Inversion of equivalent linear soil parameters during the 2011 Tohoku Earthquake, Japan

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SUMMARY:
This paper presents the inversion of linear and equivalent linear soil profile (i.e., S-wave velocity and damping factor) at the KiK-net station MYGH10 during the Great Tohoku Earthquake, 2011. Due to possible strong 2D or 3D topographic effects at the station located close to mountainous areas, we carefully select weak motions that present few of those effects. Among 50 weak motions, only 5 are selected to check the linear profile of the site. Then, the equivalent linear soil profile during the main shock is inverted, showing very interesting nonlinear effects, such as bedrock nonlinearity.

Keywords: borehole data inversion, equivalent linear soil profile, nonlinear soil behaviour, genetic algorithm

1. INTRODUCTION

On the afternoon of March 11th, 2011, an undersea megathrust earthquake of magnitude Mw 9 occurred off the Pacific coast of Tohoku, Japan, with an epicenter approximately 70 kilometers east of the Oshika Peninsula of Tohoku district. Thanks to various Japanese networks, excellent quality data have been recorded. Particularly, many strong-motion data have been recorded with long durations and high peak ground accelerations and velocities (PGAs and PGVs, respectively) in Miyagi, Ibaraki, Tochigi, and Chiba Prefectures.

Owing to the large PGAs observed, the strain level undergone by the soft sediment is large and the response of the sediments is no longer linear. Soil nonlinearity is, however, a very complex phenomena and research on this topic is essential for the future seismic design input. Thanks to the data recorded during the 2011 Tohoku earthquake, different types of nonlinear soil behavior have been observed ranging from classic high-frequency de-amplification to liquefaction.

In this article, we focus on the inversion of the soil structure at the KiK-net station Miyagi No.10 (code name MYGH10) using a genetic algorithm technique (De Martin et al., 2010). Due to possible strong 2D or 3D topographic effects at the station located close to mountainous areas, we carefully select weak motions that present few of those effects by inspecting their particle motion in different frequency range.

As for the inversions, we use band-pass filtered time histories as objective function instead of the common spectral ratio because the shape of the spectral ratio can be strongly distorted by the application of cosine shape windows used to isolate shear-wave part of time histories (De Martin, 2011). We first demonstrate on synthetics data that, for the station MYGH10, only the very beginning of the S-wave part is needed to invert robustly the velocity profile. Then, we use weak motions to verify the initial velocity profile provided by KiK-net in the frequency range 0.1 – 10 Hz and then, we invert equivalent linear soil profile during the main shock.

2. ROBUSTNESS OF THE INVERSIONS TECHNIQUE

Inverting a 1D soil profile using synthetic data (i.e., theoretical, semi-analytical or numerical results) is a good way to test the robustness of an inversion method. To do so, we use the initial velocity profile of the station MYGH10 (see Table 2.1) to simulate free surface motion using downhole motion via the Thomson-Haskell propagator matrix method; then, we use the onset of the free surface motion to invert the velocity profile. Our inversion technique use time-domain objective function (in this case, band-pass filtered acceleration time history in the frequency band 0.1 – 10 Hz). The onset of the shear wave is used as objective function. The objective function itself is simply the integrated squared residual between the target time history and the time histories from inversion. We invert 6 parameters: the shear-wave velocity of each layer and a constant damping along the entire soil column.

The inversion range 0.1 – 10 Hz has been chosen by computing the influence of the shear wave velocity of each layer on the 1D response with respect to frequency using Sobol coefficients analysis (Sobol, 2001). Figure 2.1 shows that the thick layers 5 to 3 have a strong influence on the response of the column from 0 to 50 Hz while the first two layers start having an influence from 5 Hz. In order to try to invert the shear wave velocity of each layer, we band pass filtered data into the range 0.1 – 10 Hz.

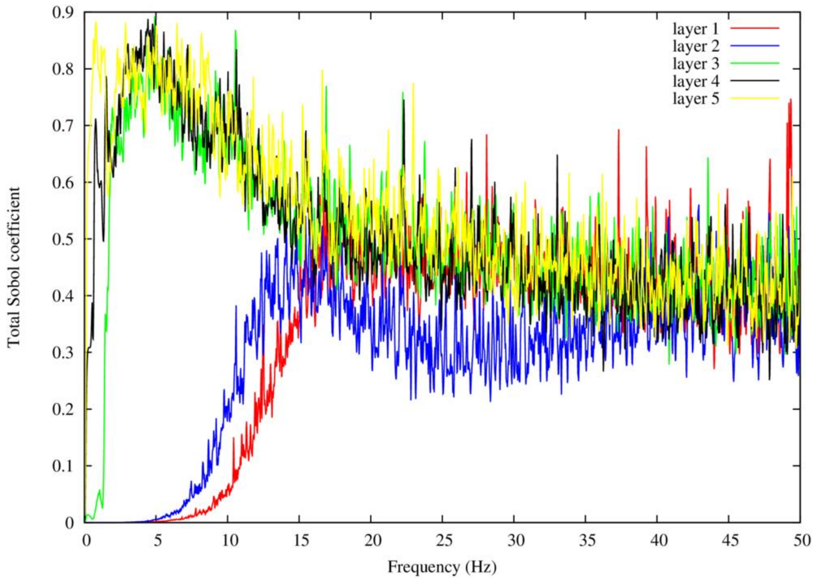

Figure 2.1. Total Sobol coefficients for layer 1 to 5.

As for the inversion process, we perform eight independent genetic algorithm inversions to compute a mean and standard deviation of the inverted parameters. Each genetic algorithm inversion runs overs 11,000 populations. A Monte-Carlo search is performed on the first 1000 populations composed by 2048 individuals (one individual represents the velocity and damping soil structure from free surface to downhole). Then, the genetic algorithm inversion runs over 10,000 populations composed by 1024 individuals. Consequently, for an earthquake, a total of 12,288,000 soil columns are compared with the observation. Such an inversion runs for about 27 h 41 min on an AMD Opteron @ 2.3 GHz. For a single inversion, elitism is activated so that the 10 best soil columns are always present from one population to another. Selection is performed by tournament and the probability of reproduction is 85%. The probability of mutation is 0.1%.

Figure 2.2 and Figure 2.3 shows the inversions' results using a synthetic time history as target. As we can see, the synthetic target time history is very well fitted by the inversions. Moreover, only the very beginning of the shear-wave part is needed to get good fitting of the entire time history. In Figure 2.3, we see that the mean and standard deviation include the target profile. These results confirm that our inversion technique can invert 6 parameters robustly.

Table 2.1. Soil column at MYGH10 provided by KiK-net.

N°	Thickness (m)	Vs (m/s)	Density (kg/m3)	Damping factor
1	1	110	1750	
2	2	250	1800	
3	31	390	1850	1.0
4	80	590	1950	
5	91	770	2030	

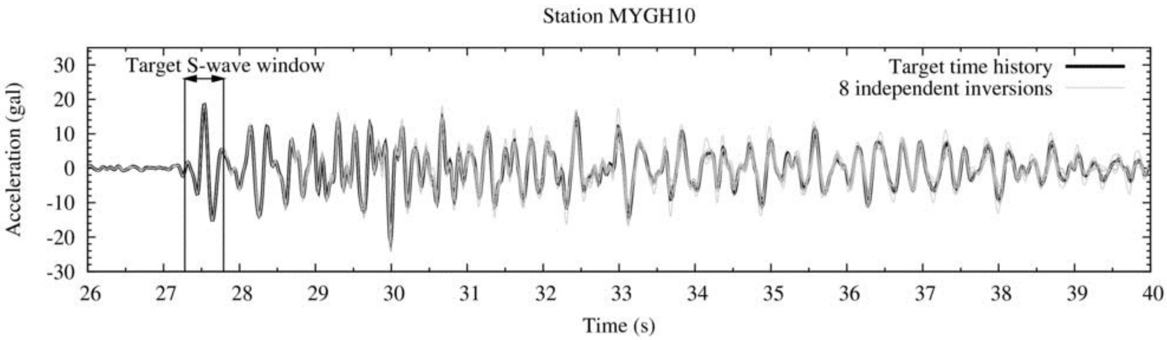

Figure 2.2. Target synthetic time history (thick black line) and inverted time histories (thin gray lines) from eight independent inversions.

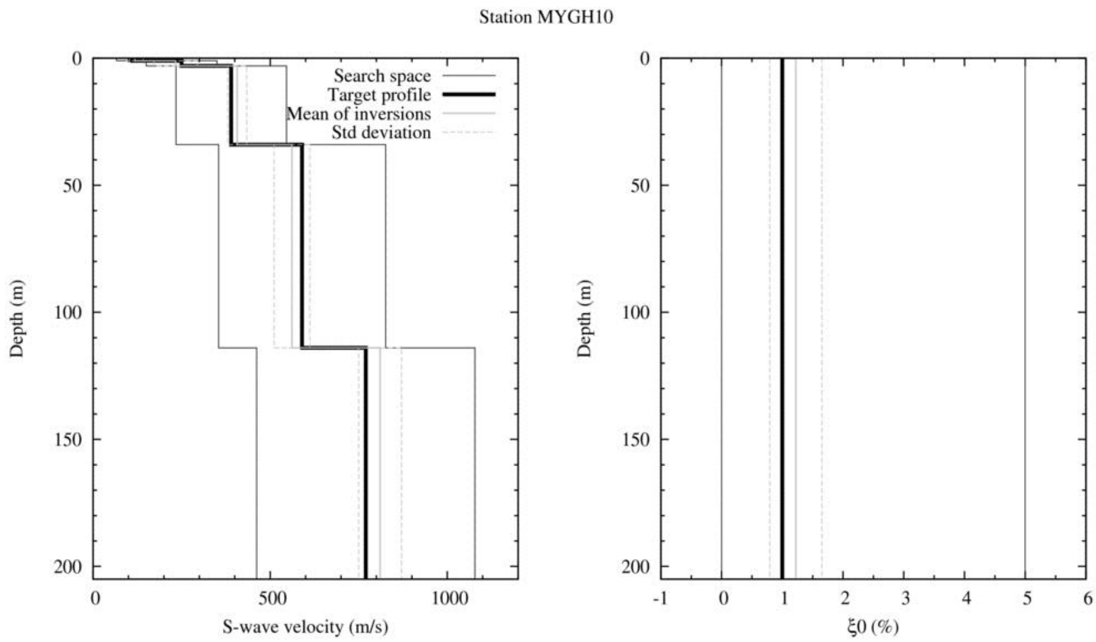

Figure 2.3. Left panel: Target shear-wave velocity profile (thick black line), mean and standard deviation from eight independent inversions (thin grey line and dashed thin grey lines, respectively) and search space of the inversions (thin black lines). Right panel: Damping profile (same legend as velocity profile).

3. REGION OF STUDY

Figure 3.1 shows the region of our study. It is worth noticing that the station MYGH10 is surrounded by mountainous areas that may influence the shear wave part of time histories or generate strong surface waves propagating toward the station. Such effects would bias inversions' result if they were included into them. As a consequence, in order to avoid bias from 2D or 3D topographic effects embedded into observed time histories, we use the two important properties of 1D inversion shown in section 2, that is to say (by assuming 1D assumption): Using only the very onset of the shear-wave part

1) is sufficient to invert robustly the entire soil profile; and
2) is sufficient to nicely fit the entire time history .

In addition, we check horizontal particle motion in the [transverse – up down] plane and pick up shear-wave parts showing only horizontal pattern.

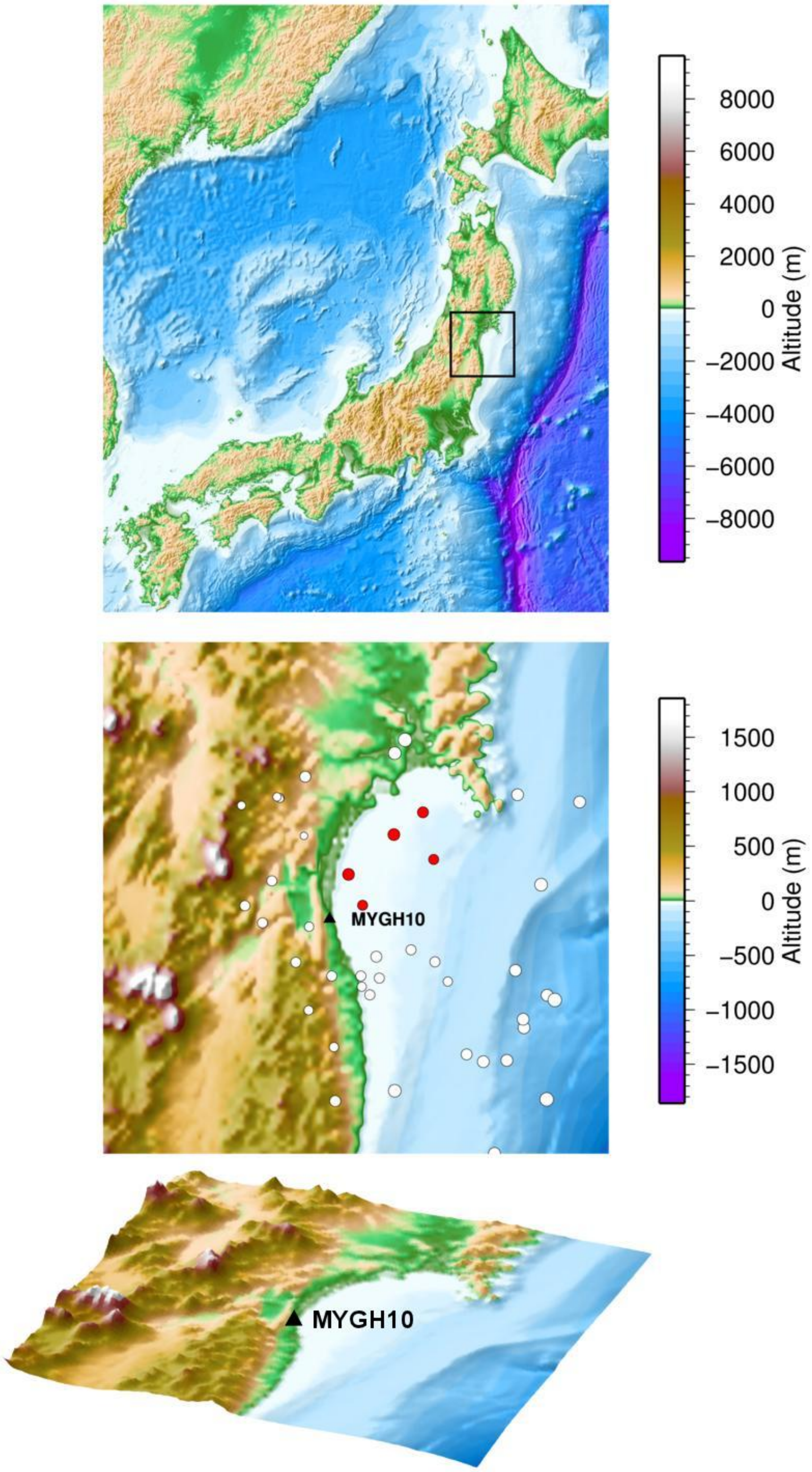

Figure 3.1. Top panel: Japan with the area under study (black rectangle). Middle panel: Location of the station MYGH10 and epicentres of the earthquakes used in this study. Bottom panel: Isometric view of the middle panel (topography's height is amplified by five). Red epicentres denote earthquakes whose inverted time history has a nice fit with observations.

4. INVERSIONS OF OBSERVED DATA

Among all the weak motions investigated (see Figure 3.1 white and red dots), only few (red dots) revealed a nice match with the observations. They are mainly located offshore at the east northern part of MYGH10. According to our investigation, all other weak motions are strongly influenced by 2D or 3D effects. Figure 4.1 shows the transverse acceleration time history of three of the weak motions represented by red dots together with their inverted time histories and their time histories obtained using KiK-net velocity profile. We note that for each earthquake, the objective function is composed of windows carefully selected where particle motion shows horizontal pattern in order to avoid 2D or 3D effects described in section 3.

In Figure 4.1, we can see that the inverted time histories generally better fit the observations than the KiK-net time histories (computed with a constant 1% damping). Figure 4.2 shows that the inverted soil profiles are close to the initial KiK-net profile. Nevertheless, due to the station localization, the inverted profile might be distorted because of 2D or 3D effects embedded at the beginning of the observed time histories.

Figure 4.3 shows the inverted time histories for the main shock. They nicely reproduce the observation whereas initial KiK-net profile lacks amplitude and phase coherence. According to the equivalent linear soil profile obtained during the main shock (see Figure 4.3), the two bottommost layers (bedrock) have a nonlinear elastic behaviour (i.e., they undergo a shear wave velocity reduction while the damping does not increase). The three topmost layers clearly exhibit an increase of damping. Only the layer 3 does not show shear wave velocity reduction.

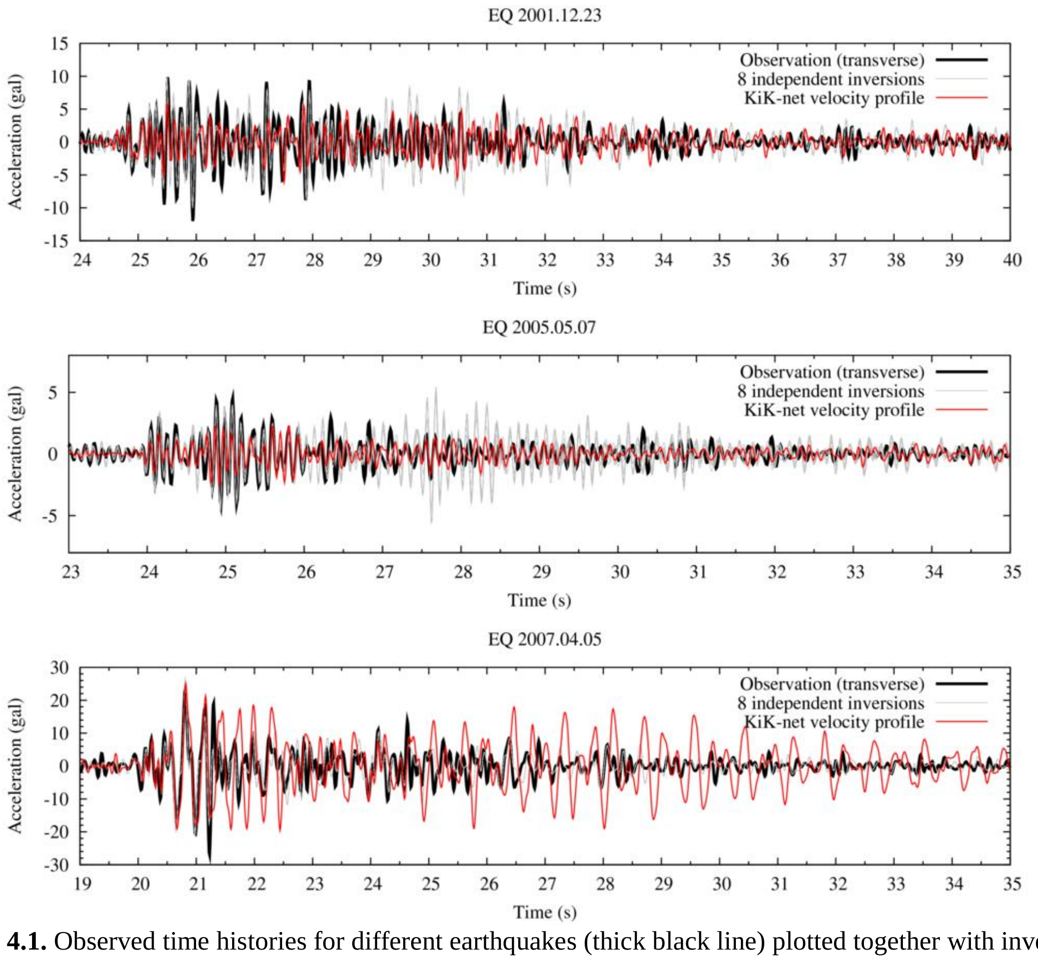

Figure 4.1. Observed time histories for different earthquakes (thick black line) plotted together with inverted time histories (thin grey line) and initial KiK-net time histories computed with a 1% constant damping ratio along the entire soil column (thin red line).

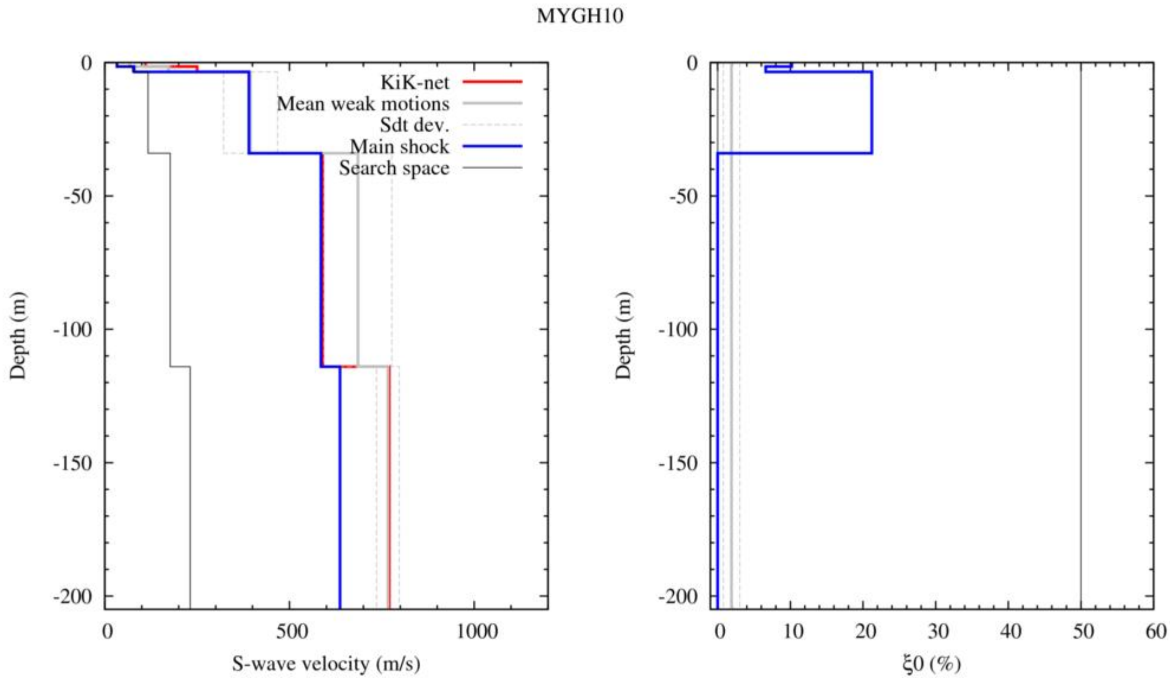

Figure 4.2. Shear wave velocity and damping profile: KiK-net (red), Mean from weak motions and standard deviation (grey) and main shock (blue).

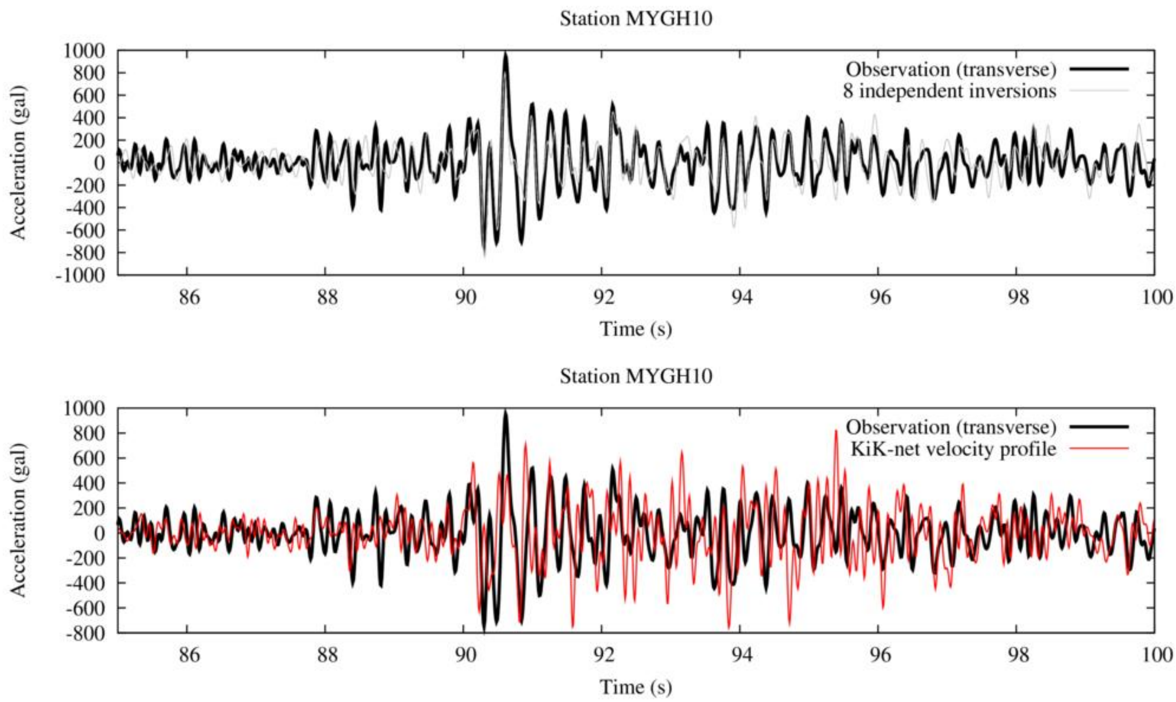

Figure 4.3. Top panel: comparison between observed acceleration time history (black) and inverted time histories (grey). Bottom panel: comparison between observed acceleration time history (black) and time history from KiK-net profile.

5. CONCLUSIONS

This article presents inversions of soil profile (i.e., shear wave velocity and damping factor) at the KiK-net station MYGH10. First, we showed an important property of borehole inversions using synthetic time histories: if we suppose a 1D geometry and a vertically incident plane wave, then, only the information contained in the onset of the shear wave part is needed to invert robustly the entire soil column and to fit nicely the entire time history (see Figures 2.2 and 2.3).

As a result, in order to avoid inverting back reflected surface waves embedded into time histories generated by 2D or 3D effects at the station MYGH10, the objective function is composed of time windows carefully selected. These time windows are mainly at the beginning of the time histories where particle motion shows horizontal pattern. We note however that such a technique cannot avoid 2D or 3D effects embedded directly into the shear wave part.

The equivalent linear profile inverted during the main shock shows very interesting features around MYGH10 station. If we suppose that our inversions do not include 2D or 3D effects, then, we can assess that:

1. High shear wave velocity layers (e.g., Vs about 600 m/s) had a nonlinear elastic behaviour during the main shock (i.e., they undergo a shear wave velocity reduction while the damping does not increase);
2. Soil nonlinearity does not imply Peak Ground Acceleration (PGA) reduction: as shown in Figure 4.3, the observed time history shows larger amplitude than the linear time history from KiK-net profile;
3. A decrease of shear wave velocity and an increase of damping do not lead to a decrease of PGA: as shown in Figure 4.3, the inverted time histories of the main shock has a higher PGA than the time history from KiK-net while the soil column has lower shear wave velocity and higher damping. This might mean that shear wave velocity reduction in some layers could increase impedance with other layers to lead to stronger amplification.

The three points mentioned above are very interesting because they are controversial to some well establish ideas as:

1. Bedrock has a linear elastic behaviour during strong ground motion;
2. Soil nonlinearity implies PGA reduction.

Nevertheless, these interesting results have to be taken carefully because our 1D inversions might be distorted by 2D or 3D effects included in MYGH10 time histories due to its localization on a mountain side.

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