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Aquifer Characterization and Monitoring by Active and Passive Seismic Surveys

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Abstract

A 3D active and passive seismic survey was carried over an aquifer in Italy. We used 1-component vertical receivers in a fine areal grid of 100x100 m. Furthermore, two orthogonal linear profiles were acquired with 3-component receivers, recording the signal of a directional vibrator in the *x*, *y* and *z* direction, so getting a 9-component wave field. The data allow studying the elastic propagation effects of seismic waves in the aquifer, getting independent measurements of direct P, SH and SV arrivals. The elastic parameters they provide allow exploiting the Rayleigh wave velocities obtained by passive seismic for aquifer monitoring.

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1. Near surface imaging

High-resolution seismic surveys provide a 3D image of the sharp changes in the acoustic impedance of rocks, as the water table is. Its resolution and penetration is normally higher than most electro-magnetic methods, but the acquisition costs are higher too. These costs and the environmental impact are significantly reduced when replacing conventional active seismic sources by virtual ones obtained by the ambient noise, by cross-correlating synchronized passive records. Rayleigh waves dominate the seismic noise on land and are a good proxy for S waves. For this reason a passive seismic survey, acquired in conjunction with a standard active one, can provide both P and S wave for the near surface, so characterizing the elastic properties of the shallowest layers. A major advantage of passive seismic is its possible continuous monitoring of fluid-bearing formations. Deploying a few permanent receivers that record the ambient noise, we can detect S-wave velocity variations due to seasonal effects. In principle, we can

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characterize 3D volumes of porous rocks within inhomogeneous formations. In this paper, we present the results obtained by studying an aquifer in S. Vito al Torre (Pordenone, Italy), extending some recent work by [1] and [2].

Some duality exists for land seismic surveys in areas with a complex near surface. High-resolution surveys are needed to model and compensate for shallow anomalies that may distort the imaging of deeper hydrocarbon reservoirs. The latter ones can only be illuminated by low-frequency signals, because of the anelastic absorption and scattering of the propagating waves. A theoretical solution is provided by doubling the surveys, i.e., combining a high- and a low-resolution set up, but its cost and logistic are mostly unaffordable. Thus, an information gap exists in most practical cases on land for the near surface [3], where the velocity in the shallowest 30-50 m is often guessed or extrapolated by a few sparse upholes [4]. A second duality occurs if we try to fill this information gap with surface waves. Rayleigh waves (or ground roll) are dispersive and their phase velocity approximates that one of pure S body waves. Standard algorithms for inverting surface waves assume 1D Earth models, which are crude assumptions and can be hardly related to inhomogeneous 3D models obtained by P waves. Integrating passive seismic into a standard active survey may reduce at least one of these dualities. Seismic interferometry may provide approximated traveltimes of direct arrivals of S waves, in the areas where the ambient noise is dominated by surface waves. In this way, we may build an elastic model for the near surface, delineating possible shallow anomalies. In other areas, where P arrivals are strong enough, we can complement the P waves from the active survey with the waveforms obtained by interferometry. As ambient noise is very rich in low frequencies, its contribution may widen significantly the spectral bandwidth for high-resolution surveys.

2. Application example

Fig. 1 shows the recording geometry of a high-resolution 3D seismic survey close to S. Vito al Tagliamento (Italy). The receivers are located on a regular grid 100x100, with 5 m interval in both the NE and SW directions. The source is a Power Weight Drop. The shot points (indicated by red circles) are located along the receiver lines (marked by blue triangles): the inline interval is 5 m, the cross-line is 10 m. We notice that the receiver distribution is perfectly regular, while some limited areas in the Eastern part could not be covered by sources.

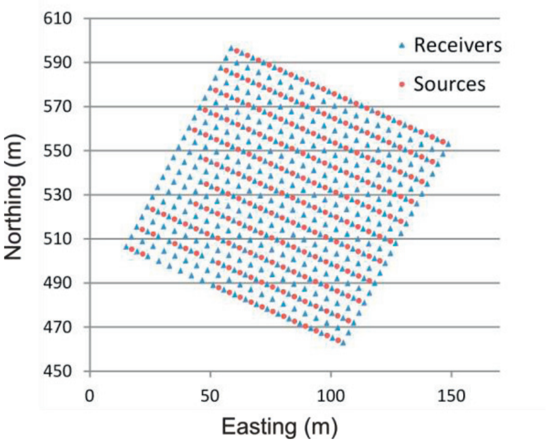

Fig. 1. Acquisition map of the high-resolution 3D survey. Blue triangles depict receivers and red circles show the source locations.

Fig. 2 allows comparing a few shots of the active survey (right) with the corresponding ones obtained by seismic interferometry of the ambient noise (left). The active seismic gathers display some shallow reflections and strong ground roll, while the records obtained by cross-correlation the first noise trace with all the others display low-frequency signal with clear hyperbolic patterns. When reordering and displaying the same traces as a function of offset (Fig. 3), these patterns become even more comparable. The delay of first arrivals from the active source (right) suggests an average velocity of about 1300 m/s, which could be due to P waves, while that one obtained by ambient noise (left) is about 400 m/s, which might correspond to S waves.

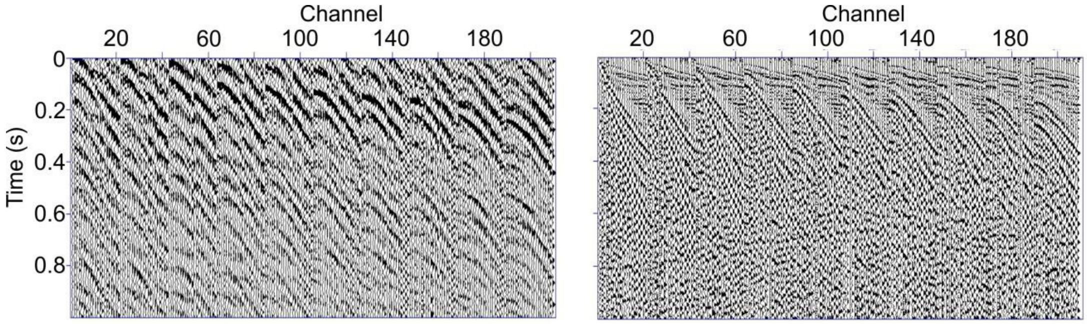

Fig. 2. Common source gathers by active seismic (right) and correlations of passive records with the first trace in the gather, so converted into a virtual source (left).

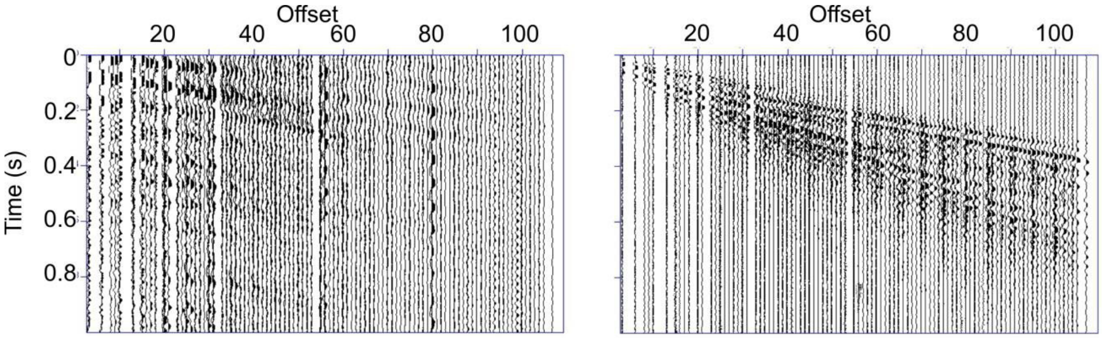

Fig. 3. The same data as in Fig. 2, but plotted as a function of the offset from the source position for passive (left) and active seismic (right). The offset is expressed in meters.

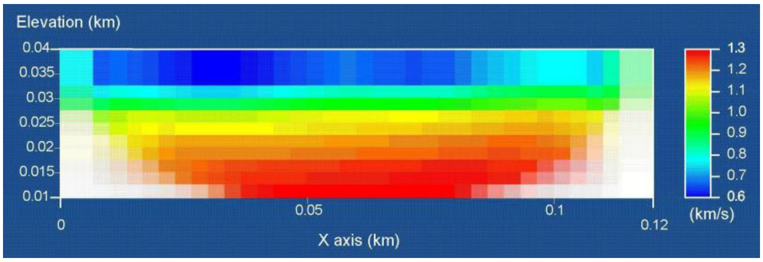

Fig. 4. Vertical section of the 3D P-velocity volume from the travel time inversion of the active seismic survey.

Fig. 4 displays the vertical section of the velocities obtained by inverting the first arrivals of P waves as diving waves. We see a shallow low-velocity layer with a thickness of almost 10 m, with velocity of 600 m/s, and a gradually increasing trend up to the likely position of the water table, at a depth exceeding 30 m. Reflected arrivals – (not considered so far) – may provide a precise estimate for its depth.

Fig. 5 shows two horizontal slices of the Vp/Vs ratio at the depth of 5 and 30 m. The Vp velocity is obtained by the diving-wave inversion of the active seismic survey, while the S-wave velocity is estimated from the cross-correlated ambient noise. The areas where reliable data is missing are colored as white. We can see smooth spatial changes of this ratio in both depth slices.

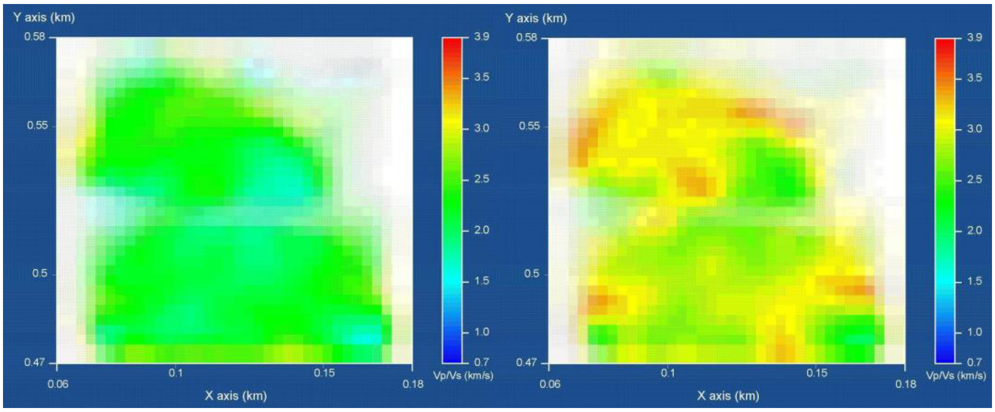

Fig. 5. Depth slices in the 3D volume for the estimated Vp/Vs ratio, at a 5 m (left) and 30 m (right).

3. Conclusions

The integration of active surveys and ambient noise interferometry may provide either an elastic model for the near surface, or a wider frequency band for land surveys aimed at shallow targets, or both. We presented a real case for the joint tomographic inversion of travel times from active and passive data, getting a reasonable 3D elastic model for the near surface that may be used for hydrological applications.

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