JOINT INVERSION OF H/V AND SURFACE-TO-BOREHOLE RATIOS TO OBTAIN S-WAVE VELOCITY STRUCTURE AND DAMPING

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ABSTRACT

With the rapid development of the diffuse field theory, the horizontal-to-vertical spectral ratios of earthquake ground motions, EHVR, at one station is turned out to be represented by the ratio of the 1-D transfer function of the vertically incident S-wave to that of the vertically incident P-wave, with amplitude correction at the bedrock. Using the EHVR we can invert the velocity structures down to the seismological bedrock where incident waves are equipartitioned. We first evaluated the EHVRs at several KiK-net sites and used them as targets for S-wave velocity inversion. We observed some directionality in the EHVRs at a couple of site, probably because of topographic and/or interface irregularity around the site. We found that the EHVR-only inversion could yield quite stable velocity structures at most sites. The comparison of the theoretical surface-to-borehole spectral ratios (H/Hb) from the inverted structure with the observed ones shows that the matching was fair and the low-frequency peak amplitudes were overestimated. The ground structures were then identified using EHVR and H/Hb simultaneously and we obtained the structures that can explain the observed spectral ratios quit well. The S-wave velocity structure identified from EHVR-only inversion was found to be similar to that identified jointly using both EHVR and H/Hb. However, the EHVR alone cannot determine the damping factors of the ground between the surface and the borehole sensors. Thus the joint inversion is advantageous in that we can determine the velocity structures down to the bedrock and the average damping factor between the sensors.

Keywords: Borehole; Diffuse field; Site amplification; Horizontal-to-Vertical ratio; Surface-to-Borehole ratio

1. INTRODUCTION

It is essential to appropriately evaluate the subsurface structure and validate previously proposed structures based on the geological data and boring exploration with the observed seismic and non-seismic data for the quantitative prediction of ground motions in urban areas. Plenty of methods can be employed to evaluate subsurface structures that can reproduce observed site characteristics. However, only a few methods can reliably determine the S-wave velocity structures down to the seismological bedrock, where the S-wave velocity reaches 3.0 km/s or higher. For more than three decades, various methods of obtaining phase velocities of propagating surface waves from array measurements of microtremors (e.g., Okada, 2003) have been successfully utilized to invert the S-wave velocity structures down to the seismological bedrock. The disadvantage of the microtremor array methods is the need to deploy as many stations as possible for the precise determination of the phase velocity at a particular frequency band. Moreover, the array size must be increased in proportion to the targeted depth. As the array size is increased, the fundamental assumption of horizontally homogeneous layering would be difficult to expect.

The spectral ratio approach with a reference site, either on the surface or inside the borehole, can be quite effective for obtaining a reliable S-wave velocity structure when combined with a standard inversion technique such as the genetic algorithm (GA). However, the spectral ratio approach with respect to the rock outcrop reference site would fail to provide reasonable site amplification either when the reference site is not sufficiently close to the target site, or when the reference site is not close to the bedrock.

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seismological bedrock in terms of its S-wave velocity. The so-called generalized spectral inversion method (Andrew, 1986) yields better site amplification characteristics if a good reference site can be found among the stations. This is because the generalized inversion makes use of all the data at once with an appropriate attenuation correction and therefore the distance between the reference site and the target site is not an issue. Once the inversion analysis is performed, the site with the smallest amplification can be selected for the reference.

With regard to the borehole-to-Surface spectral ratio (H/Hb) method there is no distance-related problem, since the horizontal locations of any two sensors should be close by. However, it is quite common to have a reference site not sufficiently close to the seismological bedrock depth, especially for deep sedimentary basin sites. Even if the borehole station would be well within a seismological bedrock formation, the borehole-to-surface spectral ratio is contaminated by the reflected phases at the free surface and the interfaces (e.g., Steidl et al. 1996; Satoh et al., 1997). Therefore, appropriate theoretical response need to be employed to account for these reflected phases. The advantage of the borehole method is that we can determine not only the S-wave velocity structures but also the damping in between the two sensors.

Recently the so-called Green’s function retrieval method based on the diffuse field concept (DFC) has been widely applied to both a lot of seismic data or long-duration of microtremors using the cross-correlation of two stations (e.g., Campillo and Paul, 2003). The dispersion characteristics of the obtained Green’s functions can be used to determine the average S-wave velocity structure between the two stations. This is quite a powerful method to determine a velocity structure averaged over the entire path between the two stations. However, the cross-correlation method cannot be used to determine the velocity structure immediately below the observed site. Moreover, earthquakes or microtremors have to be measured for a sufficiently long duration to obtain stable results.

After successfully applying the cross-correlation analysis to the seismic and microtremor data, it is natural to coincide the two stations in order to employ the auto-correlation from a single station measurement. The velocity structure immediately below the observed site can be determined using the auto-correlation approach. As a pioneering work, Margerin et al. (2009) showed that after sufficient lapse time from the onset of the S-wave the late coda could be considered to be in the diffuse field regime. Kawase et al. (2011) extended the idea of the DFC to the stack of the horizontal-to-vertical ratios of earthquakes (EHVR) and provided a simple theoretical formula assuming equipartition of energy in the incident waves at the bedrock (i.e., equipartition inside the half-space). It turned out that this is a powerful tool to determine an S-wave velocity structure below the observed site of earthquakes down to the seismological bedrock, as confirmed by Ducellier et al. (2013), Nagashima et al. (2014, 2016), and Fukihara et al. (2015). First, we provide several examples that show the successful inversion of the S-wave structures in Japan, presented in Mori et al. (2016), based on only surface records.

The disadvantage of the EHVR method is that it cannot determine the damping. This is because the effects of damping would mutually cancel out between the S-wave and P-wave amplification factors. On the other hand, the horizontal surface-to-borehole spectral ratio (H/Hb) method can be effectively used for determining damping values between two sensors. Several studies have simultaneously determined the S-wave damping factors of the layers above the borehole station and their S-wave velocities. For example, Satoh et al. (2014) analyzed one of the KiK-net stations in Japan, IBRH11, where National Institute of Earth Science and Disaster Resilience (NIED) obtained weak and strong motions during the 2011 Tohoku earthquake sequence.

In this paper we first report several examples of EHVR-only inversions for KiK-net sites in Japan. We then report our recent studies conducted based on the joint inversion of the EHVR and H/Hb ratios at a couple of KiK-net sites. As a result of the joint inversion, we successfully obtain the S-wave velocity structures down to the seismological bedrock and the average damping factors for the layers above the borehole sensors.

2. INVERSION METHOD FOR EHVR

In this chapter the background theory of the EHVR, the way of data analysis, basic characteristics of the target EHVR, and a brief description of the inversion analysis are presented.
2.1 DFC Theory for EHVR

Here we summarized the basic formulae to calculate the theoretical EHVR. Under the assumption of DFC and subsequent energy-equipartitioned condition, the diffused-wave energy spectra \( E(P, \omega) \) at point \( P \) is proportional to the normalized autocorrelation of the observed displacement \( [u(P, \omega)]^2 \), which in turn is proportional to the imaginary part of the Green’s function at \( P \) as

\[
E(P, \omega) \propto \frac{[u(P, \omega)]^2}{\int [\mathbf{u}(P, \omega)]^2 d\omega} \propto \text{Im}[G(P, P, \omega)]
\]  

(1)

For the EHVR coming from a far-field source, following Claerbout (1968), we get

\[
\frac{[u(P, \omega)]^2}{\int [\mathbf{u}(P, \omega)]^2 d\omega} = K \times |TF(\omega)|^2 = -K \times \rho_H c_H \omega \text{Im}[G_{\text{Eq}}(P, P, \omega)]
\]  

(2)

where \( \rho_H c_H \) is the impedance of the half-space and \( TF(\omega) \) is the transfer function of the corresponding body wave (\( K \) is a constant). Thus, we can obtain a simple formula for the surface observation of the seismic motions as

\[
\frac{H(0, \omega)}{V(0, \omega)} = \sqrt{\frac{\text{Im}[G_{\text{horizontal}}(0, 0; \omega)]}{\text{Im}[G_{\text{vertical}}(0, 0; \omega)]}} = \frac{\alpha_H}{\beta_H} \frac{|TF_{\text{horizontal}}(0, \omega)|}{|TF_{\text{vertical}}(0, \omega)|}
\]  

(3)

where \( \alpha_H \) and \( \beta_H \) are the P- and S-wave velocities of the half-space, respectively. In this case directional HVR (i.e., NS/UD and EW/UD) calculation is assumed (e.g., Matsushima et al., 2014).

2.2 EHVR Calculation

We show here a couple of examples of the S-wave velocity inversions based only on the EHVRs obtained from seismic motions observed at the K-NET and KiK-net sites in Japan. In the ordinary selection scheme we select seismic records, the peak ground acceleration (PGA) levels of which are in between 1 and 50 cm/s\(^2\) to avoid too noisy records and those with nonlinear site responses. Moreover, seismic motions of earthquakes exceeding the JMA magnitude \( M_{\text{JMA}} \) 6.5 were excluded from the analysis to remove earthquake records with significant long period contribution through the excitation of basin-induced or basin-transduced surface waves, since the aforementioned simple theoretical EHVR formula is derived by considering only body waves. Note that the average (and deviation) of all the EHVRs from individual seismograms throughout our papers is used to capture the stability of EHVRs. The first examples below are reported in Mori et al. (2016) who studied extensively the velocity structures at one hundred K-NET and KiK-net sites.

The portion before the arrival of the P-wave is considered a noise part; up to 40.96 s after the S-wave onset as an S-wave part; and 40.96 s following the S-wave part as a coda part. Figure 1 shows the waveform observed at one of the KiK-net sites, EHMH04, as an example. The data with a length less than 40.96 s are padded with zeros at the end. A standard spectral analysis is carried out both in the S-wave and coda parts, as well as the noise part to check the signal-to-noise ratio. A cosine-shaped taper is added to both ends before the fast Fourier transform (FFT) is applied. The length of the tapers is set to be 10% of the data length for the noise part and 2.0 s for the S-wave and coda parts. For K-NET data Fujiwara et al. (2007) showed that both old instruments until 2002-2006 (K-NET95 type) and instruments replaced thereafter (K-NET02 type) have a flat response up to 30 Hz. As the sampling rate of the KiK-net stations is 200 Hz, a flat response can also be expected at least up to 30 Hz. Here we should emphasize on the importance of simultaneously determining the entire basin structure in the EHVR inversion. As shown in the theoretical derivation, namely Equations 1 to 3, theoretical formula of the EHVR depends on the equipartitioned energy ratios at the seismological bedrock, i.e., \( \alpha_H / \beta_H \), and the transfer functions of the P- and S-waves from the bedrock to the surface. This means that even in a high frequency range the EHVR would be a function of the deep basin structure, not only a function of shallower sediments located above the engineering bedrock.
To show the effects of the deep basin structure on the EHVR in the high-frequency range we plot the results of a parametric study for MYG006 in Figure 2. We use the best-fit model with 14 layers as a reference and omit two layers in each step from the bottom of the reference model. As the bottommost P- and S-wave velocities decrease, the peaks in the lower-frequency range disappear, as expected. However, not as expected, the peak and trough amplitudes in the higher-frequency range increase significantly at the same time. This implies that we should not invert only the shallow sedimentary layers down to the engineering bedrock using the EHVR in the high-frequency range as a target.

Figure 1. Example of acceleration waveforms of three components at EHMH04 (2001/01/09, Epicentral distance=74km, Hypocentral depth=46km, and Magnitude=4.7). The blue and red lines indicate the onsets of P- and S-waves, respectively.

Figure 2. Parametric study on the effect of the bottommost layer on the theoretical EHVR for the best-fit model at MYG006 with 14 layers. If we omit the two layers in a single step from the original velocity model shown in the right, not only the peak amplitudes in the lower-frequency range but also the amplitudes of the peaks and troughs in the higher-frequency range are significantly affected.
2.3 Stability of EHVR

Figure 3 shows a comparison of the individual EHVRs (RMS spectra of the two horizontal components with respect to the vertical component) at EHMH04 and their averages for the S-wave portion of 40.96 s from the onset of the S-wave arrival (on the left) and a comparison of the averages of the S-wave portion and the early coda portion immediately after the S-wave portion with the same 40.96 s duration (on the right). We can see quite similar characteristics of EHVRs for S-wave and early coda, although the standard deviation for S-wave portions is about 1.5 (or 1/1.5) times of the average. The real diffusivity may not be seen until sufficiently later time after the onset of the S-wave, as delineated by Margerin et al. (2009). However, the DFC solution is applicable even to EHVRs of the S-wave portion if the average ratios for many observed records are taken. The key to success is not the diffusivity of observed waves in a strict sense but the averaging operation of the data to obtain a stable condition due to the mixture of multiple waves. We use only S-wave portions in this paper.

To show the robust nature of the similarity in the S-wave and the early coda portions, we plot examples at three other sites in Figure 4. At these sites the difference in EHVR for the S-wave and S-coda portions are quite small. Note that microtremor HVRs are also plotted for comparison.

The directionality of EHVR, namely, the difference in the spectral ratios of two orthogonal horizontal directions such as NS/UD and EW/UD, is also small at most sites. We plot the difference in the two component EHVRs in Figure 5 for EHMH04, IBRH11, and IWTH25. At some sites NS/UD and EW/UD differ systematically, strongly suggesting the 2D/3D effects of the surface topography and/or the underground interface irregularity (i.e., the basin effects), as reported by Matsushima et al. (2014) and Matsushima et al. (2017) for microtremors, which can be used to delineate local 2D/3D structures.

![Figure 3. Comparison of individual EHVRs at EHMH04 and their average for the S-wave portion (left) and comparison of the average for the S-wave and S-coda portions, together with those of microtremors.](image)

![Figure 4. Similar comparison of the average for the S-wave and S-coda portions at three sites, namely, EHMH10, FKOH01, and GIFH25, together with EHVR of the microtremors, that is, MHVR.](image)
2.4 Inversion Scheme for EHVR

For the inversion of the S-wave velocity structures we used the scheme proposed by Yamanaka et al. (2007), the so-called Hybrid Heuristic Search (HHS) method. The method does not require an initial model but it would be better to have one to constrain the searching range of the parameters. For the KiK-net sites we have the S-wave velocity information of the downhole P- and S-wave logging down to the borehole sensor depths, typically 100 to 200 m. In our S-wave velocity inversion using the EHVRs we need to determine the P- and S-wave velocities down to the seismological bedrock, the S-wave velocity of which would be greater than 3 km/s, as shown in Equation 3. It is made possible, because we use not only the peak frequencies but also their amplitudes to reproduce the observed EHVRs. For the deep basin structures at the KiK-net sites we can refer to the J-SHIS model of the shallow (<5 km) crust, which can be downloaded from the portal site of J-SHIS (http://www.j-shis.bosai.go.jp/en/, last accessed on 2017/11/28). The P-wave velocities are not the target of inversion but are translated from the inverted S-waves based on the empirical relationship (Nagashima et al., 2017). We assume a damping of 1.1% for all the layers for both P- and S-waves, if the inversion is performed only on the EHVR (it is also used as the initial value for the joint inversion shown in Chapter 4).

The misfit (residual) function to be optimized is shown in Equation 4, wherein the misfit is normalized by the frequency \( f \) because the equal sampling in frequency makes relatively increased numbers of constraints in the higher frequency range.

\[
\text{misfit} = \sum_{f=0.1}^{20} \frac{(\log(\text{EHVR}_{\text{obs}}) - \log(\text{EHVR}_{\text{theo}}))^2}{f}
\]  

We set the searching range of +- 30% for the boring S-wave velocity data (while the layer thickness is fixed) and no range for the J-SHIS thickness data (while the S-wave velocity is fixed). The numbers of population in the GA is set to be 400 and the numbers of generations (iterations) is set to be 200. We performed 10 inversions per site with different initial sets of randomly-generated genes and selected the best structure with the smallest residual (the so-called best-fit model).

3. INVERTED STRUCTURES FROM EHVR ONLY

In this chapter we report the velocity structures at selected sites inverted for EHVR only as a target.

3.1 Inversion Results

In Figure 6 we show the matching of the theoretical EHVRs with the target at EHMH10, a convergence path for 200 generations, and the obtained shallow and deep S-wave velocity structures, as an example. The blue lines in the panels indicate the different trials with different initial sets of genes, and the green lines indicate the initial (reference) model, i.e., the boring data down to the borehole sensor depth and J-SHIS deep basin structure from the borehole sensor depth down to the bedrock. A good matching of the observed EHVR is obtained with very stable results in terms of the obtained S-wave velocities.

Figure 5. Comparisons of NS/UD and EW/UD at EHMH04, IBRH11, and IWTH25.
In Figure 7 we show matching of the EHVRs and the shallow velocity structures at three other sites. The basic features of the best model correspond to the reference model quite well. However, the reference model cannot explain the entire EHVR frequency characteristics and therefore the resultant shallow structures from the inversion are not the same as the downhole measurements. This does not necessarily imply the unreliable nature of the downhole measurements. This may partly be due to the variability in the field measurement, but is largely due to the pin-point nature of the downhole measurement in situ. The horizontal extent of the seismic waves (i.e., sampling areas) that contribute to the EHVR site response for the frequency range from 0.1 to 10 Hz would be 20~1000 m, which is significantly greater than the sampling size of soil for the downhole measurement, 2~20 meters.

3.2 Surface-to-Borehole Spectral Ratios \( H/H_b \)

To check the validity of the inverted structure from the EHVR only, we calculated theoretical site responses at the surface with respect to the response in the borehole \( (H/H_b) \) and compared it with the observed spectral ratios. In Figure 8 we show the comparison at IBRH11 as an example. Notably, the peak frequencies of the observed surface-to-borehole spectral ratio \( (H/H_b) \) can be largely reproduced up to the second one. However, the peak amplitudes in the lower frequency range tend to be overestimated by the theory because the assumed damping is too low. As observed from the previous studies, this is because the apparent damping factor in the lower frequency range should be much larger than the current model of 1.1\% because of the complex scattering due to the topography and irregularity.
of the interfaces with multiple inclined incidence of S waves other than the 1-D horizontal layering for only a vertical incidence. This implies that we can effectively determine both the S-wave structures and their apparent damping factors if the joint inversion on both EHVR and H/Hb is performed.

Figure 8. Matching of EHVR after the inversion (left), the inverted S-wave velocity structure (center), and matching of the surface-to-borehole (H/Hb) spectral ratio (right) at IBRH11. We used the observed RMS value for the EHVR inversion, while the comparison of H/Hb is performed for the EW component. The green lines indicate the observation, whereas the orange lines indicate the initial (PS logging/J-SHIS) model.

4. JOINT INVERSION FROM EHVR AND BOREHOLE SPECTRAL RATIO

In this chapter we report the velocity structures at the selected sites jointly inverted for EHVR and the borehole spectral ratio (H/Hb) as the targets.

4.1 Joint Inversion Method

The data analysis for the surface-to-borehole spectral ratios is the same as that for the EHVR, although we need to consider directional rotation of two horizontal components shown in the NIED website. The theory can be easily derived from the conventional Haskell-type matrix operation for 1-D S-wave propagation analysis. The method used for the joint inversion is also the same as for the EHVR-only inversion, namely, HHS method. The only difference in the parameter that we determine is the average damping of the entire layers. No frequency dependence on the damping is considered. The misfit (residual) function is different as:

\[
\text{misfit} = \sum_{f=0.1}^{20} \frac{(\text{EHVR}_{\text{obs}} - \text{EHVR}_{\text{the}})^2}{f \ast \text{EHVR}_{\text{obs}}^2} + \frac{(\log(H/Hb_{\text{obs}}) - \log(H/Hb_{\text{the}}))^2}{f \ast \log(H/Hb_{\text{obs}})^2} \tag{6}
\]

Linear values are used for the EHVR and logarithmic values are for H/Hb, because the latter tends to have large values in amplitude and therefore when we used the same dimensions for both, the latter apparently had stronger influence to the misfit. The target of EHVRs used here are those of NS/UD and EW/UD, rather than RMS/UD, to account for the directionality even if it is small.

4.2 Joint inversion results at IBRH11

For IBRH11 Satoh et al. (2014) studied the linear and nonlinear velocity structures for the mainshock and aftershocks of the 2011 Tohoku earthquake using largely the array microtremor data and H/Hb ratios. We applied the joint inversion method to all the data with PGA from 1.0 to 50 cm/s². Figures 9 and 10 show the comparisons of the observed EHVR and the theoretical EHVRs for ten inverted velocity structures (on the left) and the H/Hb ratios (on the right) for NS and EW components, respectively.

Notably, the matching up to 10 Hz is quite good, especially for the EHVRs. The reproducibility
of the EHVR at high frequencies is remarkable, considering the much smaller amplitude relative to the fundamental peak amplitude. As the NS component shows complex characteristics in both EHVR and H/Hb, especially in the frequency range higher than the fundamental mode at around 2.5 to 3 Hz, the resultant S-wave velocity structure from the NS component, shown in Figure 11 on the left, shows larger deviation from the PS logging model than that from the EW component shown in Figure 11 on the right, especially above 30 m. In other words, the observed EW component of the EHVR and H/Hb show simpler characteristics, and therefore the simpler 1-D velocity structure close to the PS logging model can work to reproduce the observed values. The inclusion of the H/Hb in the inversion resulted in a good matching of the peak frequencies up to the fourth peak in the EW component. Note that the topmost very thin (0.5 m) layer in the structure from the NS component cannot be realistic, since the influential frequency range of this layer would be close to the highest frequency of the target, i.e., 20 Hz.

Figure 12 shows the damping values obtained from the joint inversion. For the NS component the best one yields 2.1% on the average, whereas 0.1% is selected for the EW component. However, for the other trials plotted in gray, the majority for NS is approximately 0.6% and that for EW is approximately 1%. This implied that the robustness of the inverted damping values at this site is not quite high, and some trade-offs between the velocity contrast and the damping should be expected.

4.3 Joint Inversion Results at IWTH25

A stronger directionality is observed at IWTH25. Figures 13 and 14 show comparisons of the observed
Figure 11. S-wave velocity structures inverted at IBRH11 (red and gray lines) together with the PS logging models (orange) from the NS and EW components.

Figure 12. Damping values inverted at IBRH11 (red and gray lines) for the NS and EW components.

EHVR and the theoretical EHVRs for the ten inverted velocity structures (on the left) and those for H/Hb (on the right) for the NS and EW components, respectively. The highest peak amplitude of the EHVR in the NS component is 30% greater than that in the EW component. Again the matching up to 15 Hz is quite good, especially for the EHVRs. The only difference is the higher amplitude of the inverted H/Hb ratios at the fundamental peak frequency. The PS logging+J-SHIS model performed well only near the highest peak in the EHVR. Similar to IBRH11, the NS component seems to be more deviated from the simple 1-D structure than the EW component. The resultant S-wave velocity structures shown in Figure 15 are quite similar, except for the shallower part. The topmost thin layer is required to reproduce the highest peak at around 15 Hz. Except for the shallower part, the inverted velocity structures are quite similar to the PS logging+J-SHIS model. Thus it is remarkable to see the effects of inversion in controlling the details of the observed characteristics in the EHVR and H/Hb. The damping values for the NS and EW components obtained by the inversion are also close to each other, 4.6% and 4.3%. The stability of the damping for the ten trials is also good.

5. CONCLUSIONS

In this paper we reported the results of our recent analyses on weak ground motion data at KiK-net sites in Japan. We first identified the ground structures using EHVR only, which we found possible to explain surface-to-borehole spectral ratios (H/Hb) to some extent. We then identified simultaneously EHVR and H/Hb, to obtain the ground structures that could explain both ratios quit well. As the EHVR alone cannot determine the damping factors of the ground between the surface sensors and the borehole sensors, it is
Figure 13. Matching of the observed EHVR (green) and theoretical EHVRs (red and gray) and those for H/Hb of the NS component at IWTH25. The orange lines indicate the PS logging+J-SHIS model.

Figure 14. Matching of the observed EHVR (green) and theoretical EHVRs (red and gray) and those for H/Hb of the EW component at IWTH25. The orange lines indicate the PS logging+J-SHIS model.

Figure 15. S-wave velocity structures inverted at IWTH25 (red and gray lines) together with the PS logging and J-SHIS models (solid and dotted orange lines) from the NS and EW components.
advantageous to use the proposed joint inversion, whereby the velocity structures down to the bedrock and the average damping factor between sensors can be determined. In the proposed joint inversion, the resultant damping factors obtained for several KiK-net sites range from 0.1 to 5% as the averaged value for the entire sediments, which can be considered to be realistic for the shallow part of the sediments. In contrast, several previous studies reported damping factors of the shallow part from the borehole spectral ratio as high as 10% because of the small amplitude in the fundamental peak.

7. REFERENCES


