THE RAYLEIGH WAVE ELLIPTICITY INFLUENCE ON MODES MISIDENTIFICATION

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Introduction. The surface wave method is widely diffused for shear wave velocity estimation, based on the dispersion properties of vertically heterogeneous media (Arai et al., 2004; Foti, 2002; Tokimatsu, 1995; Strobbia, 2002; Socco and Strobbia, 2004). Every surface wave technique requires firstly an high quality recorded seismograms to be analysed. From the data we can estimate the dispersive properties of surface waves, and then go forward with an inversion process of the dispersion curve, controlling the observed Rayleigh wave dispersion, in order to estimate a realistic shear wave velocity profile. One of the most neglected problem in surface wave analyses concerns the complexity of the multimodal wave propagation which can lead to modes misidentification (Tuan et al., 2011). Even if several issues must be fronted, e.g. attention must be paid to the presence of subsurface structure more complex than simple one-dimensional layering (Strobbia and Foti, 2006; Vignoli et al., 2009, 2011), the inversion of the dispersion curve remains one of the most critical aspect of all the procedure (see Lai et al., 2005, Maraschini et al., 2010). Commonly dispersion curves are identified as energy density maxima in transformed domains, for example the frequency-wavenumber or the frequency-velocity domain. For each frequency the energy maxima are identified in correspondence of certain modal wavenumbers \(k\) or velocities \(v\), and it is commonly assumed that the highest modal \(k\), corresponding to the lowest phase velocity \(v\), belongs to fundamental mode of propagation (Weaver et al., 1982; Karray et al., 2008; Park et al., 1999).

Generally common surface wave users consider only the largest spectrum energy frequency by frequency, and the fundamental mode is assumed as dominant even if this is not always verified (Foti et al., 2002; Zhang et al., 2003). Often from surface wave analyses we observe only an apparent dispersion curve which represent the contribution of several modes. The focus of this study is on evaluating the effects of mode mis-identification, in particular as a consequence of the well known ‘osculation’ phenomenon (Malischewsky et al., 2008). Osculation points are point at which two modal dispersion curves get very close and often have the appearance of crossing each other (Cercato, 2009). We want here to show as the osculation phenomenon is strictly related with the polarization of Rayleigh motion in the case of strong impedance contrast in the first subsoil (Boaga et al., 2012). The use of a multi components analyses of motion can be really useful in certain particular geological conditions.

Osculation and Polarization in presence of high impedance contrast. The frequency at which two modes have quite similar phase velocity is called ‘osculation frequency’. Osculation appear in multi channels surface wave analyses in presence of a strong impedance contrast (Tuan et al., 2011). This type of behaviour can take place between two modes of any order. In common practice the most important osculation point that can lead to mode misidentification occurs between the fundamental and the first higher mode. It is in fact known that, for frequencies larger than the
Oscillation frequency, the fundamental mode of vertical component is the one carrying most energy. Near the singularity of the oscillation frequency the amplitude of the fundamental mode drops rapidly while the first higher modes increases rapidly. For frequencies smaller than the oscillation frequency the first mode appears as more energetic than the fundamental one. The result is that for lower frequency domain below the oscillation frequency the fundamental mode is not dominant. Since the transition between the two modes can be smooth, both in terms of velocity and amplitude, it could give the impression of a single “apparent” dispersion curve that corresponds to neither the fundamental nor the first higher mode. The misidentification of the two modes contribution are more and more relevant on case of poor K resolution, i.e. for limited array length or limited number of receivers, which is common logistic problems for engineering purposes. This kind of recording
can lead to the mode misinterpretation between the fundamental and the first higher mode, with a consequent strong influence in the inversion process and relevant misleading of the subsoil structure results. Since in earthquake engineering surveys one of the most critical challenge are correct seismic response in presence of strong impedance contrast the mode osculation becomes a more serious problem. The osculation phenomenon is observed in fact in subsoil which present strong impedance, such as a soil layer lying on top of fast bedrock (Tuan et al., 2011; Cercato, 2009), which are extremely critical for the seismic scenario aspects. A typical osculation case is presented in Fig. 1. The figure shows a 48 vertical channels synthetic seismic records, with geophones spacing of 2m for a total length array of 96 meters. The synthetic datasets (full-waveform seismic records) are generated using the SEM2DPACK software (Ampuero, 2008). The excitation source is, in all cases, a Ricker wavelet with 20 Hz frequency peak, located at the ground surface and corresponding to a vertical motion. The simulated recorded data are considered reliable up to 50 Hz. At the bottom and at the lateral boundaries we applied Stacey (1988) absorbing conditions.

The synthetic subsoil model has in this case two layers: a first layer of 5 m of thickness with a Vs of 300 m/s and a second half-space layer considered as a stiff bedrock with Vs of 1100 m/s. This kind of subsoil structures is expected to present an osculation frequency near 25 Hz. The Figures panels below show the corresponding f-k spectrum and the dispersion curves (in blue), assumed as the relative maxima on the theoretical modal curves of the fundamental, the first and the second modes (in black). In this subsoil model case, which represents a very common condition in the seismic surveys tools of the engineering practice, the k resolution does not allow a clear identification of the modes and the osculation point is then not clearly recognizable in the f-k spectrum.

In this condition the observer of the f-k spectrum can identify an apparent dispersion curve ignoring it has the contribution of two modes. If this curve is inverted as referred to only to a single mode (e.g., the fundamental one) this could lead to an erroneous subsoil description with a large overestimation of a bedrock, which is particularly dangerous for earthquake engineering and a-seismic purposes. Moreover we must consider that our synthetic case shows an ideal noise free recording. In the applied practice of multi-channels analysis of Rayleigh wave (e.g., MASW, Park et al., 1999), given to the measurement site noise jointed to the limited spectral resolution of finite array lengths, this ambiguity can be expected even with larger velocity differences. As discussed by Tuan et al., (2011) and Malischewsky et al., (2008), the osculation phenomenon occurs only for certain impedance contrast cases, and has great consequences also for the seismic
response analysis (Castellaro and Mulargia, 2009; Mucciarelli et al., 2009; Boaga et al., 2011). High impedance contrasts have, in fact, not only a strong impact onto seismic amplification, being a primary target for the site characterization (Nogoshi et al., 1970; Mulargia et al., 2008) but also strong influence on Rayleigh waves polarization. It is well known that the Rayleigh wave particle motion is elliptical and can be strongly polarized. The ratio between the vertical and the horizontal components, i.e. the vertical ellipticity, depends on the velocity profile and on the thickness of the layers. In vertically heterogeneous media in fact the ellipticity is a function of frequency, and its character is strongly dependent on the velocity contrasts. The polarization of surface waves is related to the velocity structure and his signature becomes larger with large velocity contrast. For the simplest case of one layer model over an half-space, the ellipticity varies with frequency and its range increases with increasing velocity contrast between layers. We described as an high impedance contrast condition lead modal curves to present a singular frequency where fundamental and first mode travel with similar phase velocities, and how this osculation point are strictly related to the velocity contrasts. The ellipticity polarization also increases with increasing velocity contrasts and we want to describe here that also the relationship between polarization and osculation is direct.

In the example of Fig. 2 we show what happens assuming a large impedance contrast in a two layers model. The synthetic model in this case has a first layer of 6m thickness with $V_s=200$ m/s over an half-space with $V_s=900$ m/s. this condition can efficiently be representative of an ideal geological reality e.g. a soft covers over a rigid bedrock in mountain region. This condition lead to a typical osculation phenomenon at the frequency of ca 14 Hz (obviously lower then case 1 since first layer thickness is higher), which is shown as the frequency ‘$F_v$’ in Fig. 2. Near this frequency also Rayleigh polarization presents a singularity, in fact at ‘$F_v$’ horizontal particle motion vanishes. At this singular frequency the Rayleigh wave is purely vertically polarized, while at frequency ‘$F_h$’ the vertical particle motion vanishes, and the polarization becomes horizontal. These singularities are also points where the direction of the elliptical particle motion changes: from counter clockwise to clockwise and to counter clockwise again. The peak of the vertical ellipticity takes place very close to the osculation frequency. This points out the strict relationship between osculation and polarization in case of strong impedance contrast in the subsoil.

It is evident as large contrasts in the subsurface produce both the mode osculation and the high peak of vertical ellipticity at the same frequency, with a strong influence on mode misidentification on the vertical component. The ellipticity of Rayleigh wave in this synthetic cases points out also a relevant observation: motion presents different polarization before and after the osculation point frequency. The example shows as, focusing only on the vertical component of the seismogram, we can easily fall into the modes misidentification described above. This is due to the characteristic of particle motion because below the frequency ‘$F_v$’ the fundamental mode is predominantly
horizontal. On the contrary below that frequency the first mode presents mainly vertical polarization, and this explains why the energy seems to shift from the fundamental mode to the first one in the case of a common vertical component surface wave analyses. It suggests the same linear array of common MASW prospecting should be integrated with multi-component receivers, acquiring multiple shots.

The Multi-components Analysis of Surface Wave (McASW). We have seen how, below the osculation point frequency, the Rayleigh wave ellipticity polarization makes the vertical component of the first higher mode much more energetic than the fundamental one. This implies that if only the vertical component of soil motion is acquired and analyzed in a multi channel seismic records, energy seems to shift from the fundamental mode to the first higher mode at a certain frequency function of the subsoil profile. The inverse polarization of the horizontal component of motion suggests that, if we take in consideration also the horizontal transversal components of motion we can be able to follow the fundamental mode also below the osculation frequency. It is expected in fact horizontal component spectrum maxima do not present shift of energy between fundamental and the first higher mode. Fig. 3 shows the spectra from the vertical and horizontal component data for the same case of Fig. 1. The vertical component spectrum presents the very well known osculation phenomenon close to 25 Hz where energy leaves the fundamental theoretical mode to shift to the higher one, as shown in Fig. 1. The horizontal component spectrum on the contrary allows the identification of the fundamental mode, even below the osculation frequency, with no ambiguity. This is done to the mostly prevalent horizontal polarization of the fundamental mode below the osculation frequency. In particular the horizontal component f-k spectrum shows as, below the osculation frequency, energy maxima still remain on the fundamental theoretical mode, except for the very low frequencies. This representation produces a more easily identifiable correct dispersion curve.

These synthetic results and the supporting theory indicate that the use of horizontal component receivers in multichannel arrays can allow a correct definition of the fundamental mode dispersion down to low frequencies, well below the osculation point. The use of both vertical and horizontal components of the seismograms, in case of strong impedance contrast, allows in fact to easily detect the osculation frequency singularity. Moreover it allows to recognize as, below that frequency, the f-k maxima of the vertical component spectrum insist on faster phase velocities which are not part of the fundamental modal curve. The correct fundamental modal curve at low frequencies are instead well identified by the horizontal component spectrum.

Conclusion. Below the osculation frequency the f-k spectrum energy maxima of the vertical component of motion do not insist on the only fundamental theoretical mode. This can lead to large errors in the inverted models if modes contribution is not considered, with large over estimation of bedrock velocity. The osculation frequency is directly related to the thickness and the velocities of the layers and a similar behaviour is observed in the theoretical Rayleigh ellipticity. Our synthetic tests show that the osculation frequency is practically the same frequency at which Rayleigh ellipticity fundamental mode has a minimum. We note how the osculation frequency, at which we observe the shift of energy between fundamental and first higher mode, is the same frequency at which fundamental and first higher mode have similar ellipticity. We described as the fundamental mode below that singular frequency has a predominantly horizontal motion, while first mode has a predominantly vertical motion. If we look only on the vertical component energy seems to shift from the fundamental to the first mode while, on the contrary, the use of horizontal components can help to avoid mode misidentification. This evidence has been experimentally demonstrated in Boaga et al 2012.

These synthetic results and the supporting theory indicate that the use of horizontal component receivers in multichannel arrays can allow a correct definition of the fundamental mode dispersion down to low frequencies, well below the osculation point. This is the reason to employ a Multi-components Analyses of Surface Wave (McASW). This approach can lead to the design of alternative operational practice that can avoid any overestimation of bedrock seismic velocity as a
consequence of the osculation problem. Since one of the main use of shear wave profiles is for the seismic amplification analysis, and that bedrock velocity overestimation could lead to serious misleading, the value of McASW approach here proposed is evident.

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