COMPARISON BETWEEN ULTRASHALLOW REFLECTION AND REFRACTION TOMOGRAPHY IN A GEOTECHNICAL CASE STUDY

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Introduction. From the last decades of the past century, an intense research to investigate the possibility and convenience of using the ultra-shallow reflection technique in engineering and environment - both with P- and SH-wave - has been developed, as witnessed by the abundant literature including theoretical papers and technical papers dealing with real case studies (e.g. Steeples *et al.*, 1997; Ghose *et al.*, 1998; Miller *et al.*, 1998; Miller and Xia, 1998; Steeples and Miller, 1998; Baker *et al.*, 2000; Deidda and Balia, 2001; Balia *et al.*, 2001, 2003; Balia and Gavaudò, 2003; Schmelzbach *et al.*, 2005; Balia and Littarru, 2010).

Almost at the same time there has been a significant evolution of refraction seismology, with the final transition from classical techniques, based on the analysis and interpretation of the traveltime curves, to refraction tomography (e.g. White, 1988; Moser, 1991; Hole, 1992; Mandal, 1992; Boschetti *et al.*, 1996; Sheehan *et al.*, 2005).

Presently, there is the feeling that, in spite of the continuous development of the shallow and ultra-shallow reflection, the use of this technique for operational, non-scientific purposes is still relatively uncommon. Very likely, this is also due to the greater ease of use and the effectiveness attained with refraction tomography so that in most of the cases, especially in engineering and environmental problems in which more often than not the targets are just a few meters deep, the latter technique is preferred.

As known, ultra-shallow reflection requires specific instruments and field procedures: high natural frequency geophones, when available, placed at very short spacing, CMP cables, very short shot-point spacing; the problems become even more challenging in the processing: strong interference with refractions, ground-roll and air-wave, data sets generally characterized by poor signal-to-noise ratio, great difficulty for compensation of static effects and for velocity analysis, and so on. Of course, a good processing package is strictly necessary.

Even refraction tomography requires a good processing package, but: geophone interval and shot interval can be less, the spread management is less demanding and nowadays processing simply requires the coordinates of detectors and shot-points, and obviously the first-arrival times; moreover the most complete processing packages allow to process jointly surface data and down-hole/up-hole/cross-hole data.

The aim of this paper is to show, analyze and discuss the results obtained along one same profile by means of shallow reflection and refraction tomography respectively, using the same base materials and, obviously, the respective processing packages.

Experimental site and instruments. The experimental site is located in the old town of the city of Cagliari (Sardinia, Italy). In this case, the accurate knowledge of the subsoil to a depth of 10-15 m from the ground level was requested for designing an underground car parking. Apart from the road paving (0.3 m thick) the near-surface geological scheme of the site is constituted, top to bottom, by: 1) a more or less compacted backfill made up of sand, gravel and abundant clay, with thickness from zero to several meters, 2) a bedrock constituted by Miocene argillaceous limestone, more or less fractured and weathered, more than twenty meters thick, belonging to the intermediate member of the so-called "Miocene Cagliaritano", and named "Tramezzario" (Barrocu *et al.*, 1981). The excavation for the parking should have a depth of about 12 m, and therefore the aim of the survey was to define the depth to Miocene limestone bedrock and to identify both characteristics and possible changes especially within the bedrock, at least in the first fifteen meters from ground surface. The ground surface of the site is regular and the line along which seismic data acquisition has been performed, about North-South oriented, has a dip of 5%. The basic equipment employed for the two surveys is listed below:

- geophones with natural frequency of 14 Hz, un-damped;
- data acquisition system ABEM - Seistronix RAS 24, two units with a maximum of 48 active channels;
- energy source: 5 kg sledge hammer with vertical stacking for refraction; accelerated dropping weight, single shot, for reflection;
- CMP cables and accessories.
- refraction data processing has been performed by means of the SeisOptPro V5.0 package which simply requires the first-arrival times and the acquisition geometry, and works through a non-linear optimization technique, the so-called Adaptive Simulated Annealing (e.g. Lindsay and Chapman, 1993). Ultra-shallow reflection data have been processed by means of the SPW - Seismic Processing Workshop package.

Ultra-shallow reflection section. The reflection section is shown in Fig. 1. It has been obtained with:

- 36 channel off-end spread;
- geophone interval = shot interval 1 m; maximum CMP fold 1800%;
- in-line minimum offset 6 m, maximum offset 41 m;
- shots 100; acquisition time 3,5 hours, spread assembly-disassembly included;
- processing time, record uploading included, one full day.

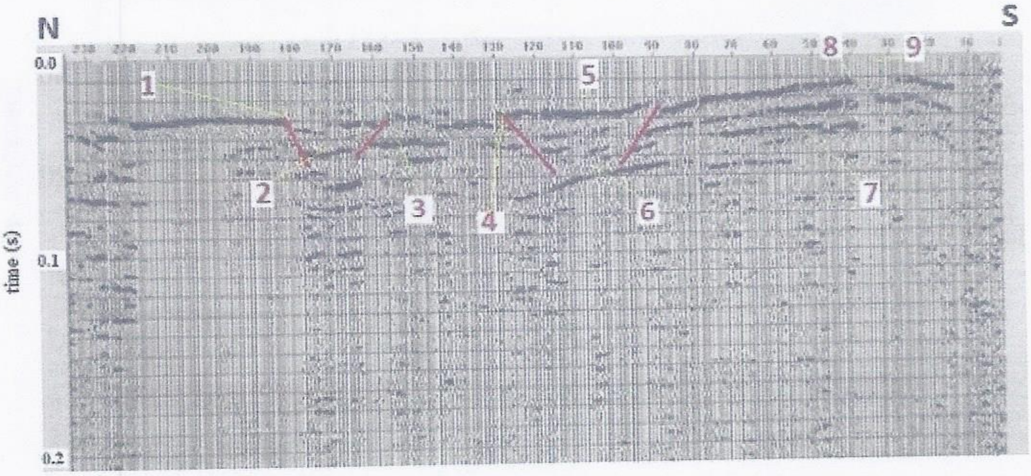

Fig. 1 – The utrashallow reflection section. CMP trace interval 0.5 m; red lines represent faults; red numbers indicate reflectors and structural details.

The processing flow has been rather simple and included the following main steps: trace edit, frequency analysis and filtering, spectral whitening, sorting into CMP gathers, velocity analysis, NMO correction and brute stack, spatial noise filtering, 2-traces horizontal stack. Though ambient noise level was very low, reflections were not very clearly detectable and several attempts to apply more sophisticated processing steps have not provided satisfactory results; eventually, the most convenient way for velocity analysis revealed the constant velocity sections method (CVS): the seismic section at hand has been obtained with a constant stack velocity of 850 m/s. At a glance, a near surface reflector affected by several discontinuities can be individuated; the dominant frequency of reflections is of the order of 100-170 Hz. It is located at a depth of 3-12 m from South to North, values estimated on the basis of the stack velocity which is the only available information for time-to-depth conversion. Several faults are also visible but, for the same lack of information said above, quantifying their possible throw is not easy. Actually, taking into account the geological information, namely the good knowledge of the base geology in the study area, the raw geotechnical model can be described as constituted by a more or less shallow bedrock, more or less fractured, made up of Miocene limestone and covered by loose, soft materials: that's not exactly a high detail information. However, the seismic section shows several interesting details as indicated in the figure: a small step affecting the shallowest reflector (1), a deeper reflector (2) (3), another step (4), another portion of the shallowest reflector (5), a deeper reflector (6) (7), a sudden lack of reflections close to surface (8) (9); but it must be said that both identification and significance of these details are largely dependent on what has resulted from the next refraction survey.

Refraction tomography. The refraction tomography section is shown in Fig. 2, where the position of the reflection section is also indicated. It has been obtained with:

- 48 channel single spread;
- geophone interval 3 m, shot interval 6 m;
- shots 27; acquisition time 2 hours, spread assembly-disassembly included;
- first-break picking (manual) and uploading: 2 days;
- processing time 9 hours overnight.

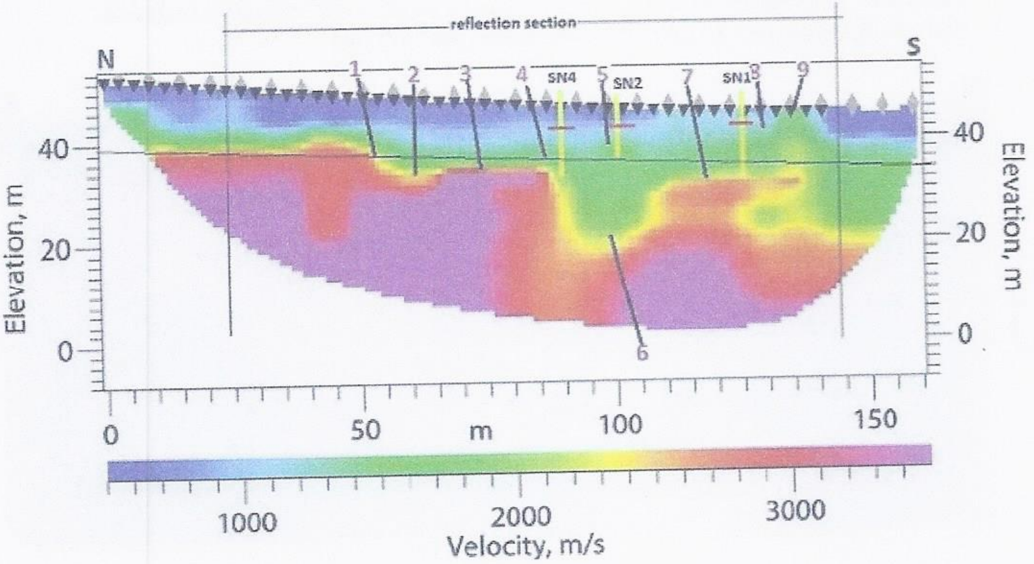

Fig. 2 – The refraction tomography. Grey triangles and black triangles represent shot-points and geophones respectively. Boreholes are indicated with the yellow lines and the red dashes represent the backfill-to-limestone transition; red numbers indicate relevant details and the black line parallel to ground-surface is the bottom of the excavation for the car park to be built.

The immediate feeling is that the tomography contains four primary velocity fields, namely, top to bottom: 1) a dark-blue field, corresponding to P-wave velocity of 500-1000 m/s; 2) a green field, corresponding to 1300-1900 m/s; 3) a red field, corresponding to 2800-3100 m/s; a purple field, corresponding to velocity exceeding 3400 m/s. The secondary fields (light-blue and yellow) appear to represent essentially the transitions from a primary field to the other. The geotechnical interpretation is made easier thanks to three boreholes drilled along the seismic line -though not exactly coincident with the line itself- whose position and depth are shown in Fig. 2 (SN1, SN2 and SN4); these boreholes are not very deep, but they provide the depth of the backfill-to-limestone transition, marked with the red horizontal dashes in Fig. 2. As can be seen, this transition roughly corresponds to transition from dark-blue to light-blue, which means that the light-blue field doesn't represent the simple graphical effect of a velocity gradient, but the nearest-to-surface limestone, highly weathered and fractured, with P-wave velocity of the order of 1000 m/s. Based on this evidence, it can be said that the green, red and purple fields represent the progressive improvement with depth of the limestone quality. The P-wave velocity associated with the green field is 1300-1900 m/s, then corresponding to still highly fractured material: in fact P-wave velocity laboratory measurements on integer limestone samples give velocity exceeding 3000 m/s, that is in the red and purple fields. Apart from this short description, the meaning of the refraction tomography will be further discussed in the next paragraph.

All the features numbered in the reflection section can be easily located in the refraction tomography. Apart from the apparent slope inversion of the structures from one section to the other -essentially due to the fact that the refraction tomography is referred to the real ground surface, while the reflection section is drawn with respect to a horizontal reference line- it must be admitted that the correspondence between the two sections is beyond all expectations. However one must ask: would have been possible to give a reliable interpretation of the reflection section, in the absence of the refraction tomography? And again: what is the level of information of each of the two products, especially in geotechnical terms?

Discussion and conclusions. First of all must be recalled that, in agreement with a decision declared in the introduction, the two surveys have been purposely carried out using the same basic equipment and with acquisition-processing sequences equivalent in terms of time and overall effort. Actually a more challenging work could have been made for the ultrashallow reflection profile, but one cannot be sure that the additional effort would have given an adequate improvement of the results. This said, let us consider the whole information given by each of the two surveys.

The shallow reflection section appears attractive due to the inherent ability of the reflection method to provide a visual representation intuitively associated with the real structures of the subsoil. Actually it contains very good information as far as the structural conditions are concerned, since faults and main geological transitions are clearly depicted. However the velocity field, rather uncertain and approximate, is substantially useless for geotechnical purposes. To this must be added that the reliable interpretation of the section is strongly dependent on the availability of the refraction tomography: for example, only after examining the refraction tomography it can be concluded that the closest-to-surface reflector does not represent the same geotechnical transition everywhere along the line and, without considering the tomography, the capability of interpreting the reflection section improves just a little even considering the information from the three boreholes.

On the other hand the refraction tomography, probably less attractive in spite of its multicolor structure, seems also less real, probably due to the smoothing of the abrupt velocity changes inherent in the processing technique. But it shows a highly detailed and reliable velocity field and, at least in the case at hand, its meaning in geotechnical terms is clearly understandable, and more with the contribution of the even few and shallow boreholes. In Fig. 2, the black thin line drawn at elevation of 41-33 m and parallel to ground surface represents the bottom of the excavation that must be realized for building the car parking. Thus, from the refraction tomography one can deduct that the volume to be removed is constituted by a loose backfill with thickness of 1-6 m, and by weathered and fractured limestone: both easily workable materials, removable with digging machines, without need for high energy systems such as dynamite or demolition hammer. It is also clear that the deepest level of the car park will be based on the limestone, which is a further very useful information for designers.

Summing up, if one is forced to choose between the ultrashallow reflection and the refraction tomography, very likely the latter must be preferred thanks to the completeness and the high detail that can be reached with this technique, mainly regarding the velocity field, and also for the ease of use of the results. But eventually the base response from the comparison between the results provided by the two techniques, at least in the case at hand, is that they are strongly complementary and mutually explaining and validating. Therefore, since the two products can be obtained by means of the same basic equipment, better with some additional not very expensive equipment -such as higher frequency geophones for the reflection survey-, the conclusion could be that whenever possible and justified, both surveys should be executed.

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