NEAR-SURFACE SHEAR WAVE ATTENUATION BY DECONVOLUTION OF BOREHOLE RECORDS: A SENSITIVITY ANALYSIS BASED ON SYNTHETIC WAVEFIELDS

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ABSTRACT

Near-surface shear wave attenuation characteristics of a site are crucial for the accurate prediction of seismic ground motion. However, attenuation is usually either approximated by means of empirical correlations or inferred based on limited laboratory data. An empirical method for the assessment of attenuation, which uses high-quality borehole earthquake data, has been proposed by Fukushima et al. (2016). The method is based on a deconvolution analysis of the seismogram recorded downhole and at the wellhead, which allows the separation of the incident and surface-reflected waves on the deconvolved time series. A frequency-dependent attenuation is, then, estimated from the transfer function between the incident and reflected waves. In this study we aim to define the limitations in the applicability of this method, which essentially depends on how well the incident and reflected waves are separated on the deconvolved time series. To this end, we use 1D synthetic wavefields to perform a sensitivity analysis through examining the effect of different parameters involved in the methodology, such as downhole sensor depth, existence of a high shear wave velocity contrast and location of the downhole sensor with respect to the velocity contrast depth. Additionally, the frequency band for which the method results in satisfactory estimates of attenuation is examined. Results are promising for extending the application of the method to sites of relatively shallow borehole instrumentation.

Keywords: Attenuation; Deconvolution; Borehole

1. INTRODUCTION

As revealed by observations of ground motion recorded in the last four decades, local soil conditions have a significant influence on the amplitude level, frequency content, and duration of surface ground motion (Assimaki et al. 2006). This influence, i.e. the changes in seismic waves as they travel through unconsolidated sediments overlaying stiff formations, usually considered as “bedrock”, is commonly described using the term “site effect”. So far, site effect studies have focused more on the estimation of the shear wave velocity structure, while near-surface shear wave attenuation (anelastic, scattering, higher damping due to nonlinear behavior of the soil), which is equally important to interpret and predict seismic ground motion in a realistic manner, is usually either inferred based on limited laboratory data or approximated by means of empirical correlations (e.g. Olsen et al. 2000). Although such correlations have been found to be adequate for low frequencies (Maurfroy et al. 2015), they are not efficient for high frequencies (Laurendeau et al. 2017).

One of the challenges in studying attenuation and site effects in general is the use of proper reference

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motion, which can be considered “clear” of any site effect. An additional troublesome task is the isolation of the site effect from its combined imprint in ground motion records with the earthquake source and travel path effects. In order to overcome these difficulties, vertical arrays of ground motion recording sensors are being deployed around the globe at increasing rates. Using proper techniques, downhole records are deconvolved from surface records at the wellhead to provide the transfer function in-between the two sensors (e.g., Abercrombie 1997 and references therein, Abercrombie 1998; Sawazaki et al. 2009; Parolai et al. 2009; Bindi et al. 2010, Pech et al. 2012). Recently, Fukushima et al. (2016) proposed a promising method to study shear-wave (S-wave) attenuation in sediments by the use of borehole array data, which is based on a deconvolution analysis of the seismogram recorded at the bottom of the borehole with respect to the seismogram recorded at ground surface. The effectiveness of the method depends on whether it is possible to clearly separate the incident (upgoing) and surface-reflected (downgoing) waves on the deconvolved time series, which, in its turn, depends on the S-wave travel time between surface and borehole sensors. In its original form, the method is suggested to be restricted to applications in rather deep vertical arrays (>300 m depth), with theoretical S-wave two-way travel time between surface and borehole sensors being larger than 0.5 s. In the present work, we implement and present several synthetic tests using the method as originally proposed by Fukushima et al. (2016) as well as with some improvements, in order to conclude on the ability of the method to accurately predict attenuation and on a potential extensibility of the application of the method to shallower borehole arrays.

2. SHEAR WAVE ATTENUATION ESTIMATION METHOD

The method proposed by Fukushima et al. (2016) is based on a deconvolution analysis of the seismogram recorded at the bottom of the borehole with respect to the seismogram recorded at ground surface and the identification of the incident and surface-reflected waves on the deconvolved time series. The transfer function $H(f)$ between the incident and reflected waves can then be used to estimate frequency-dependent S-wave attenuation ($Q_s^{-1}(f)$) values using the following equation:

$$Q_s^{-1}(f) = -\frac{\ln[H(f)]}{\pi f \tau'}$$  

where $\tau'$ is the two-way travel time (2r) between the bottom and the top of the borehole, which corresponds to the time separation between the incident and surface-reflected waves.

In the present study the method was applied to simple site models with a constant shear wave velocity $V_s$ and quality factor $Q_s$ (see Section 3.1), using synthetic wavefields. Through this modeling, we aimed to check whether the assumed attenuation characteristics of the adopted site models are accurately recognized, as well as to identify the frequency band for which the method results in satisfactory estimates of attenuation.

The synthetic wavefields were computed using linear SH-1D simulation approach implementing the 1D reflectivity method of Kennett (1974). This approach allows the theoretical transfer function computation of a horizontally stratified layered medium using velocity, attenuation and density profiles. We used the original Fortran software written by Gariel and Bard and applied in several previous studies (e.g., Bard and Gariel 1986; Laurendeau et al. 2017). For one given computation case (one given $V_s$ profile and one $Q_s$ profile), we compute the theoretical transfer function (TTF) from the bottom of the modeled soil column to a “virtual” sensor at surface and to a “virtual” sensor located at a given depth (that includes both upgoing and downgoing wavefield effects). All computations were performed using a vertically incident S plane wave.

As for input signals, 30 actual acceleration time histories were used. These signals were selected from the database of the ARGONET vertical array (Cephalonia Island, W. Greece; Hollender et al. 2015; Theodoulidis et al. 2018), in order to perform analysis on waveforms that are representative in terms of frequency content, duration, phase, etc. of signals that may be used for a later application of attenuation estimation by the deconvolution approach. The selected time histories correspond to the 30 strongest recordings [in terms of Peak Ground Acceleration (PGA)] at the deepest sensor of the vertical array (83 m), which has been placed within the engineering bedrock. Recordings of events
with magnitude higher than 5 were excluded from the selection procedure to avoid time histories that carry significant source effects. The finally selected input signals correspond to events of magnitude 2.5 to 4.9, with hypocentral distances from 15 to 45 km, recorded between August 2015 and September 2016 with a time step $dt=0.005s$. Amplitude spectral density of the 30 selected signals as well as their geometrical mean are shown in Figure 1.

These signals, after the application of a very basic processing (linear trend removal, taper) were convolved to the TTFs computed with the 1D reflectivity method for different profiles at surface and at a given depth corresponding to the downhole sensor depth of each model to obtain the acceleration time histories at the surface and downhole sensor depth, resulting in 30 pairs of synthetic accelererograms (downhole and at the wellhead). The accelerograms at the downhole sensor were then deconvolved from the respective accelerograms at the ground surface applying a regularized Tikhonov deconvolution approach (Tikhonov and Arsenin 1977; Parolai et al. 2009; Petrovic et al. 2017). The upgoing and downgoing waves were finally identified at the deconvolved time traces.

Time-window length $w$ for both the incident and reflected phases was initially selected so as to maximize a coherence-dependent coefficient $C$ (Fukushima et al. 1992; 2016). This process, hereafter referred to as “coherence-based approach”, was occasionally found to result in quite short durations for the incident and reflected waves (e.g., Figure 2a). For this reason, we tested an additional approach for the selection of $w$, hereafter referred to as “travel-time-based approach”, in which $w$ is proportional to the travel time $\tau$ between the bottom and the top of the borehole value, with a maximum value of 2s:

$$w(s) = \max\begin{cases} 2\tau, & \tau < 1s \\ 2, & \tau > 1s \end{cases}$$  

A representative example of the selection of the upgoing and downgoing waves for a homogeneous soil profile with $V_s = 500m/s$, $Q_s = 50$ and downhole sensor located at 405 m depth using the two approaches described above is shown in Figure 2.

In order to estimate a mean attenuation from the 30 different pairs of synthetic accelerograms, two approaches were followed. The different steps are described in detail in the following, while a schematic description of the two approaches is shown in Figure 3. In the first approach, deconvolution analysis was performed individually for each one of the 30 pairs of input signals (Figure 3a). Each deconvolved time series was subsequently used to calculate a transfer function between the incident and surface-reflected waves. The derived transfer functions (30) were then stacked to estimate the logarithmic mean transfer function (Figure 3b). A mean $Qs^{-1}$ was finally estimated from the logarithmic mean of the stacked transfer functions using Equation (1), as proposed by Fukushima et al. (2016) (Figure 3c). This approach will be referred to as “stacked transfer functions approach” in the following. In the second approach the deconvolved time series obtained from the individual 30 pairs of accelerograms were stacked and upgoing and downgoing waves were identified on the average of the stacked time series (Figure 3d). The transfer function between the incident and reflected waves obtained from the average of the stacked deconvolved time series was then calculated (Figure 3e) and
was used to estimate a mean $Qs^{-1}$ using Equation (1) (Figure 3f). This approach will be referred to as “stacked time series approach” in the following. The purpose of both stacking processes was to reduce the effect of noise in the estimation of $Qs^{-1}$ values.

Figure 2. Example results of the deconvolution of a synthetic accelerometric time history at a downhole sensor from the respective trace at a surface sensor. Synthetic waveforms correspond to a homogeneous soil profile of $V_s = 500\text{m/s}$ and frequency-independent $Qs = 50$. Automatically selected durations of incident and reflected waves are shown in color (red and blue, respectively) for two different approaches: (a) the “coherence-based approach” after Fukushima et al. (1992, 2016) and (b) the “travel-time-based approach” suggested herein.

Figure 3. Schematic description of the steps in the estimation of attenuation using the “stacked transfer functions approach” (top; a-c) and the “stacked time series approach” (bottom; d-f). (a) Normalized deconvolved time series for the 30 pairs of synthetic accelerograms (in gray), (b) Transfer functions from the individual deconvolved time series of Figure 3a (in gray) and logarithmic mean transfer function (in black) and (c) Mean $Qs^{-1}$ resulting from the logarithmic mean transfer function of Figure 3b. (d) Normalized deconvolved time series for the 30 accelerograms (in gray), stacked mean deconvolved time trace (in black), incident (in red) and reflected (in blue) waves identified on the stacked mean deconvolved time trace, (f) Transfer function resulting from the stacked mean deconvolved time trace of Figure 3d (in black) and (f) Mean $Qs^{-1}$ resulting from the transfer function of Figure 3e.
3. SENSITIVITY ANALYSIS WITH SYNTHETIC WAVEFIELDS

3.1 Description of Synthetic Models

The applicability of the Fukushima et al. (2016) method is investigated through a series of synthetic tests with respect to the following parameters: i) the depth of the downhole sensor, ii) the depth of the input motion, iii) the existence of a high shear wave velocity contrast and iv) the location of the velocity contrast with respect to the location of the downhole sensor. In particular, six sets of synthetic tests were performed. The basic characteristics of the sets are summarized in Table 1 and described in detail in the following.

Table 1. Characteristics of the synthetic sets (From left to right: Code name of the synthetic test; Bedrock Depth; Downhole sensor depth; shear-wave velocity in sediments, \( V_{S,\text{sed}} \); shear-wave attenuation factor in sediments, \( Q_{S,\text{sed}} \); sediments material density, \( \rho_{\text{sed}} \); shear-wave velocity in bedrock, \( V_{S,\text{bed}} \); shear-wave attenuation factor in bedrock, \( Q_{S,\text{bed}} \); bedrock material density, \( \rho_{\text{bed}} \) and input signal depth).

<table>
<thead>
<tr>
<th>Synthetic Test Code</th>
<th>Bedrock depth (m)</th>
<th>Downhole sensor depth ( H ) (m)</th>
<th>( V_{S,\text{sed}} ) (m/s)</th>
<th>( Q_{S,\text{sed}} )</th>
<th>( \rho_{\text{sed}} ) (kg/m³)</th>
<th>( V_{S,\text{bed}} ) (m/s)</th>
<th>( Q_{S,\text{bed}} )</th>
<th>( \rho_{\text{bed}} ) (kg/m³)</th>
<th>Input depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 01</td>
<td>-</td>
<td>5-2000</td>
<td>500</td>
<td>50</td>
<td>2200</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3000</td>
</tr>
<tr>
<td>Set 02</td>
<td>-</td>
<td>5-2000</td>
<td>500</td>
<td>50</td>
<td>2200</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>7.5-3000 (1.5-( H ))</td>
</tr>
<tr>
<td>Set 03</td>
<td>5.0-2000</td>
<td>5-2000</td>
<td>500</td>
<td>50</td>
<td>2200</td>
<td>2500</td>
<td>250</td>
<td>2700</td>
<td>7.5-3000 (1.5-( H ))</td>
</tr>
<tr>
<td>Set 04</td>
<td>5.5-2200 (1.1-( H ))</td>
<td>5-2000</td>
<td>500</td>
<td>50</td>
<td>2200</td>
<td>2500</td>
<td>250</td>
<td>2700</td>
<td>7.5-3000 (1.5-( H ))</td>
</tr>
<tr>
<td>Set 05</td>
<td>4.5-1800 (0.9-( H ))</td>
<td>5-2000</td>
<td>500</td>
<td>50</td>
<td>2200</td>
<td>2500</td>
<td>250</td>
<td>2700</td>
<td>7.5-3000 (1.5-( H ))</td>
</tr>
<tr>
<td>Set 06</td>
<td>182</td>
<td>5-182</td>
<td>500</td>
<td>50</td>
<td>2200</td>
<td>2500</td>
<td>250</td>
<td>2700</td>
<td>273 (1.5-( H ))</td>
</tr>
</tbody>
</table>

Set 01 (Figure 4a) consists of 16 homogeneous sedimentary models, with downhole sensor located at 16 different depths, \( H \), ranging from 5 m to 2000 m with a constant ratio of 1.491 between successive depths. Shear wave velocity \( V_{S,\text{sed}} \), quality factor \( Q_{S,\text{sed}} \) and density \( \rho_{\text{sed}} \) for the sediments material are listed in Table 1. Input motion for 1D analyses is introduced at 3000 m for all 16 models regardless of downhole sensor depth. This simulation detail may result in a significant limitation of the effectiveness of the attenuation estimation method at high frequencies for shallow sensor depths, due to the significant anelastic attenuation of short wavelengths before they reach the downhole sensor. In order to gain insight into this issue, which is related mostly to the adopted simulation methodology rather than to the attenuation estimation methodology itself, Set 02 was composed (Figure 4b). Set 02 consists of 16 homogeneous models with the same geometric and material characteristics as those of Set 01 but differentiates from Set 01 in the depth at which input motion is introduced, which in this case was selected to “follow” the downhole sensor depth at a small distance and is located at a depth equal to 1.5-\( H \), where \( H \) is the downhole sensor depth. In order to investigate the effect of the existence of a high shear wave velocity contrast, Set 03 was designed (Figure 4c), which differentiates from Set 02 in the fact that the 16 models consist of a homogenous sedimentary layer, which is located above a homogeneous half-space. Material properties for the half-space (\( V_{S,\text{bed}}, Q_{S,\text{bed}}, \rho_{\text{bed}} \)) are listed in Table 1. The interface between the sediments and the bedrock for Set 03 is always located at the downhole sensor depth, which is a very common case for downhole arrays installation projects. However, since it is not always obvious to know whether the downhole sensor is actually located at the sediments / bedrock interface, two more sets were designed: Set 04 is the same as Set 03 but the bedrock depth is 10% deeper than the sensor depth, so that the sensor is located within the sediments but close enough to the bedrock and Set 05 is the same as Set 03 but the bedrock depth is 10% shallower than the sensor depth, so that the sensor is located within the bedrock but close enough to the sediments. Finally, in order to examine the effect of the existence of a high shear wave velocity contrast when the interface is located far below the sensor, an additional set was composed (Set 06),...
which has the same properties as Set 03 but the bedrock interface is located at a fixed depth (Figure 4d). A depth equal to 182 m was selected for the location of the interface for Set 06, which is a case close to most vertical arrays in operation around Europe. Input motion for models of Set 06 is introduced at 273 m depth.

3.2 Application of the Near-Surface S-wave Attenuation Estimation Method

The methodology applied for each model of each set can be summarized in steps as follows:
1) 1D site response analysis was performed using 30 accelerograms as input motion to obtain the acceleration time histories at the surface and downhole sensor depth.
2) The acceleration time history recorded at the bottom of the borehole was deconvolved with respect to the acceleration time history at the surface.
3) Incident and surface-reflected waves were identified on the deconvolved time series using the “coherence-based” and the “travel-time-based” approaches for window selection.
4) Mean attenuation was calculated using the “stacked transfer functions” and the “stacked time series” approaches. Combination of steps 3 and 4 resulted in four different “mean” attenuation curves for each model.
5) The frequency band for which the estimated attenuation was within a 20% tolerance interval with respect to the actual attenuation of the model was identified for each of the four “mean” attenuation curves of each model.

An indicative example of the four “mean” attenuation curves resulting from the application of the adopted methodology for the model with downhole sensor depth $H = 1341$ m of Set 02 is illustrated in Figure 5. The target value of attenuation, i.e. the actual attenuation of the model assumed for the 1D analysis, and the respective 20% tolerance interval are also plotted in the figure. The frequency band for which each of the four “mean” attenuation curves falls within the adopted tolerance interval
(hereinafter referred to as “valid frequency intervals”) are shown at the bottom of Figure 5. An example of how the valid frequency interval for the “coherence-based - stacked transfer function” approach was obtained from the respective “mean” attenuation curve is also included in Figure 5 (black arrows).

Figure 5. $Q_s^{-1}$ derived for the synthetic test with downhole sensor depth $H = 1341$ m of Set 02. Top: Mean attenuation curves obtained using the “coherence-based - stacked transfer functions approach” (continuous red line), the “coherence-based - stacked time series approach” (dashed red line), the “travel-time-based - stacked transfer functions approach” (continuous blue line), and the “travel-time-based - stacked time series approach” (dashed blue line), superimposed on the target value of attenuation (gray dashed line) and the respective 20% tolerance interval (gray shaded area). Bottom: Valid frequency intervals for each of the approaches of top figure. Black crosses and arrows mark the exact boundaries for the valid frequency interval of the “coherence-based – stacked transfer functions” approach.

### 3.3 Results

Figure 6 summarizes for all sets the results in terms of valid frequency interval. Each subplot of Figure 6 represents the results of a specific set. In each subplot the results referring to both approaches for window selection (coherence-based in red color and travel-time based in blue color), as well as for “mean” attenuation estimation (stacked transfer functions in continuous line and stacked time series in dashed line) are plotted. For the models with a shear wave velocity contrast (Sets 03, 04, 05, 06), the fundamental frequencies, as well as the frequencies of the first, second and third higher modes are also plotted as continuous gray lines.

It is reminded that the main parameter affecting the applicability of the method is the travel time between the downhole and surface sensors, however, for convenience, the discussion in the following will take place in terms of downhole sensor depth rather than travel time, as all the models share the same shear wave velocity.
Figure 6. Frequency intervals for which attenuation is adequately retrieved (actual input value ± 20%) for synthetic test sets a) 01, b) 02, c) 03, d) 04, e) 05 and f) 06. Results of different approaches for the window selection of up going and down going waves, as well as for the estimation of attenuation (stacked transfer functions and stacked time series) are shown in different colors and lines, respectively. Gray lines correspond to the fundamental frequency and frequencies of the first three higher modes and are presented only for models that include a shear-wave velocity contrast (bedrock to sediments).

An overall observation of Figure 6 reveals that the applied method is in most cases able to accurately identify the actual attenuation for models with downhole sensor depths greater than about 40-50 m, however the valid frequency intervals for the different models and depths vary significantly. The comparison between the results obtained from the different sets allows us to draw some conclusions on the ability of the methodology, originally proposed by Fukushima et al. (2016) and modified in this study, to accurately predict attenuation, depending on the one hand on the alternatives offered by the methodological framework and on the other hand on the inherent characteristics of the site under investigation. Discussion of results with respect to the different tested approaches in the implementation of the Fukushima et al. (2016) method, as well as different characteristics of the tested
models is presented in the following.

3.3.1 Input motion

In order to examine the effect of the input motion depth, which is rather a matter of simulation methodology than of applicability of the methodology for attenuation estimation by deconvolution, results obtained for Set 01 (Figure 6a) and Set 02 (Figure 6b) are compared. It is reminded that Sets 01 and 02 have the same geometric and material characteristics. However, in Set 01 input motion for 1D analyses is introduced at 3000 m for all models regardless of downhole sensor depth, while in Set 02 the input motion depth is located at a small depth below the downhole sensor, equal to $1.5 \cdot H$, where $H$ is the downhole sensor depth. It is observed that the valid frequency intervals for the models of Set 02 extend to higher frequencies compared to the respective models of Set 01. This can be explained as follows: for the models of Set 01, short wavelengths propagated within the 1D soil columns are already significantly attenuated by the time they reach shallower depths and their amplitude is not sufficient to reveal the desired result. On the contrary, in Set 02 the input signal is gradually migrating, following the downhole sensor depth, i.e. the signal to noise ratio (SNR) at high frequencies is strong enough to reveal the correct attenuation. Taking advantage of this observation, input motion for sets 03, 04, 05 is introduced at a small depth below the downhole sensor similarly to Set 02, which in the following will serve as a reference for comparisons with results from the other sets. It should be noted that these results are probably related also to the quality factor value of the bedrock ($Q_{s,\text{bed}}$), and thus cannot be extrapolated to structures with lower $Q_{s,\text{bed}}$ values or lower SNR at high frequencies.

3.3.2 Alternative approaches for window selection

Valid frequency intervals obtained from the “travel-time-based” approach for window selection of upgoing and downgoing waves are wider compared to those obtained from the “coherence-based” approach. This result is more pronounced in subplots 5b and 5d, where at larger depths the valid frequency intervals extend to significantly lower frequencies. This is valid for both the “stacked transfer functions” and the “stacked time series” approaches for attenuation estimation. For example, for the model of Set 03 with downhole sensor located at 2000 m depth (Figure 6c), the valid frequency interval when using the “coherence-based - stacked transfer functions” approach (red continuous line) is 4.9-9.9 Hz, while for the “travel-time-based- stacked transfer functions” approach (blue continuous line) it is 1.1-8.9 Hz, i.e., significantly wider for the latter. This observation implies that the use of travel times instead of the coherency factor $C$ in the selection of upgoing and downgoing waves windows result in more stable estimations of the attenuation at lower frequencies. This is compatible, of course, with the fact that the “travel-time-based” approach provides, in general, wider windows with respect to the “coherence-based” approach and, thus, allows the incorporation of information carried by larger wavelengths.

3.3.3 Alternative approaches for “mean” attenuation estimation

The use of the “stacked time series” approach for attenuation estimation results in a wider valid frequency interval compared to using the “stacked transfer functions” approach, especially at high frequency. This is more pronounced when the “coherence-based” approach is applied for the window selection of upgoing and downgoing waves. For example, for the model of Set 03 with downhole sensor located at 2000 m depth (Figure 6c), the valid frequency interval when using the “coherence-based - stacked transfer functions” approach (red continuous line) is 4.9-9.9 Hz, while for the “coherence-based - stacked time series” (red dashed line) it is 1.2-13.4 Hz.

3.3.4 Downhole sensor depth in homogeneous media

In purely homogeneous media (Set 02), the depth of the downhole sensor has a significant impact on the effectiveness of the tested method. As the downhole sensor depth increases, the valid frequency interval is more extended and shifted to lower frequencies (Figure 6b). The evolution of the lower bound of the valid frequency interval towards lower frequencies for larger depths is probably related
to the length of the analyzed windows, which are wider for the deeper cases and thus more appropriate for a low frequency analysis. On the other hand, the evolution of the high bound of the valid frequency interval towards lower frequencies for larger depths is related to the lack of high frequency in signal for the deeper boreholes.

For downhole sensor depth greater than 50 m, the proposed methodology seems to be able to accurately predict attenuation for a very wide frequency interval, ranging between around 0.6-1 Hz and 10-45 Hz, depending on the downhole sensor depth and the selected approaches for window selection and “mean” attenuation estimation. For example, for Set 02, the valid frequency interval resulting from application of the “travel-time-based- stacked time series” approach (blue dashed line) is 0.8-43.2 Hz for the model with downhole sensor depth equal to 271 m and 0.5-12 Hz for the model with downhole sensor depth equal to 2000 m. This observation supports the relaxation of the criterion set by Fukushima et al. (2016), which suggests the method to be applicable to deep vertical arrays with borehole seismometers located at a depth greater than 300 m, as far as the relevant frequency range is considered.

For very shallow boreholes (<25 m), the overall applicability of the method is limited likely due to the impotence of the method to separate upgoing and downgoing waves. However, the method is still able to accurately predict the actual attenuation of the site for a limited frequency range shifted to high frequencies. In applications of the method with real data, this practically means that the attenuation could be estimated even at quite shallow depths, provided that the input signal is rich in high frequencies, and digitized with a small enough time step.

3.3.5 Existence of shear-wave velocity contrast when downhole sensor is close to the interface

A comparison of the results obtained for models of Set 02 (Figure 6b), which are homogeneous, and those of Set 03 (Figure 6c), for which there is a sharp shear wave velocity contrast at the downhole sensor depth of each model, shows that the existence of the sediments-bedrock interface significantly limits the effectiveness of the proposed methodology for low frequencies, especially when the “travel-time - based” approach is used for the window selection. This observation is more evident for deep boreholes. For example, for the model with downhole sensor depth located at 603 m, the lower boundary of the valid frequency interval when using the “travel-time - based” approach is about 0.8 Hz for the homogeneous case (blue continuous and dashed lines in Figure 6b), while it is about 2 Hz for the homogeneous over half-space case (blue continuous and dashed lines in Figure 6c). It should be noted, however, that the “travel-time – based” approach continues to present better or comparable performance to the “coherence – based” approach. For shallower boreholes (< 122 m), the presence of the interface limits the validity frequency range also at high frequencies, while for very shallow boreholes (<55m) the applicability of the method is practically inadequate. Regarding the relation between the valid frequency interval and the resonant frequencies, an overall look of Figure 6c shows that the methodology is ineffective for frequencies below that of the second higher mode.

In order to further investigate how the location of the bedrock interface with respect to downhole sensor location affects the valid frequency intervals, results from Set 03 are compared to those of Set 04, where bedrock depth is 10% deeper than the sensor depth, and Set 05, where bedrock depth is 10% shallower than the sensor depth. It can be observed that the lower performance of the method for deep boreholes at low frequencies due to the existence of a bedrock interface described in the previous paragraph can be overcome if the downhole sensor depth is located close to the bedrock but within the sediments, as suggested by Fukushima et al. (2016). For the model with borehole sensor located at 603m depth, the lower boundary of the valid frequency interval when the sensor is within the sediments is around 0.8Hz or lower (blue continuous and dashed lines in Figure 6d), i.e., it is equal to the respective value for the homogeneous case (Figure 6b). On the other hand, when the sensor is within the bedrock (Figure 6e), results are similar to those of the case of the sensor located exactly at the interface.

3.3.6 Existence of shear-wave velocity contrast when downhole sensor is far from the interface

A comparison of the results between Set 06 (fixed interface at 182m - Figure 6f) and Set 02 (purely homogeneous - Figure 6b), shows that when the interface is located far below the sensor as in Set 06,
the results are similar to those for homogeneous media for frequencies higher than the frequency of the 2nd higher mode. The upper limit of the valid frequency interval in Figure 6f appears to be stable in all combinations of approaches and depths. We attribute this result to the fact that the input signal is close enough (at 283 m depth) to re-assure significant amplitudes of the wavelengths carrying the information that we wish to extract.

4. CONCLUSIONS

The deconvolution method of borehole records proposed by Fukushima et al. (2016) for the estimation of near-surface shear-wave attenuation was investigated through a series of synthetic tests with respect to the strictness of its originally suggested application criteria and more specifically with respect to the minimum depth of the borehole, which according to Fukushima et al. (2016) should be 300 m with theoretical S-wave two-way travel time between surface and borehole sensors being larger than 0.5 s. We tested the method in its original form, as well as with modifications aiming to increase the width of the frequency interval within which attenuation in synthetic models is retrieved accurately.

Overall, results from synthetic tests derived in the present study converge to the conclusion that the method proposed by Fukushima et al. (2016) may be extended to attenuation studies in boreholes of shallow depth (several tens to several hundreds of meters), or more precisely, with two-way travel time smaller than 0.5 s. However, one should keep in mind that as the investigation depth gets smaller, the desired information on attenuation should be sought at higher frequencies, i.e., at wavelengths of the order of the investigation depth or smaller. In practice, this means that attenuation studies in shallow boreholes require input signal enriched in high frequencies as, for example, records from close-by earthquakes, which would also satisfy the general prerequisite in interferometry studies, i.e., that of the verticality of the incoming waveform.

Additionally, the present work highlights the effect of the inherent characteristics of the site under investigation on the effectiveness of the method. More specifically, the method is more effective when the site is either purely homogeneous, or has a bedrock interface located below the downhole sensor depth. However, results obtained for downhole sensors placed at the soil/bedrock interface (or close to it) still remain acceptable within a given frequency range. These outcomes could be taken into account when designing new synthetic tests to investigate different aspects of the method or for the deployment of actual borehole arrays, which aim at estimating near surface attenuation.

Regarding the alternatives offered by the methodological framework presented in this study, it was shown that the “travel-time-based” approach for the window selection of the upgoing and downgoing waves and the “stacked time series” approach for attenuation estimation in general result to wider valid frequency intervals and should therefore be preferred in future analyses.

The present work could be extended by performing additional synthetic tests to examine the applicability of the method to sites with more complex shear wave velocity structures (including strong short-wavelength vertical variations that may induce large scattering), frequency-dependent quality factor, event to event variability of incidence angles, different $Q_s$ values in rock or sediments, shorter time steps etc. From a methodological point of view, the effect of noise introduction on synthetics should also be addressed. The effect of the input signal duration may also be examined. The use of stochastically generated input would be useful to address this issue. The application of the method to real sites with real borehole data remains a great challenge. This may be realized in association with simulations, as shown in this paper, in order to assess the maximum frequency range of applicability of the method for a given geometry and a priori velocity structure.

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6. REFERENCES


