Reply to comment on ‘Shear wave profile from surface wave inversion: the impact of uncertainty on seismic site response analysis’

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REPLY

Reply to comment on 'Shear wave profile from surface wave inversion: the impact of uncertainty on seismic site response analysis'

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Abstract
Socco *et al* (2012 J. Geophys. Eng. **9** 241) comment on our study about the effect of non-uniqueness of surface wave solutions on seismic site response analysis. In particular, they refer to the approach we adopted for the selection of equivalent shear wave velocity profiles and argue that it leads to overestimation of the uncertainty due to the inherent ill-posedness of the problem. Moreover, for one of the synthetic cases of our original paper, they calculate a different set of equivalent velocity profiles, retrieving the corresponding amplification spectra. From these results, Socco *et al* claim that their general conclusion that the impact of solution non-uniqueness on seismic response simulations is negligible. In this reply we demonstrate that (a) the uncertainty bounds used by Socco *et al* in their prediction analysis, as a consequence of their surface wave inversion procedure, are unreasonably narrow; (b) consequently, their shaking predictions appear to suffer no impact from their underestimated uncertainty; and (c) their presented case shows an amplification spectrum that is only the result of assuming the existence of a bedrock at 150 m that causes resonance of the overlying layer—practically independent of the details of the *S*-wave velocity distribution.

Keywords: surface waves, inversion, seismic site response, soil resonance period

(Some figures may appear in colour only in the online journal)

In their comment, Socco *et al* (2012) compare the strategies for the selection of equivalent models described in Foti *et al* (2009) and Socco and Boiero (2008) against the one used in Boaga *et al* (2011). They conclude that the approach in Boaga *et al* (2011) overestimates the variability of 'equivalent' shear wave velocity (V_s) profiles.

Definitely, the two approaches are quite different. In fact, on one hand, for Boaga *et al* (2011) the only two criteria that define equivalent V_s profiles are (1) to be close enough to the reference profile and (2) to generate dispersion curves that are close enough to the dispersion curve corresponding to the reference profile. On the other hand, in Foti *et al* (2009) the equivalence is based upon the same previous criteria, but a further step is introduced that makes use of a statistical *F*-test where the null hypothesis is that any tested dispersion curve

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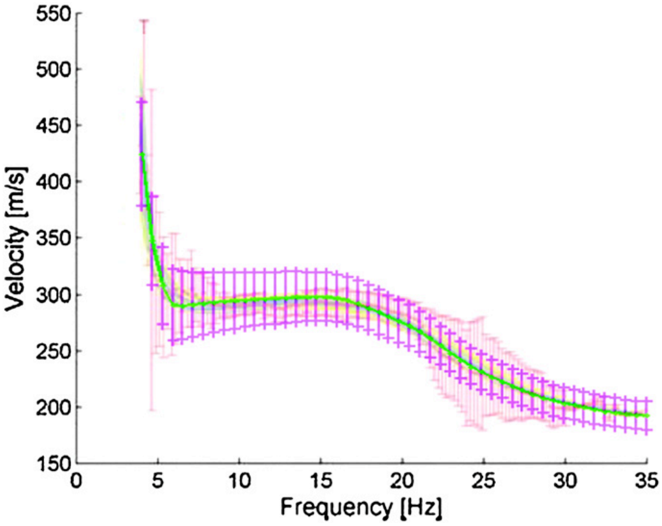

Figure 1. Rough comparison of the experimental dispersion curve (and corresponding uncertainty—in orange) in Socco and Boiero (2008) and the uncertainty calculated by means of the relation adopted in Boaga *et al* (2011).

is statistically indistinguishable from the best-fit dispersion curve, using a level of confidence α that is, in addition, taken at the unusually low level of 1% (at least in the papers referred to in the comment).

This selection strategy of equivalent velocity models in Foti *et al* (2009) is clearly more binding as it imposes a condition on the weighted squared summation of the residuals between the possible dispersion curves and the reference one. In practice, as in the philosophy of statistical tests, this is equivalent to considering *only* the best-fit curve as the others are statistically indistinguishable. The variations still allowed by $\alpha = 1\%$ are necessarily negligible with respect to the data variability (this is the philosophy of statistical tests).

This is evident in figure 1(*b*) in the comment by Socco *et al* (2012): clearly their equivalent dispersion curves do not span the entire volume in the data space defined by the uncertainty assumed for each Rayleigh velocity value V_R; their equivalent curves lie in a tiny neighbourhood of the reference curve. Note also the paradoxical result showing smaller uncertainty at larger depths (see realization curves in figure 1(*a*) as opposed to the wider bounds), i.e. in correspondence to the lower frequencies, notoriously more uncertain (as shown in figure 1(*b*)).

A wider set might probably be generated by setting a higher value of α (unfortunately the actual value is not indicated in the comment by Socco *et al* (2012)).

As we clearly state in Boaga *et al* (2011), the choice of the mathematical expression $\pm\Delta V_R = \pm(0.05V_R + 100/f)$ that we have used to define the equivalence volume in the data space is arbitrary (as much as the α of Socco *et al* (2012)). It was designed to take into account the general behaviour of the uncertainty with respect to frequency and velocity. However, the chosen coefficient values guarantee that the uncertainty bounds are compatible with the usual uncertainty range for this kind of measurement. As an example (figure 1 in this reply), it is worth considering the representative real dataset reported in Socco and Boiero (2008) characterized by a data uncertainty that is in general comparable (and, for many frequencies, larger) than the one used in Boaga *et al* (2011). Moreover, it is important to remark once again that the selection criteria are two; thus, not only the uncertainty in the data space but also the admissible velocity and thickness ranges play an important role in the selection of the equivalent V_s profiles (and corresponding dispersion curves). In Boaga *et al* (2011), the constraints concerning the model space avoids instability problems (i.e. the possibility that two very close dispersion curves can correspond to extremely different V_s profiles) and, at the same time, prevents too extreme dispersion curves being considered acceptable. For this reason, in all the cases in Boaga *et al* (2011), the dispersion curves do not span uniformly the wide uncertainty range characterizing the very low frequencies.

Note that even if the equivalence criteria in Boaga *et al* (2011) allow for a larger variability of V_s profiles, the results obtained in the presence of a fast shallow bedrock coincide with the conclusions of Foti *et al* (2009): in all cases where a strong impedance contrast is present, the true value of the shear velocities is irrelevant for engineering purposes. That is also confirmed by Socco *et al* (2012) in their comment: by adding a *generic* (in Socco *et al* 2012, the characteristics of the bedrock are not specified) shallow fast seismic bedrock at the bottom of a quite smooth velocity profile (like the one considered in case A in Boaga *et al* (2011)), the seismic amplification becomes independent of the actual V_s profile. The seismic site response reported in Socco *et al* (2012) is a harmonic response (see their figure 2), i.e. is only a function of the depth of the added bedrock. Since Socco *et al* (2012) impose a seismic bedrock at 150 m depth under soft layers (with an average V_s around 300 m s^{-1}), it is not surprising that the system is forced to a frequency resonance about 0.5 Hz (and relative multiple $\pi/2, 3\pi/2, \ldots$). Concerning the request by Socco *et al* (2012) for further clarification regarding the way we performed the deconvolution procedure, it is well known that SHAKE91 automatically deconvolves the signal, transferring the seismic input of an outcrop record (Schnabel *et al* 1972, Idriss and Sun 1992, Rota *et al* 2011).

Conclusion

Boaga *et al* (2011) extends the analysis discussed in Foti *et al* (2009) to a wider range of (very important) cases when it is not possible to recognize a fast bedrock. In Boaga *et al* (2011), we investigate different scenarios, and adopt several simplifications, which, even if they might seem rough, are shown to be compatible with the usual dataset collected for seismic site response evaluations. In contrast, we have severe reservations about the uncertainty bounds as defined by Socco *et al* (2012), as they only consider uncertainty *within* the set of theoretical dispersion curves statistically indistinguishable from the best fit.

After Boaga *et al* (2011), we can conclude that when no sharp impedance contrast is detectable, the accuracy of the shear velocity profile becomes essential for the correct evaluation of the local seismic hazard. In contrast, if a seismic wave resonator (e.g. soft layer over a rigid bedrock) is considered, the details of the shallower layers are not important for the estimation of seismic response. This result, related to this specific kind of scenario, is paradoxically confirmed also in the comment to Boaga *et al* (2011) by Socco *et al* (2012).

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