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INVERSION OF EQUIVALENT LINEAR SOIL PARAMETERS DURING THE 2011 TOHOKU EARTHQUAKE, JAPAN

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ABSTRACT: 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. This station has been selected among other KiK-net stations thanks to a proxy stress-strain technique showing that nonlinear behavior of the soil structure under this station may be possible during strong ground shaking. The inversions, performed by genetic algorithm coupled with Thomson-Haskell propagator method, show that the entire soil column might have behaved nonlinearly during the Great East Japan earthquake.

Key Words: Great East Japan earthquake, borehole data inversion, equivalent linear soil column

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. Such long durations and high PGAs are probably characteristics of records lengthened and amplified by site effects (i.e., modification of the waves coming from the source due to the impedance contrast between the bedrock and the soft sediment basins). Owing to the large PGVs observed, the strain level sustained 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 paper, we tried to determine the one-dimensional “equivalent soil profile” (i.e., a soil profile having their S-wave and damping factors inverted to match the observed nonlinear response in terms of shear modulus reduction and damping ratio curves) during the main shock of the Great East Japan earthquake at some KiK-net stations. First, among a large number of KiK-net stations, we identify using a stress-strain proxy technique (Idriss, 2011), which KiK-net's soil structures are susceptible to behave nonlinearly. Then, among the identified sites, we check the linear soil structure using weak motion and invert the equivalent linear soil structure during the main shock by using a genetic algorithm inversion technique (De Martin et al. 2010).

KIK-NET SITES IDENTIFICATION

In order to select KiK-net sites that may behave nonlinearly during strong ground motions, we use the stress-strain proxy technique introduced by Idriss, 2011. In this technique, the stress-strain relationship is roughly approximated by the PGA-PGV/Vs30 relation where PGA is proportional to the stress and PGV/Vs30 is a proxy for the strain. This technique is well suited to indicate which sites may behave nonlinearly.

Fig. 1 shows the proxy stress-strain relation for different values of Vs30 at KiK-net sites using earthquake database from September 2000 to April 2011. The proxy technique shows that low Vs30 sites may behave nonlinearly whereas high Vs30 site may not. Among these sites, we select the site MYGH10 for which its proxy stress-strain relation is shown in Fig. 2.

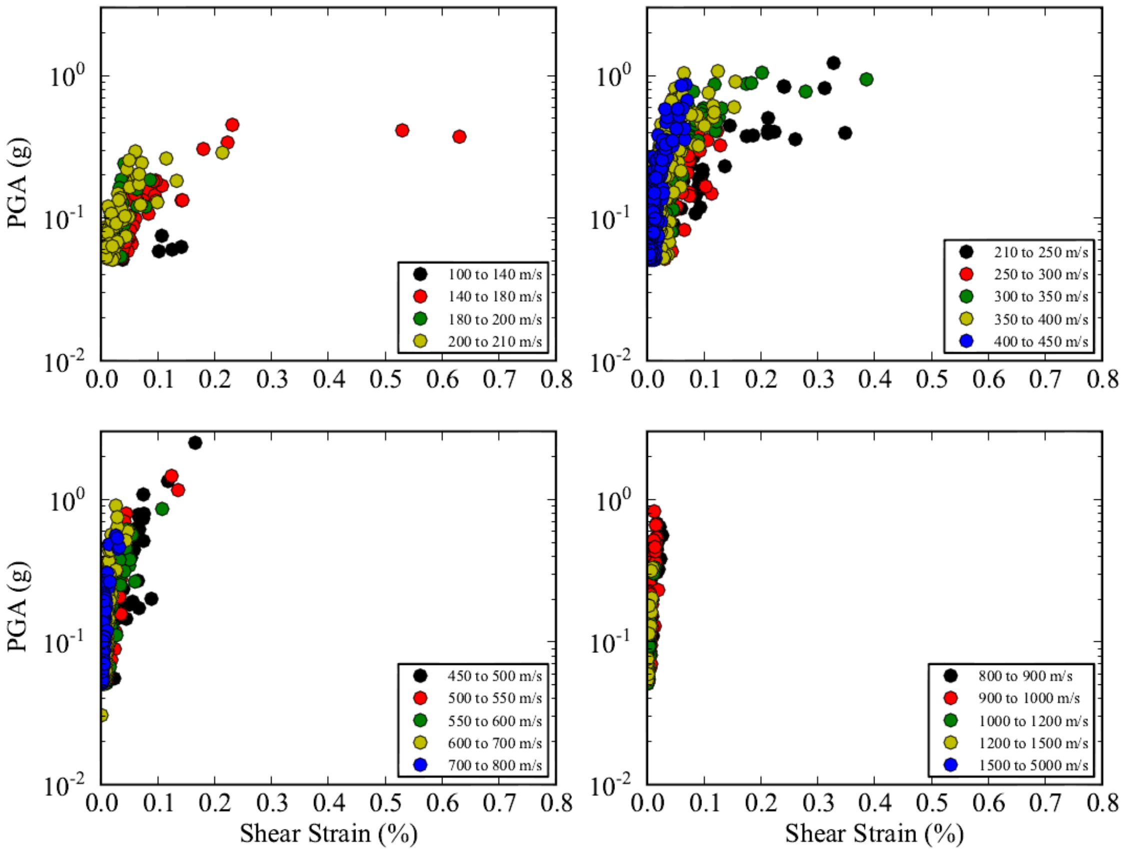

Fig. 1 Proxy stress-strain relation for different value of Vs30. "Shear Strain" is approximated by PGV/Vs30. The Vs30 binning is the same as Idriss (2011).

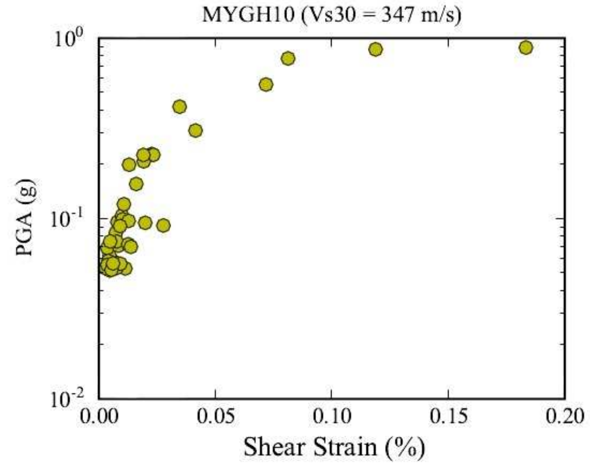

Fig. 2 Proxy stress-strain relation for MYGH10.

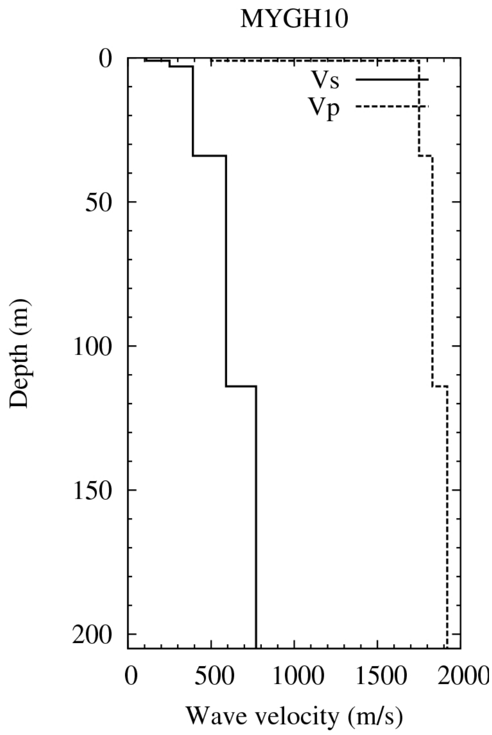

Fig. 3 Initial velocity profile of MYGH10 (left) provided by KiK-net.

MYGH10 VELOCITY PROFILE AND DATABASE

The initial velocity profile of MYGH10 provided by KiK-net website is shown in Fig. 3. The shear-wave velocity Vs range from 110 m/s at the free surface to 770 m/s at the downhole (205 m). The initial soil column used for inversions at MYGH10 is presented in Table 1. Ground motions used for inversions are listed in Table 2.

Table 1 Soil column at MYGH10. S-wave factors are used to determine the search space of genetic algorithm inversions of weak motions data.

N°	Thickness (m)	Vs (m/s)	Density (kg/m^3)	S-wave factors for search space
1	1	110	1750	0.5 – 1.5
2	2	250	1800	0.5 – 1.5
3	31	390	1850	0.5 – 1.5
4	80	590	1950	0.5 – 1.5
5	91	770	2030	0.5 – 1.5

Table 2 Ground motions used for inversions

N°	Date YY.MM.DD/HH.MM	Lon. (°)	Lat. (°)	Mag. Mw	PGA_{NS} (cm/s^2)	PGA_{EW} (cm/s^2)	PGA_{UD} (cm/s^2)
EQ1	11.03.11/14.46	142.8610	38.1035	9.0	871	853	622
EQ2	09.09.22/20.40	141.6645	37.5968	4.7	27	23	11
EQ3	09.06.01/00.33	141.6313	37.7778	4.6	27	29	13
EQ4	08.12.04/17.29	141.4370	37.5140	4.4	14	15	5
EQ5	08.10.30/00.48	141.7323	38.0462	5.1	37	36	16
EQ6	06.03.29/19.28	141.5482	37.2018	4.8	32	34	11

OBJECTIVE FUNCTION AND S-WAVE WINDOW SELECTION

As shown by De Martin (2011), the use of a frequency-domain objective function for inverse problems at borehole stations can lead to biased results. In practice, the length of the cosine-shaped windows used to isolate the S-wave portion is fixed as a percentage of the length of the S-wave portion. Common values range (as a rule of thumb) between 15% and 50% and one can show that for such a range, the spectral ratios may strongly change: the location of the resonant peaks along the frequency axis can be slightly affected and the amplitude of the peaks can be greatly affected. As a result, the inversion of the S-wave velocity and damping factors can be distorted because of an arbitrary application of the cosine-shaped window.

Therefore, the inversions performed in this paper use a time-domain objective function which is the summation of the square residual between observed and simulated acceleration time histories on the S-wave window. By using this technique, the objective function is computed on raw time history data (or filtered time history data). In our case, we use time history band-pass filtered in the frequency range [0.1 – 5.0] Hz.

The S-wave portion used as objective function is determined by examination of the particle motion on acceleration time history in the [transverse – up down] and [radial – up down] planes. An example of particle motion for EQ2 is shown in Fig. 4.

GENETIC ALGORITHM INVERSIONS

Inversions' information

For each earthquake listed in Table 2, we perform eight independent genetic algorithm inversions in order 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%.

Linear soil structure

The linear soil structure is obtained by inversions EQ2 to EQ6. The search space of the S-wave velocity is, for each layer of MYGH10, [0.5 – 1.5] times the S-wave KiK-net initial velocity. The interval [0.5 – 1.5] is decomposed in 16 equally spaced values. The damping factor of each layer is searched in the interval [0 – 5] % decomposed in 16 equally spaced values as well. As a result, a total of 1.1E+12 solutions are possible. Only 1.1E-3% of the solutions is computed during a genetic algorithm inversion. The convergence curves for eight independent inversions are shown in Fig. 5. At the end of the inversion, one unique optimum is found.

Fig. 6 shows that for EQ2 the inversion improves the time history simulation compared to the initial KiK-net velocity profile. A mean and standard deviation over all the best soil profiles of each inversion computed for the EQ2 to EQ6 are shown in Fig. 7. We see that except for the first two layers, the standard deviation includes the KiK-net velocity profile.

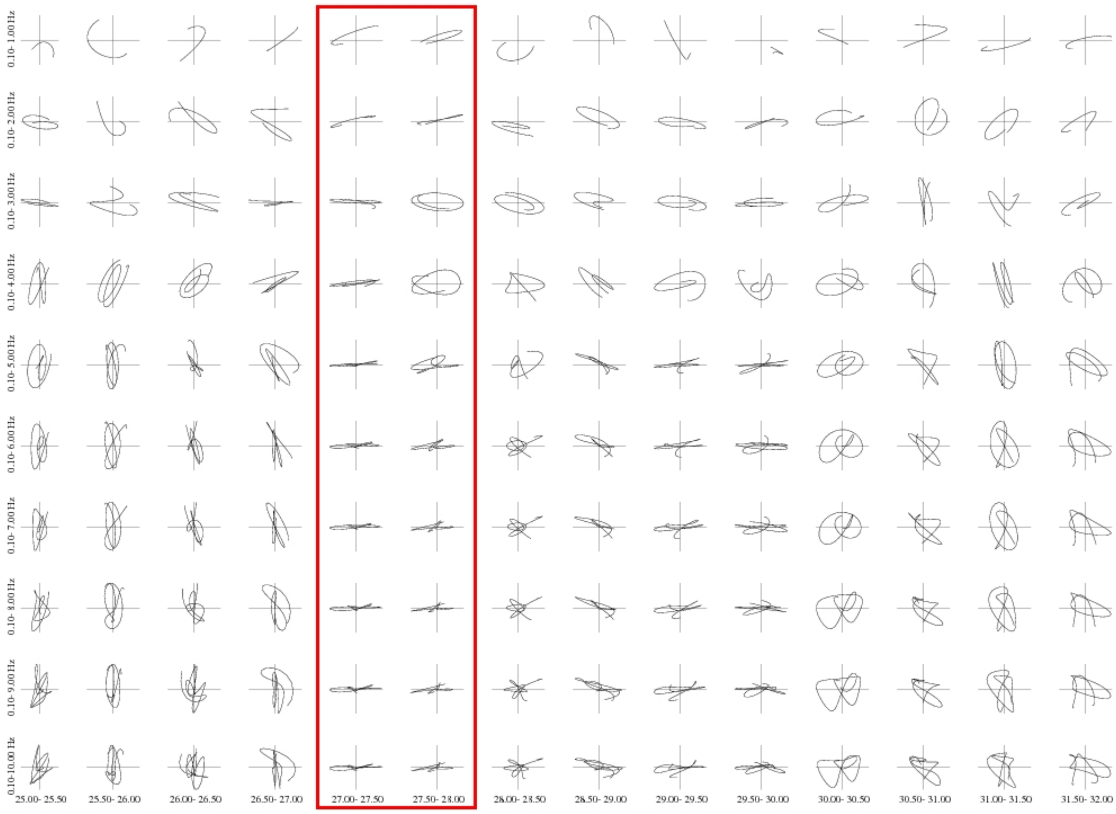

Fig. 4 Acceleration particle motion in the [transverse – up down] plane at downhole for EQ2 between 25 and 32 seconds (left to right) and in the frequency range from [0.1-1.0] to [0.1-10.0] Hz (top to bottom). S-wave arrival between 27 and 28 s, within the red box, shows a clear horizontal motion in the transverse direction.

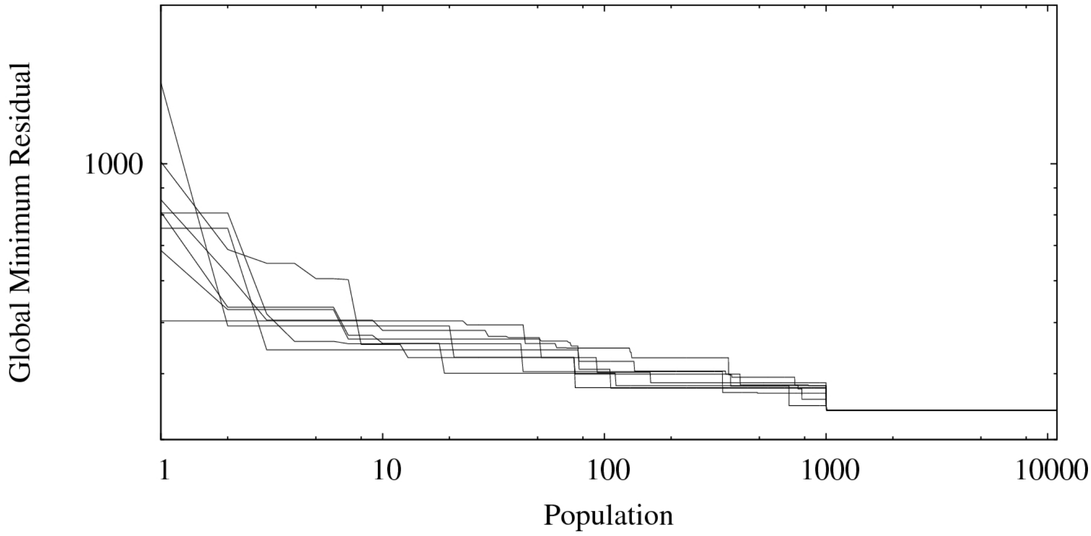

Fig. 5 Convergence curves of eight independent inversions for EQ2.

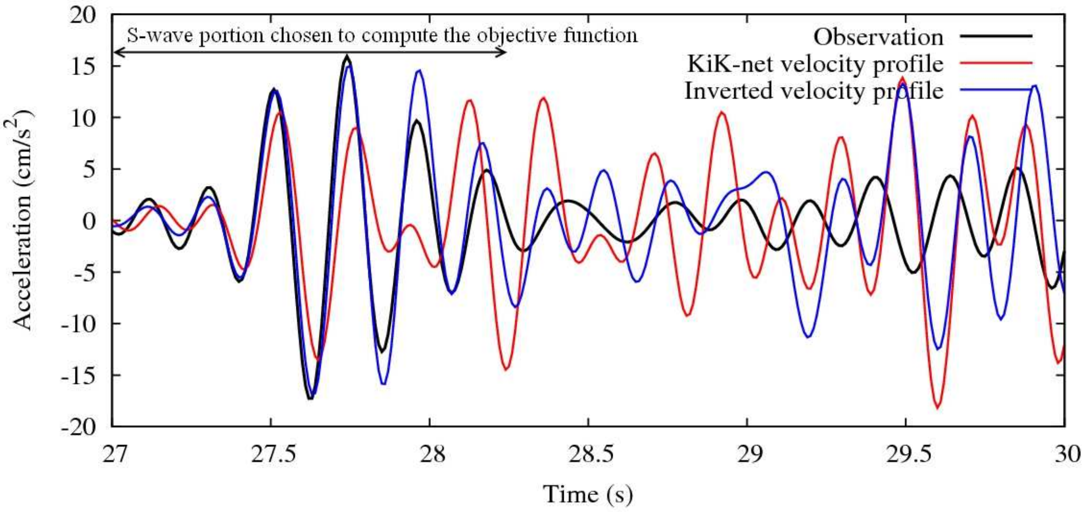

Fig. 6 Comparison between transverse time histories for EQ2 for MYGH10 in the frequency band [0.1 – 5.0] Hz: Observations (black), KiK-net velocity profile simulation (red) and inversed velocity profile simulation (blue).

Equivalent linear soil structure

The mean soil column found from the inversions of EQ2 to EQ6 is used as starting point for inverting the main shock (EQ1). The search space for the S-wave velocity is [0.5 – 1.0] times the mean soil column of Fig. 7. The damping is search in the interval [0.0 – 50.0] %. Over 8 independent inversions, a common single optimum soil profile is found.

The observed S-wave window used for the computation of the objective function is shown in Fig. 8 together with the observed and the time history computed via the inversed velocity profile. We can see that the S-wave window is well reproduced in term of frequency content, but could be improved in terms of amplitude. The inverted soil profile is shown in Fig. 9 and the shear modulus reduction with the strain is shown in Fig. 10. According to the inversion, all soil layers sustain a shear-modulus reduction but only the first three layers have an increase of damping.

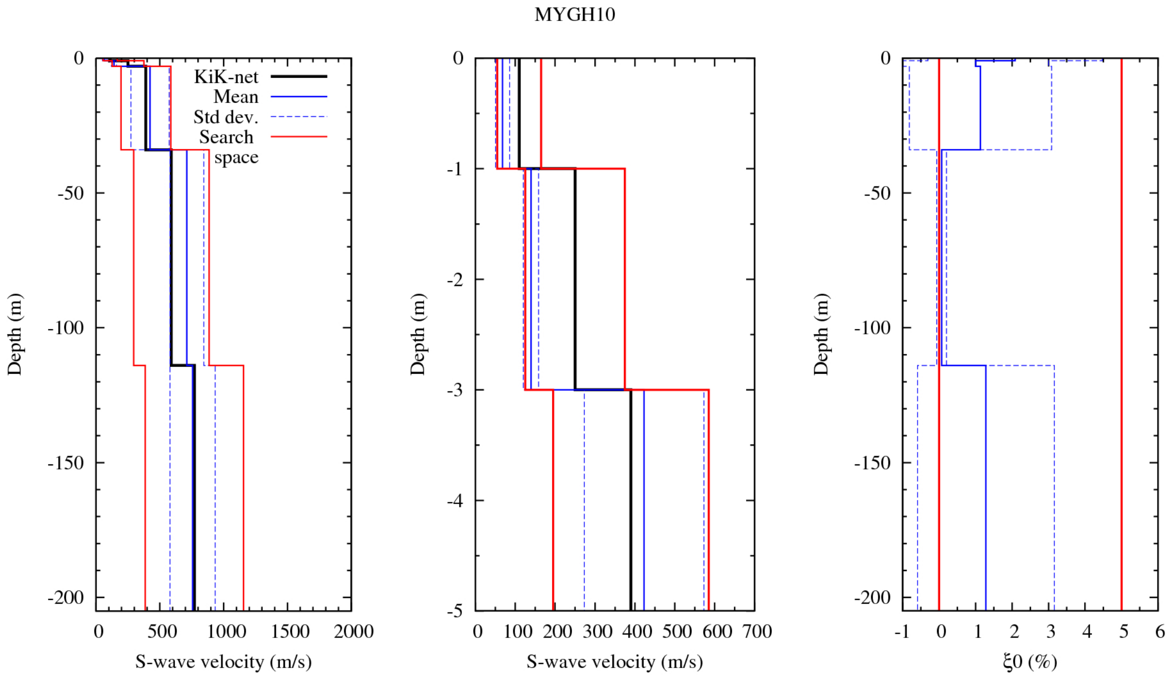

Fig. 7 Mean and standard deviation computed over all best soil profile of all inversions for EQ2 to EQ6. Left panel: S-wave velocity profile from 0 to -205 m depth. Middle panel: Zoom from 0 to -5 m depth. Right panel: Damping factors from 0 to -205 m depth.

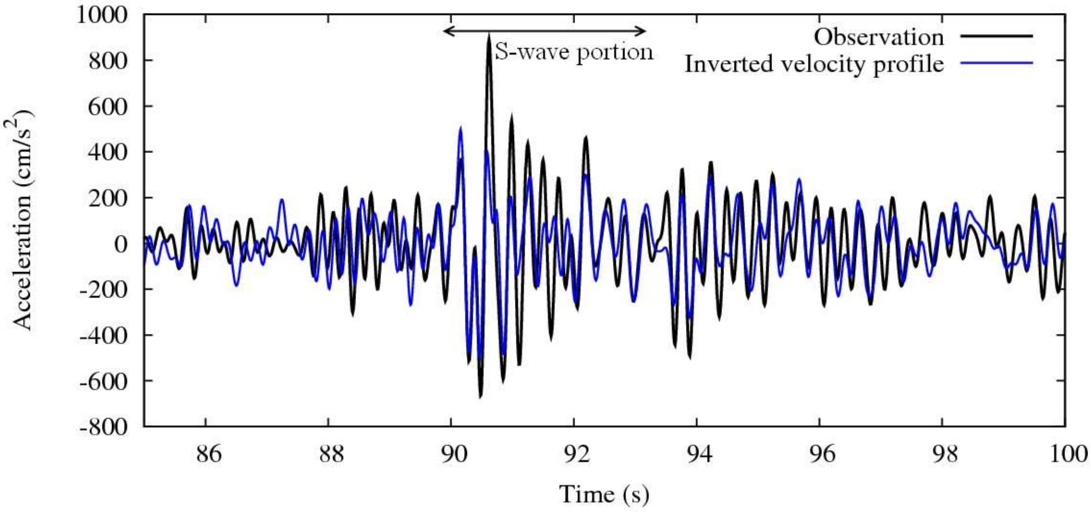

Fig. 8 Comparison between observed and simulated transverse time histories for the main shock (EQ1).

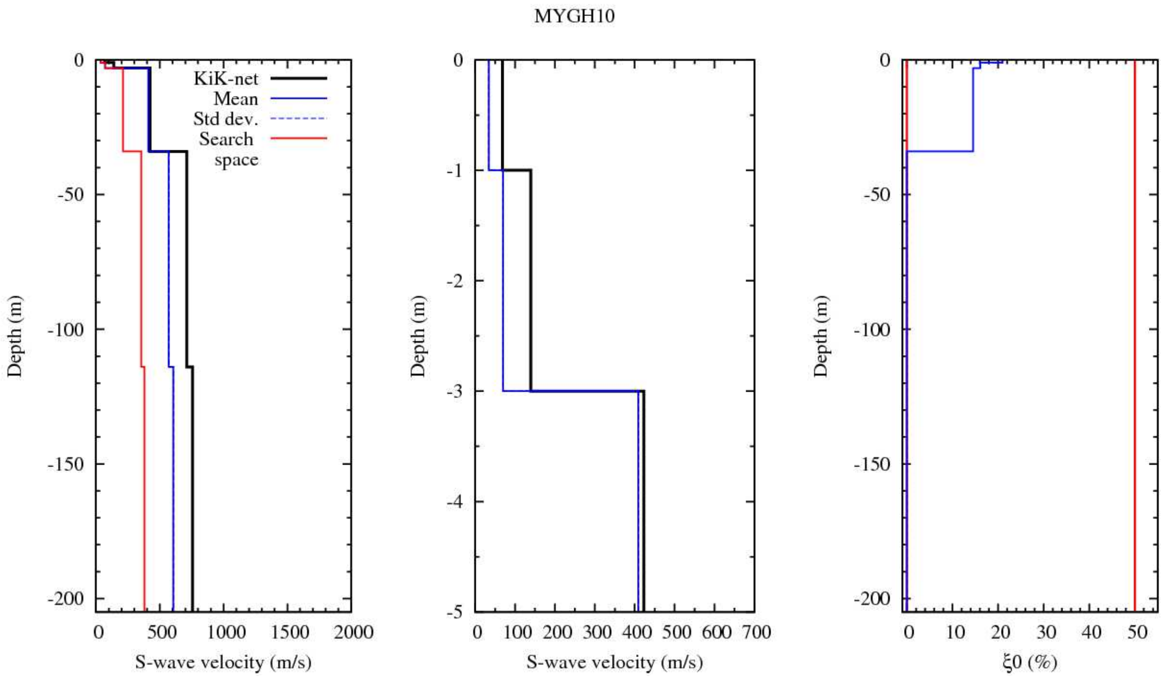

Fig. 9 Mean and standard deviation computed by inversion for EQ1. Left panel: S-wave velocity profile from 0 to -205 m depth. Middle panel: Zoom from 0 to -5 m depth. Right panel: Damping factors from 0 to -205 m depth.

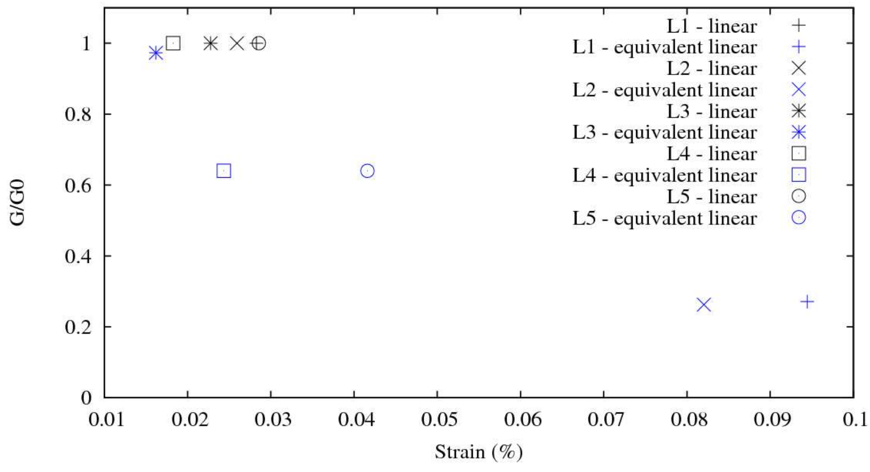

Fig. 10 Shear modulus degradation in layer 1 (L1) to layer 5 (L5). G0 is computed using the mean inverted velocity profile shown in Fig. 7.

CONCLUSIONS

This study shows preliminary results for the inversion of the linear and equivalent linear soil profiles of the station MYGH10. This station has been selected among other KiK-net stations thanks to a proxy stress-strain technique showing that nonlinear behavior of the soil structure under this station may be possible.

After the inversions of the linear and equivalent linear soil parameters (i.e., S-wave velocity and damping factors), the match with the observed time histories is fair, but it could be improved by increasing the number of layer of the initial soil profile to give more freedom to the inversions.

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