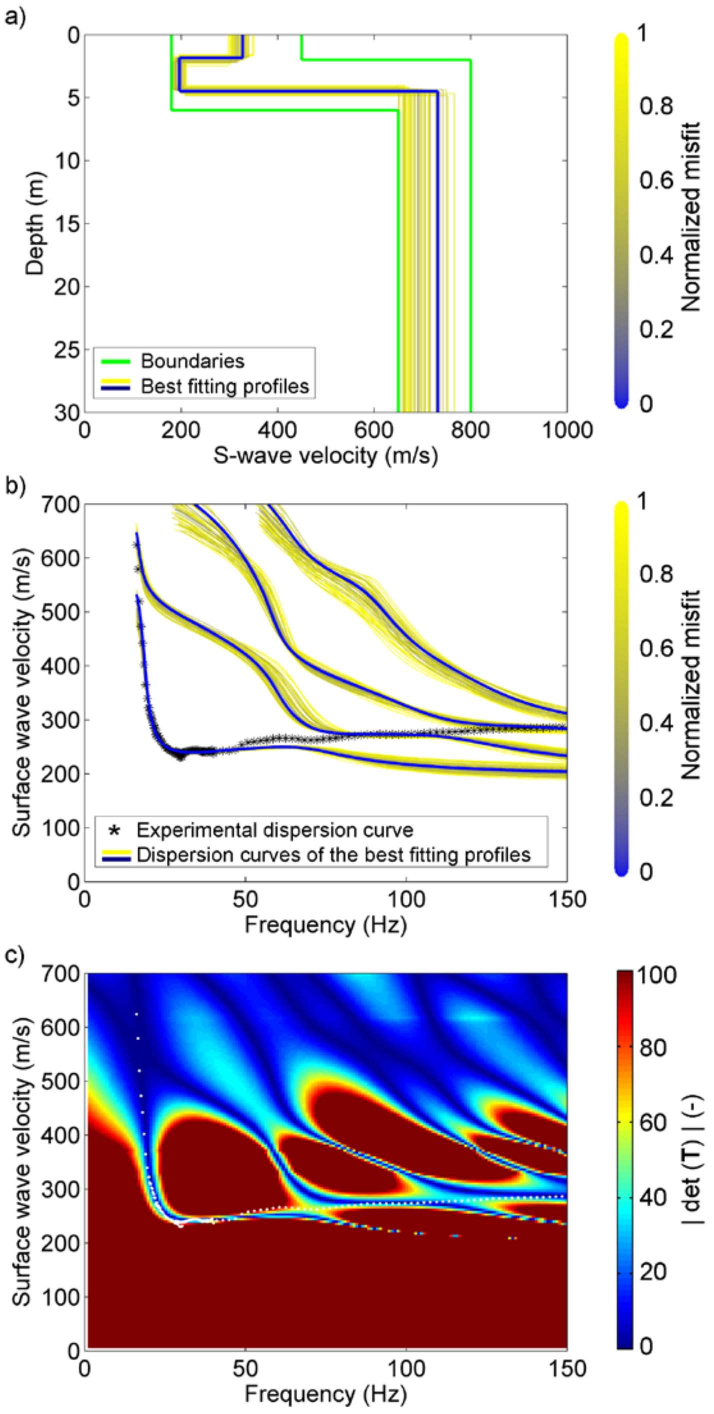
Figure 4 Varese Ligure Site: a)Best fitting profiles; b) Dispersion curves of soil profiles compared with the experimental dispersion curve; c) Absolute value of the Haskell-Thomson matrix determinant for the best fitting model compared to the experimental dispersion curve.

Figure 5 Amplification functions for the soil profiles at each site compared to the theoretical resonance frequencies: a) Sestri Levante; b) Ispica; c) Santa Croce; d) Varese Ligure.

Figure 6 Comparison of amplification functions for the soil profiles, theoretical resonance frequencies and H/V spectral ratios: a) Sestri Levante; b) Varese Ligure.

Figure 7 Box plots representing the uncertainty in the profile parameters (velocities and thicknesses) and in the local site response characteristics ($V_{S,h}$ and fundamental frequency) for a) Sestri Levante and b) Varese Ligure sites.

Figure 1


a)
0
5
10
15
20
25
30
Depth (m)
0
200
400
600
800
1000
S-wave velocity (m/s)
Boundaries
Best fitting profiles
1
0.8
0.6
0.4
0.2
0
Normalized misfit
b)
700
600
500
400
300
200
100
0
Surface wave velocity (m/s)
0
50
100
150
Frequency (Hz)
* Experimental dispersion curve
Dispersion curves of the best fitting profiles
1
0.8
0.6
0.4
0.2
0
Normalized misfit
c)
700
600
500
400
300
200
100
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Surface wave velocity (m/s)
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Frequency (Hz)
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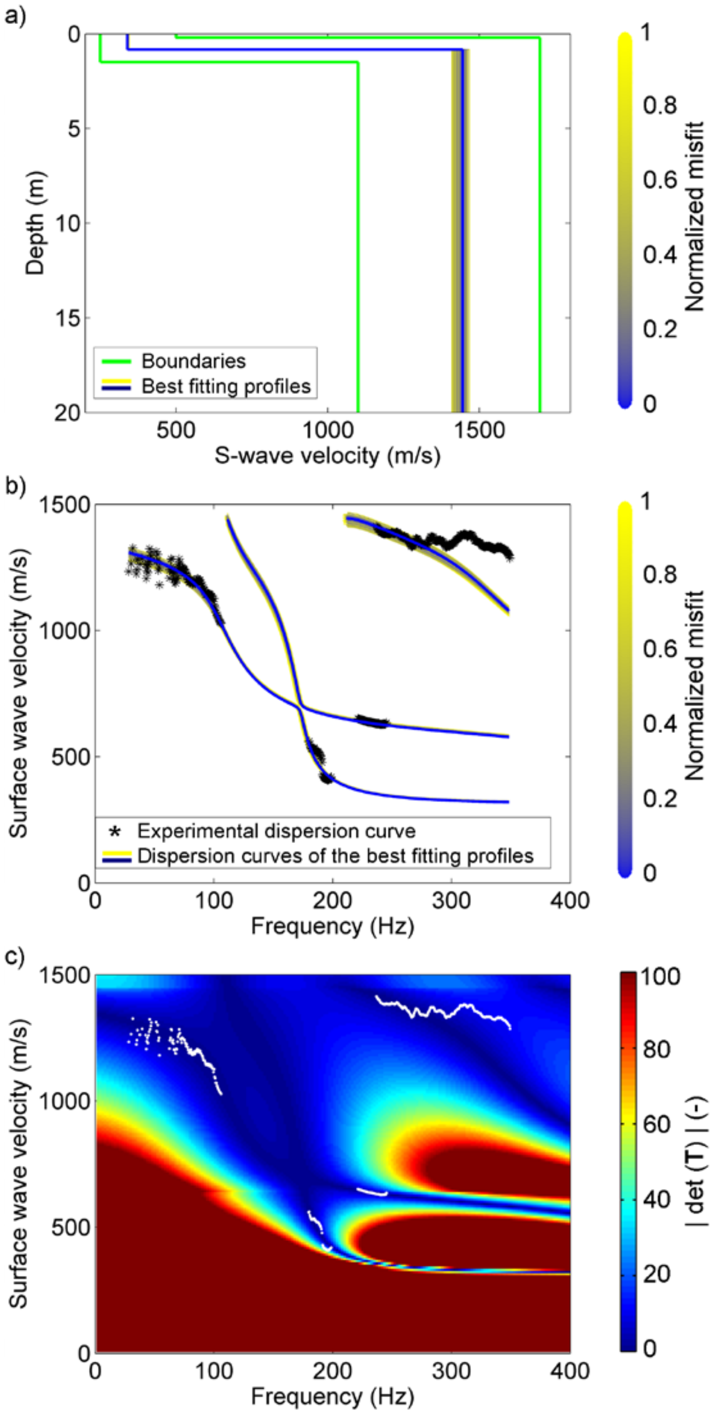
| det (T) | (-)

Figure 2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Depth (m)
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S-wave velocity (m/s)
Boundaries
Best fitting profiles
Normalized misfit
1
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0.6
0.4
0.2
0
b)
Surface wave velocity (m/s)
1500
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500
0
100
200
300
400
Frequency (Hz)
* Experimental dispersion curve
Dispersion curves of the best fitting profiles
Normalized misfit
1
0.8
0.6
0.4
0.2
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c)
Surface wave velocity (m/s)
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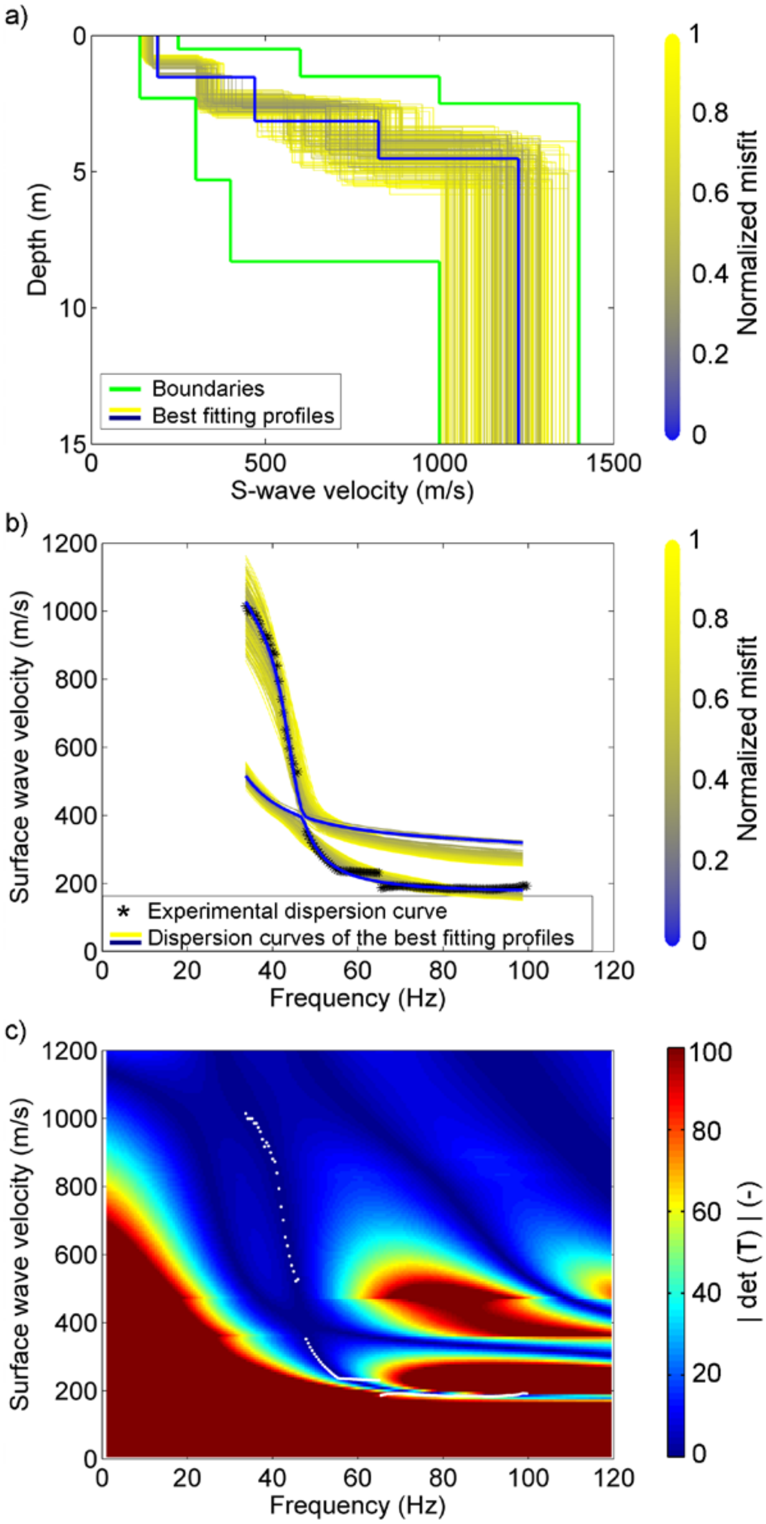
Figure 3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S-wave velocity (m/s)
Boundaries
Best fitting profiles
Normalized misfit
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0.8
0.6
0.4
0.2
0
b)
Surface wave velocity (m/s)
1200
1000
800
600
400
200
0
Frequency (Hz)
0
20
40
60
80
100
120
* Experimental dispersion curve
Dispersion curves of the best fitting profiles
Normalized misfit
1
0.8
0.6
0.4
0.2
0
c)
Surface wave velocity (m/s)
1200
1000
800
600
400
200
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Frequency (Hz)
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| det (T) | (-)
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40
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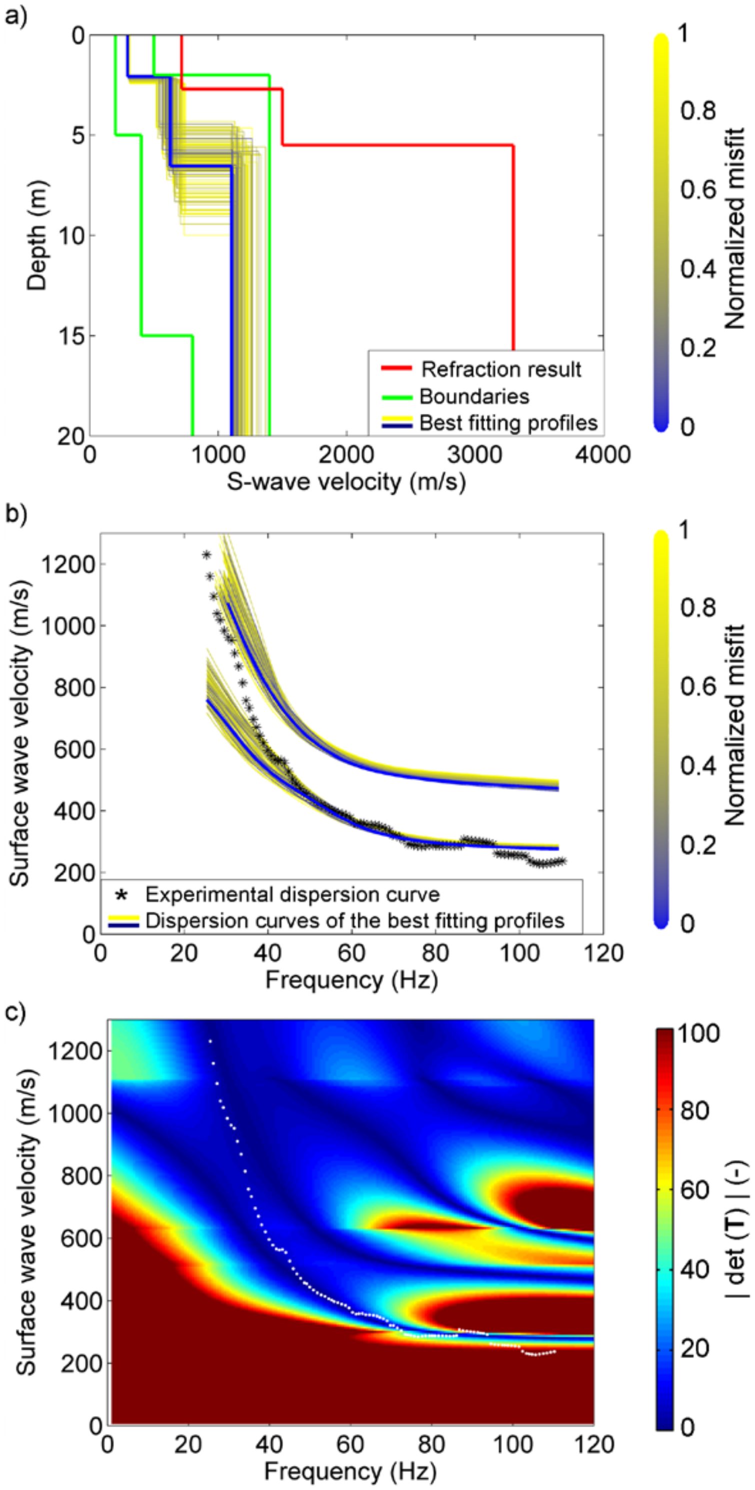
0

Figure 4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Depth (m)
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10
15
20
0
1000
2000
3000
4000
S-wave velocity (m/s)
Refraction result
Boundaries
Best fitting profiles
Normalized misfit
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0.8
0.6
0.4
0.2
0
b)
Surface wave velocity (m/s)
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
Frequency (Hz)
* Experimental dispersion curve
Dispersion curves of the best fitting profiles
Normalized misfit
1
0.8
0.6
0.4
0.2
0
c)
Surface wave velocity (m/s)
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1000
800
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200
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80
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120
Frequency (Hz)
| det (T) | (-)
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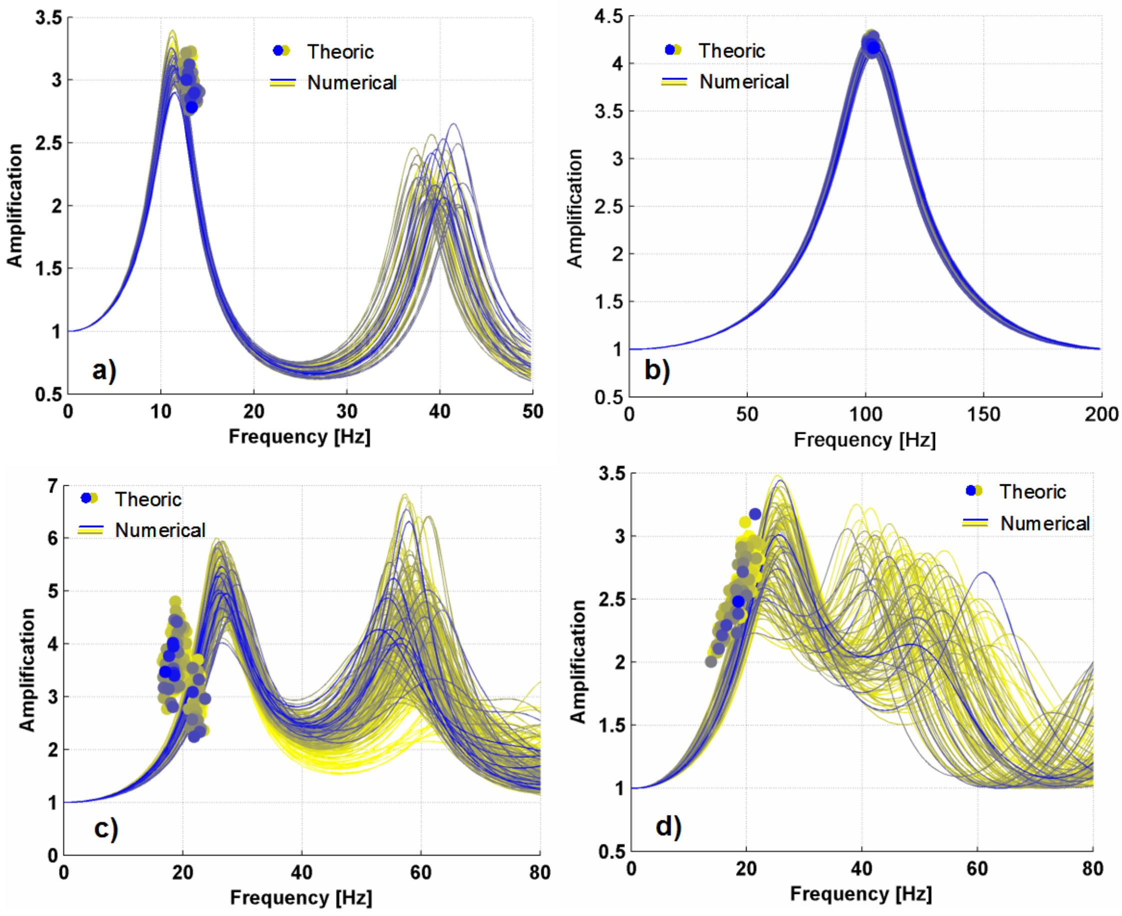
Figure 5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Theoric
Numerical
Amplification
Frequency [Hz]
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2.5
3
3.5
0
10
20
30
40
50
b)
Theoric
Numerical
Amplification
Frequency [Hz]
0.5
1
1.5
2
2.5
3
3.5
4
4.5
0
50
100
150
200
c)
Theoric
Numerical
Amplification
Frequency [Hz]
0
1
2
3
4
5
6
7
0
20
40
60
80
d)
Theoric
Numerical
Amplification
Frequency [Hz]
0.5
1
1.5
2
2.5
3
3.5
0
20
40
60
80

Figure 6

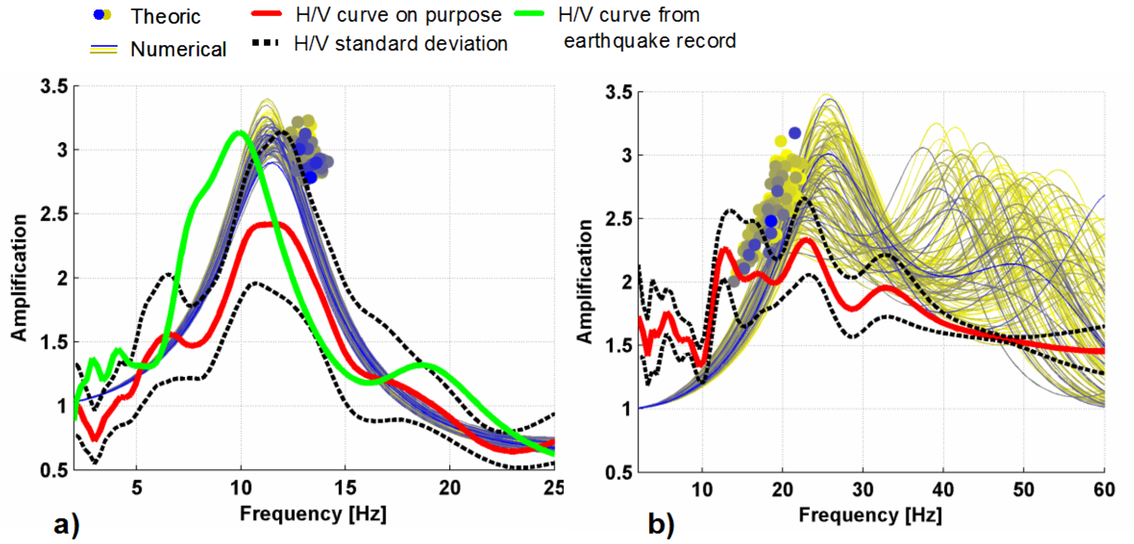

Figure 7