

# SH-wave reflection seismic survey at the Patigno landslide: integration with a previously acquired P-wave seismic profile

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**Introduction.** Seismic investigation on landslide is hampered by several factors that could prevent the use of the reflection seismic method to characterize the subsurface architecture (Jongmans and Garambois, 2007). Moreover, acquisition and processing of reflection seismic data are more time consuming compared with other geophysical techniques such as refraction seismic and electrical resistivity tomography (ERT), leading inevitably to higher costs. Notwithstanding these difficulties, recently some attempts to delineate the deep slip surface of large landslides have been carried out using P-wave reflection seismic surveys (Apuani et al., 2012; Stucchi and Mazzotti, 2009; Stucchi et al., 2014;). P-wave reflection seismic method is effective in imaging the slip surface at a depth sufficiently greater than the seismic wavelength, whereas, for very shallow horizons, it suffers from the limited resolution that can be obtained by the use of compressional waves. In this regards, SH-waves can be used to overcome this limitation (Deidda and Balia, 2001; Guy, 2006; Pugin et al., 2006,), but they require a specifically-designed energy source for waves generation, geophones measuring horizontal components of particles motion and an accurate choice of acquisition parameters. On the contrary, due to attenuation, the depth of investigation for SH-waves can be lower than for P-waves (Pugin et al., 2006). Therefore the geological understanding of a mass movement can take advantage of a combined use of both these geophysical methodologies.

This is the case of the Patigno landslide, a great landslide located in the upper basin of Magra River, in the Northern Appennines, Italy (Fig.1), where a P-wave study carried out in the last years (Stucchi et al., 2014) was able to image the deepest discontinuity of the landslide body at around 40-50 m depth, but no description of the shallower layers can be inferred. Because these surface layers are the slip surfaces of quick reactivation movements of the landslide, an SH high-resolution reflection seismic survey was planned along the previous P-wave profile (Fig.1). This new survey associated to the P-wave investigation allows a more robust description of the landslide body, from the deepest discontinuity up to the very shallow portions of the landslide.

This work describes the planning, acquisition and processing of the SH reflection seismic survey, and also gives a possible combined interpretation of both P and SH seismic images.

**Acquisition and processing.** The SH seismic survey was acquired using 48 10-Hz horizontal component geophones and a source specifically designed and built for this work, which consisted of a swinging weight of 16 kg striking a baseplate firmly anchored on the ground. The total length of the seismic line was 85 m in NW-SE direction, overlapping part of the previously acquired P-waves seismic profile (Fig.1).

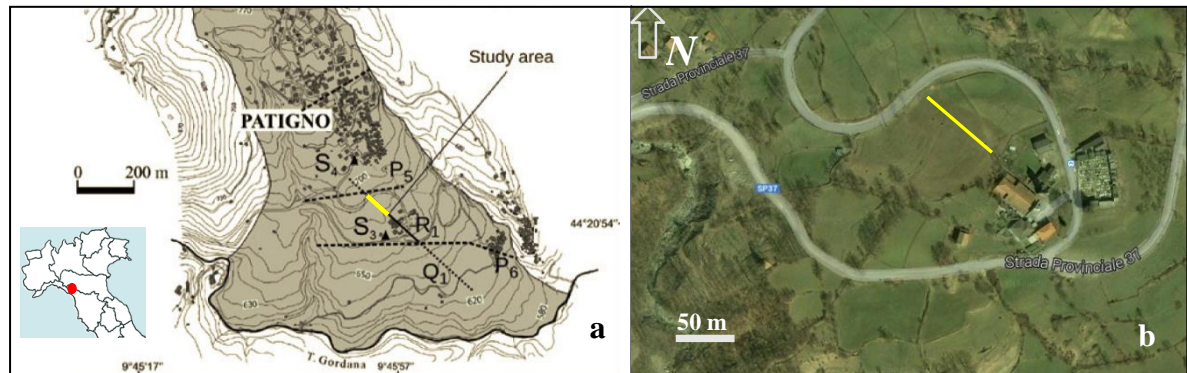


Figure 1: a) Location of the P-wave reflection seismic line R1 (from Stucchi et al., 2014 ) with overlapped the SH-wave reflection seismic profile in yellow.  $S_3$  and  $S_4$ : boreholes;  $Q_1$ : ERT line;  $P_5$  and  $P_6$  refraction seismic lines; b) close-up showing the SH profile.

To obtain an accurate data record it is important to pay attention at the correct positioning of equipment because to generate SH wave is required to energize the ground in transversal direction respect to line acquisition direction; also the appropriate positioning of the geophones along the seismic line is of fundamental importance; in fact, S-waves generated by the source are divided into a vertical (SV) and a horizontal component (SH). In order to record only the SH waves is therefore necessary to exclude from registration SV waves, positioning geophones with the direction of oscillation perpendicular to the acquisition line. The eventuality to also record events related to P converted waves is at least theoretically excluded a priori, since the geophones do not records vertical components. A geometry acquisition was planned to obtain the best advantage from the survey, with the purpose to better manage the equipment supplied in function of the complex geological context to investigate. With the aim of obtaining a sufficiently high fold coverage and a good lateral continuity as required in a landslide context, receiver interval was set at 0.75 m and source interval at 1.5m.

The survey was composed by 6 patterns; in the first pattern the source was originally located in the first station, with a 6 m as minimum offset, and it represented the beginning of the seismic line at 687m m.s.l. The subsequent shots were done shifting progressively the source of 1.5m along the line, obtaining a gradual decrease of minimum offset (which become equal to zero at the fifth shot) and a transition to a split-spread shot from an off-end shot for the last two.

At this point of the work, the source was left in its position and the geophones were instead shifted downwards of 8.25 m along the line, passing to the second pattern, where the entire procedure was repeated until the reach of the last pattern in which the source was progressively shifted upwards until the end of the line, at station 115. Using this scheme the maximum nominal coverage was 24, further doubled in the processing phase applying an interleaving procedure.

To exploit the polarization of SH waves, each shot point was acquired using both directions of energisation and in the processing lab these two records were appropriately summed to enhance the SH-waves while attenuating other unwanted phases in case they were recorded.

To increase the signal to noise ratio 6 shots were done for each polarity (i.e. directions of energisation). In the processing lab, these 6 shots with NE-SW polarization were added together and the same operation has been done for the 6 shots belonging to the same station but with SW-NE polarization, after reversing the polarity of these traces. The two resulted shots were then summed together to enhance the SH-waves while attenuating other unwanted recorded phases. Figs. 2a and 2b show an example of a raw shot gather before the vertical stacking for each direction of energisation (NE-SW and SW-NE respectively) and Fig.2c shows the resulting shot after vertical stacking.

The SH events identified on the seismogram in Fig. 2c are: the direct waves in orange, the refracted waves in red and green and strong event with a characteristic dispersion trend corresponding to the Love waves. No reflections can be observed at this stage but they are evident after the de-noising procedure aimed at attenuating the various types of noise present. This is clearly shown in Fig. 2d which displays the same gather as in Fig. 2c at the end of the processing steps applied to reduce the noise.

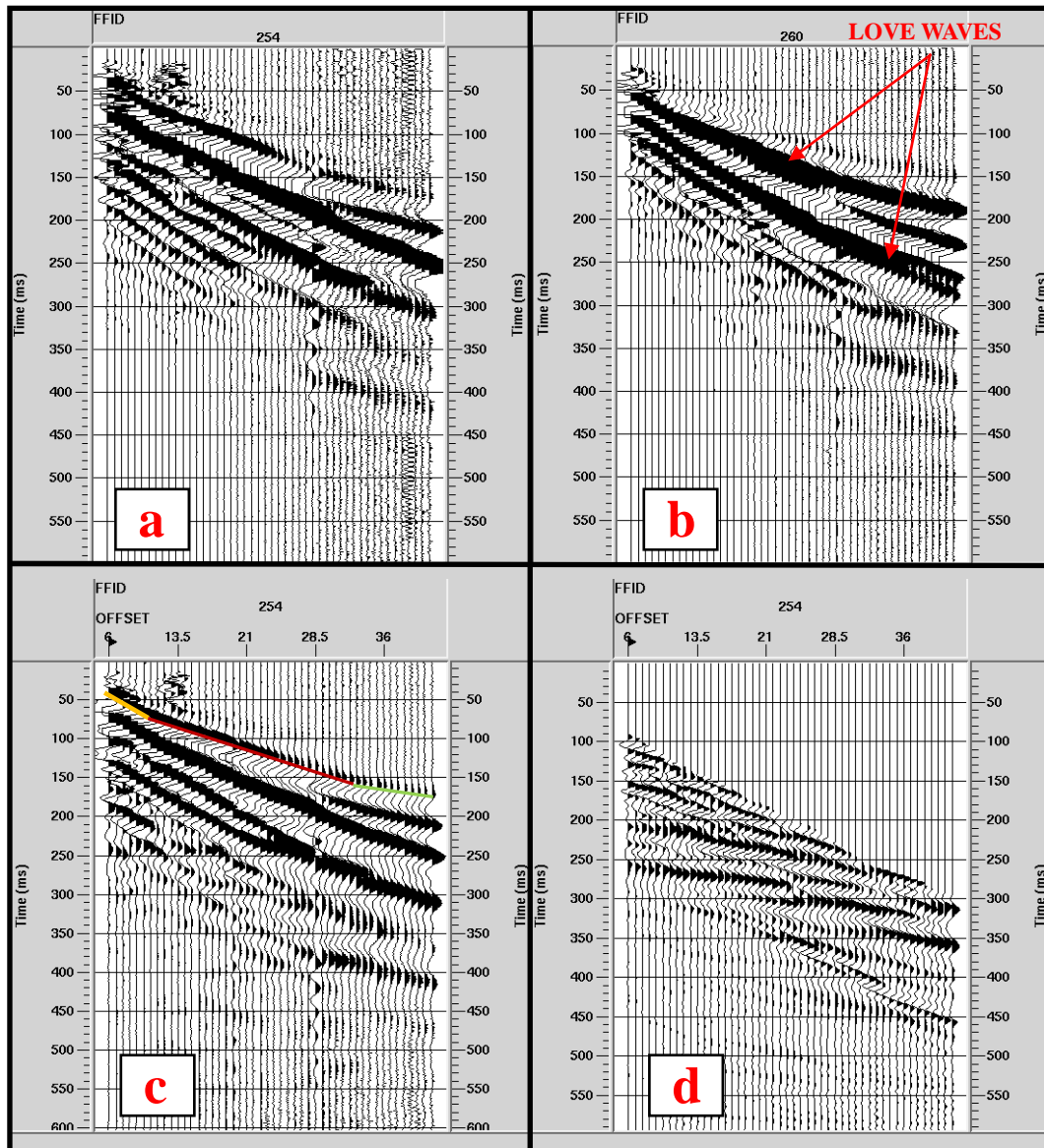


Figure 2: a) Raw shot gather acquired with NE-SW polarization; b) Raw shot gather with SW-NE polarization, belonging to the same location of the shot displayed in a); c) Shot resulting from an optimized sum of shot in a) and shot in b) whose polarity was reversed. In orange, red and green are indicated the direct arrivals and the arrivals from the first refractor and the second refractor respectively; d) Shot in c) after the following processing steps: static correction, band pass filter 5-15-100-120 [Hz], eigen filter, F-K filter, top mute .

Taking advantage of the symmetry of the path trajectory in case of SH-SH reflection, for the processing of the SH wave data we can use the same software and algorithms developed for the P-P reflection seismic data, tailoring the parameters accordingly to the required needs. The main additional and different step required in the sequence consists in a calibrated difference between the records of the sources at the same location with opposite polarization, as described before. Besides the conventional steps of database building and cmp (common mid point) gathering (with interleaving), kill of anomalous traces, static corrections, band-pass filter, velocity analysis, normal move out, residual static application and stack, some dedicated operations are applied to remove the Love waves. They constitute a particular type of coherent noise that is characterized by high energy, dispersion behaviour, recording time and frequency band coincident with those of the desired signal. With an accurate design of directional (frequency-wavenumber) and eigenvalues filters applied on the shot domain, it was possible to attenuate these wave modes early in the processing, thus increasing the signal to noise ratio at the pre-stack level as shown in Fig. 2d.

The resulting stack section was depth migrated by means of the Kirchhoff algorithm using as the velocity model a smoothed and Dix converted version of the stacking velocity field. The migrated seismic section exhibits a good signal to noise ratio from the very shallow layers up to 40 m in depth, with many continuous events displaying a trend in accordance to the expected geomorphological and geological setting. This image and the depth converted P-wave seismic section in Stucchi et al. (2014) are the ones used for a combined interpretation.

**Comparison between SH- and P-waves seismic sections.** The main feature that induces to use the SH-wave reflection seismic compared to P-wave reflection seismic is the higher resolution that can be achieved with SH-waves at very shallow depths (Guy et al., 2003; Guy, 2006). Accepting as threshold for the vertical resolution a quarter of the dominant wavelength ( $\lambda/4$ ) (Sheriff and Geldart, 1982; Yilmaz, 2001; Sheriff, 2002;), it is easy to deduce that SH seismic method benefits of a higher resolution than P seismic method. In fact, if we consider for the Patigno case a mean velocity of ~280 m/s and a dominant frequency of 35 Hz for SH waves, a resolution around 2 m results at the slip surface depth, compared to approximately 10 m for P-waves (using 2000 m/s and 50 Hz for velocity and dominant frequency respectively). Then the shorter wavelength provides a higher resolution for the SH-waves, but at the same time it causes an earlier signal attenuation because of increased absorption.

On the basis of this considerations, to better characterize the internal structure of the landslide in the investigated area and to exploit the differences and the potentials of the two seismic methods, the resulting P-wave and SH-wave seismic sections have been analyzed and compared separately and then overlapped. Fig.3a shows that P-waves seismic method is effective in locating the deepest slip surface, recognized as the main reflector in the P-wave seismic image in Stucchi et al. (2014) (dashed line in Fig. 3a). This reflector appears as a continuous and well defined event that slightly deepens along the line with two small upwards concavities. At shallower depth, above this event, no information is provided by the P-wave seismic image, therefore the internal structure of the geological body is not resolved by this method.

On the contrary, the SH-wave reflection seismic technique gives the best results in the shallower portion of the subsurface, where many continuous events are visible with a good signal to noise ratio (Fig.3b). The trend shown by these events is in accordance to the expected geomorphological setting, therefore they can be interpreted as reflectors and related to the small reactivation slip surfaces delineating minor landslides that dismantled the main complex landslide. The main slip surface can also be observed on the SH section, even though it has a lower amplitude due to the progressive decrease in signal to noise ratio with increasing depth. It marks the different trends between the near surface layers and the dipping layers at depth (green band in Fig. 3b.)

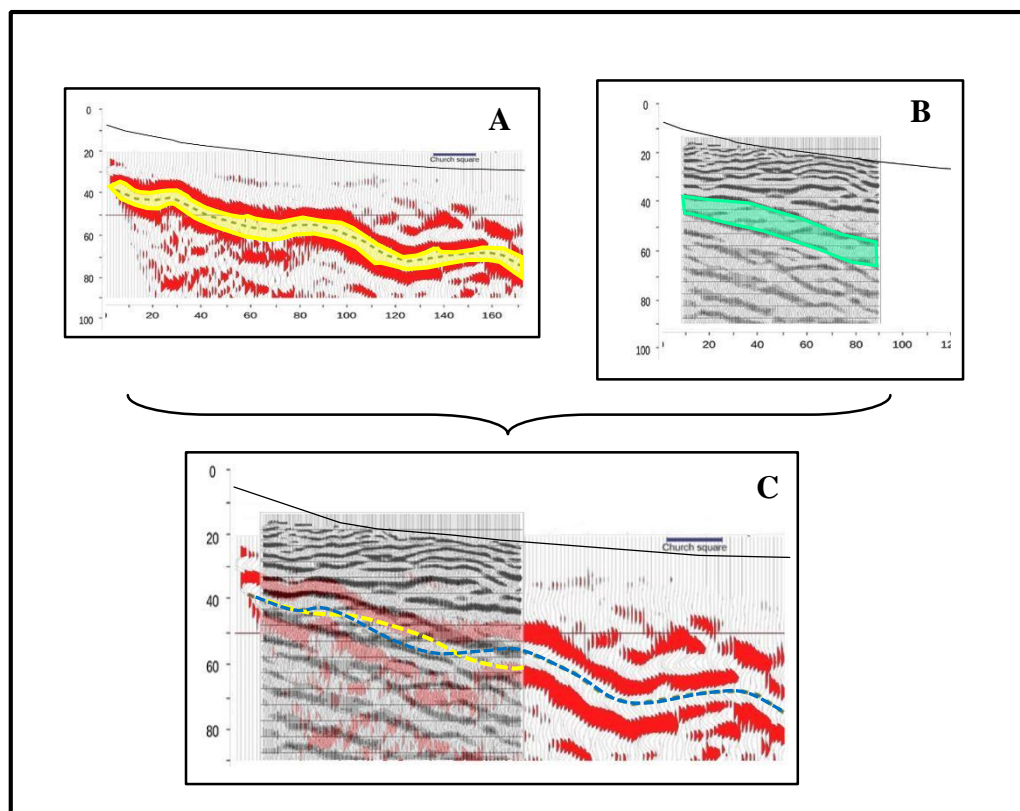


Figure 3: a) P-wave reflection seismic section. In yellow is highlighted the reflector related to the main slip surface; b) SH-wave seismic section. In green is highlighted the region related to the main slip surface; c) Overlap of the two seismic sections.

**Conclusion.** This work and the procedural choices about acquisition and data processing lets generalize SH-wave methodology to the study of landslide, because the obtained high resolution results at depth interval relevant for this type of mass movements. Indeed, the Patigno landslide stigmatizes the destabilization phenomena commonly affecting the Apennine slopes, i.e. complex deep landslide, reactivated by surface movements that often are the most destructive.

The combined use of P-waves and SH-waves offers the possibility to insight the whole body of a landslide, overcoming the limitation linked to low resolution for shallow horizons of P-waves method and low investigation depth of SH-method.

Both of seismic methodologies exposed in this work can be employed to study landslide of big dimension and the choice of which to prefer mainly depends by the purpose of the work: if it is merely the individuation of the main deep slip surface it is preferable to use the P-wave reflection seismic method because it allows a quickly data acquisition, and it requires standard processing steps and devices. If the aim to pursue is instead the reconstruction of the internal architecture of the body landslide, SH-waves method offers greater guarantees of success, thanks to its higher resolution.

Taking into account the results obtained in this work it is possible to conclude stating that SH-wave seismic reflection methodology has revealed excellent potentialities that makes it applicable in contexts in which it is generally underestimated due to difficulty of execution, complexity of data processing and high costs. Notwithstanding these difficulties, SH-wave seismic reflection methodology provides many information about the shallow part of subsurface and the union of these data with deeper P-waves seismic data gives a more robust description of the whole landslide body from the deepest discontinuity up to the very shallow portions of the complex landslide. In

this regards, the complete knowledge of the landslide internal setting is fundamental to plan adequate and effective defence strategies.

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## References.

- Anfuso A.; 2010: *Metodologie geofisiche (geoelettrica e sismica) applicate allo studio dei corpi franosi: il caso della frana di Patigno di Zeri (Appennino Settentrionale)*. Ms Thesis, University of Pisa, 155 pp.
- Apuani T., Arosio D., De Finis E., Stucchi E., Zanzi L. and Ribolini A.; 2012: *Preliminary seismic survey on the unstable slope of Madesimo (Northern Italy)*. 25th Symposium on the Application of Geophysics to Environmental and Engineering Problems (SAGEEP), Tucson, Arizona, USA, 452-459.
- Cercato M., Cara F., Cardarelli E., Di Filippo G., Di Giulio G. and Milana G.; 2010: *Shear-wave velocity profiling at sites with high stiffness contrasts: a comparison between invasive and non-invasive methods*. Near Surface Geophysics, **8**, 75-94.
- Crane J.M., Lorenzo J.M. and Harris J.B.; 2013: *A new electrical and mechanically detonatable shear wave source for near surface (0–30 m) seismic acquisition*. Journal of Applied Geophysics, **91**, 1-8
- Cricca F.; 2008. *Migrazione di Kirchhoff pre e post stack in tempi e profondità: applicazioni su modelli sintetici e dati reali*. Ms Thesis, University of Pisa, 125 pp.
- Deidda G.P. and Balia R.; 2001: *An ultrashallow SH-wave seismic reflection experiment on a subsurface ground model*. Geophysics, **66** (4), 1097–1104.
- Guy D.E.; 2006: *High-Resolution P- and S-wave Seismic Reflection Investigation of a Shallow Stratigraphic Sequence*. Electronic Journal of Geotechnical Engineering, 11, 37 pp.
- Guy E.D., Nolen-Hoeksema R.C., Daniels J.J. and Lefchik T.; 2003: *High-resolution SH-wave seismic reflection investigations near a coal mine-related roadway collapse feature*. Journal of Applied Geophysics, **54**, 51 – 70.
- Federici P.R., Puccinelli A., Chelli A., D'Amato Avanzi G., Ribolini A. and Verani M.; 2000: *La Grande Frana di Patigno di Zeri (Massa Carrara)*. Memorie della Accademia Lunigianese di Scienze, **70**, 3-51.
- Haines S.S.; 2007: *Comparison Of Compressional And Shear Wave Seismic Reflection Methods For Characterizing Aquifer Stratigraphy At The Former Fort Ord, California*. EAGE.
- Lowrie W.; 2007: *Fundamentals of Geophysics*. Cambridge University Press, 393 pp.
- Novotny O.; 1999: *Seismic surface Waves*. Universitade Federal da Bahia, Brasil, 155 pp.

- Pugin A.J.M., Sargent S.L., Hunt L.; 2006: *SH and P-wave seismic reflection using landstreamers to map shallow features and porosity characteristics in Illinois*. Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP).
- Roger Young A. and Hoyos J.; 2001: *Near-surface, SH-wave surveys in unconsolidated, alluvial sediment*. The Leading Edge., 20, 936-948.
- Sheriff R.E., 2002; *Encyclopedic Dictionary of Applied Geophysics*. Society of Exploration Geophysicists, Tulsa, Oklahoma, U.S.A., 376 pp.
- Sheriff R.E. and Geldart L.P.; 1982: *Exploration Seismology: Vol. 1. History, Theory, and Data Acquisition*. Cambridge Univ. Press., 628 pp.
- Steeple W.; 2000: *A review of shallow seismic methods*. Annali di Geofisica, **43**, N.6. 1021-1044.
- Stucchi E. and Mazzotti A.; 2009: *2D seismic exploration of the Ancona landslide (Adriatic Coast, Italy)*. Geophysics **74**(5), B139.
- Stucchi E., Ribolini A. and Anfuso A.; 2013: *High-resolution reflection seismic survey at the Patigno landslide, Northern Apennines, Italy*. Near Surface Geophysics, **4**, 559-571
- Van Zanen L. F.; 2004: *Removing Love waves from shallow seismic SH-wave data*. Delft University of Technology, 138 pp.
- Yilmaz, O.; 2001: *Seismic Data Analysis: Processing, Inversion, and Interpretation of Seismic Data*. Society of Exploration Geophysicists, 2024 pp