Fibre-Optic Strain Sensing: Game Changer for (Urban) Seismic Surveying ?

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Summary

Natural hazard prediction and efficient crustal exploration benefit from densely designed surveys. Seismological techniques provide ground-motion data, while active seismics aims at structural imaging and increasingly on physical properties determination. Dense networks exist on some volcanoes and in exploration plays, but not in urban areas where data acquisition is more challenging.

We demonstrate that dynamic strain determination is now possible with conventional fibre-optic cables deployed for telecommunication. This is a new tool for earthquake location or for crustal exploration using unexpected sources. Thereby, this method provides key records for understanding subsurface dynamics, especially in urban areas.

Introduction

Fibre optic technologies are used in an increasing number of research fields in Natural Sciences and Engineering Applications not only for data transmission but also for sensing. Distributed fibre optic sensing has gained a lot of attention over the past decades. Intrinsic physical properties of optical fibres allow, when engineered appropriately and interrogated with an adequate light source, to be sensitive to the variation of a number of environmental parameters, e.g., temperature, strain, concentration, also in harsh conditions (e.g., Daley et al., 2013; Becker et al., 2017; Hartog et al., 2018; Jousset et al., 2018; 2019).

Distributed optical fibre sensors can provide a continuous reading of environmental parameters with a high spatial resolution along the sensing fibre (meter scale) and high sampling rate (> kHz) over long distances (several km). Depending on the interrogation technology, the physical measurement principle is related to a variety of scattering phenomena of the light within the fibre (e.g., Brilloin, Rayleigh, Raman). When interrogated appropriately, sensing can be achieved by measuring the light properties (e.g., intensity, phase, transit time, polarization).

Applications include integrity monitoring, perimeter security, defaults of telecom networks, and also geophysical applications (in oil and gas industry, geothermal fields exploration and monitoring, CO2 sequestration, etc.), such as vertical seismic profile, microseismicity monitoring during hydraulic fracturing, fluid flow monitoring through production, earthquake detection, exploration of the structure of the Earth's crust (Kobs et al., 2014; Lindsey et al., 2017; Jousset et al., 2018). In this contribution, we focus on technologies to measure distributed strain data.

Method

Phase-sensitive, optical time domain reflectometry (ϕ-OTDR) is typically used for Distributed Acoustic Sensing (DAS) (c.f., Wu et al., 2015 and references therein; Masoudi and Newson, 2016). Successive laser pulses are launched into the fibre. The backscattered (Rayleigh scattering) signals are recorded so that the phase difference from light scattered at neighboring positions within the fibre can be analysed. The change of the local interferometric pattern thereby reveals the strain recorded at a specific location, assuming that the phase response is linear to the induced strain (Fig. 1).

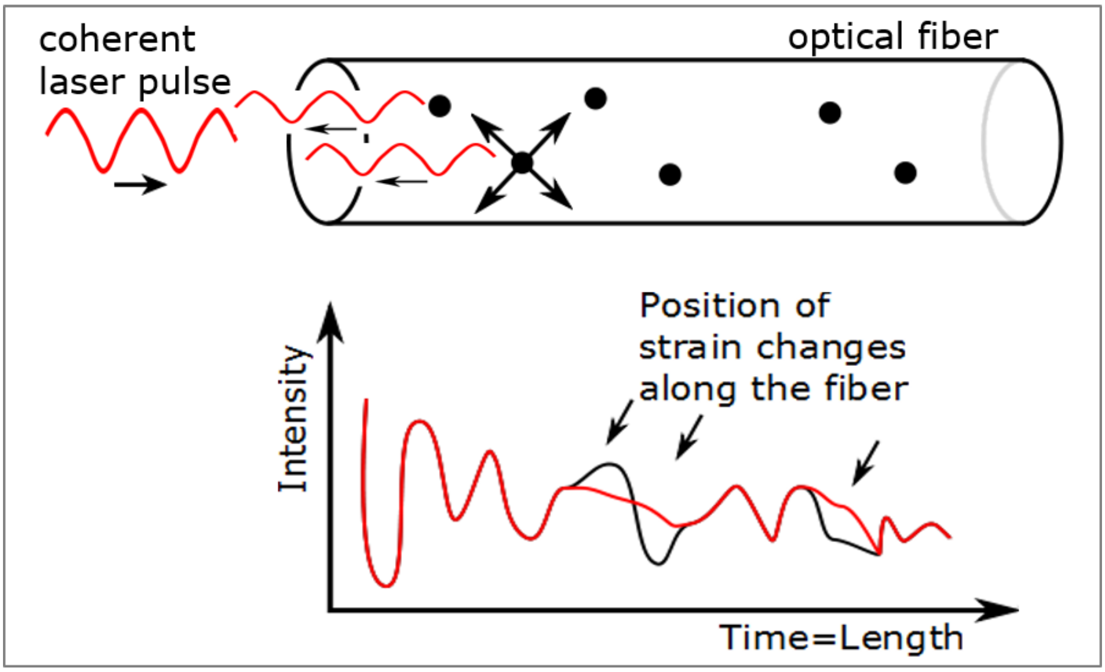

Figure 1 *Principle of Distributed Acoustic Sensing along a fibre optic cable.*

Parameters that have to be chosen for an experiment comprise the gage length (length along the cable, for which the phase difference is measured; usually between 2-10 m) and the bandwidth of the DAS signal (ranging from mHz to kHz) (see Jousset et al., 2018 and references therein).

Case study Iceland

The Reykjanes Peninsula, SW Iceland lies within the Western Volcanic Zone. The extensional tectonic activity between the North American and Eurasian tectonic plates (2 cm/year, since 6-7 Ma) induce intense seismic activity associated with rifting processes with faults and several recent volcanic systems, with young and highly permeable basaltic formations of Pleistocene age.

Extending recent DAS studies, we provide spatially un-aliased broadband nano-strain data (Fig. 2). We continuously recorded seismic signals from natural and man-made sources with 4-m spacing along a 15-km-long fibre-optic cable layout for nine days. For the acquisition, we used a standard telecommunication cable deployed in 1994. The cable lies at ca. 0.5 m depth. To estimate the coupling of the cable, we used a simple theoretical approach (Reinsch et al., 2017). It could be shown that we have an almost perfect strain transfer between the subsurface and the optical fibre for the frequency range and signal amplitude experienced in Iceland.

The optical telecommunication cable passes a fault zone known from its damage zone at surface (Fig. 2, left). Across this zone, we observe an increase in both, duration and amplitude of trapped waves excited by local earthquakes (Fig. 2, right). Such trapped phases are often seen in large scale surveys, but not with this high spatial sampling. Thus, the spatially dense fibre-optic cable records allow us to follow details of the earthquake phase's propagation within the fault zone.

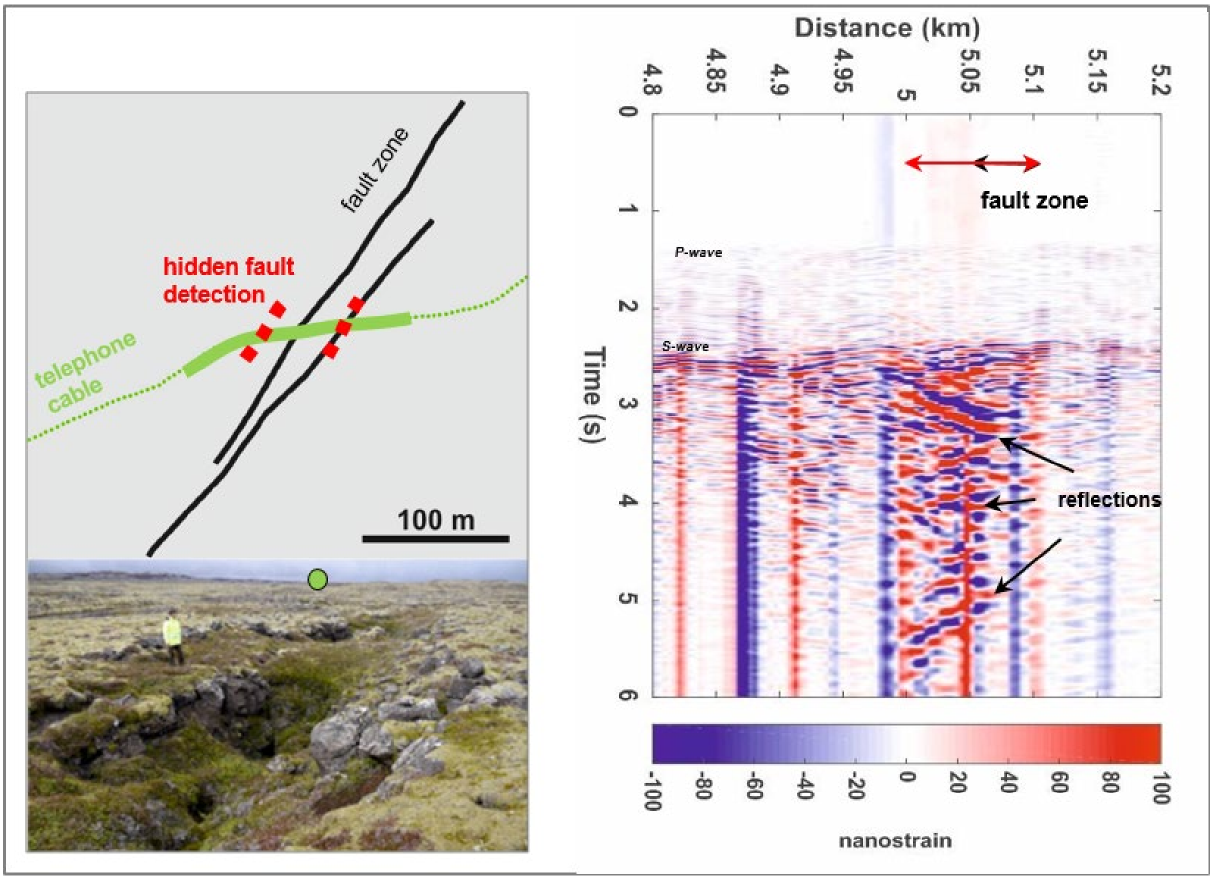

Figure 2 *Fault damage zone on Iceland. In addition to the surface exposure of the fault (left), the newly acquired data evidence hidden fault traces (right) (modified after Jousset et al, 2018).*

The effect of passing cars and traffic generally causes an environmental impact on the ground surface. Modelling on the basis of DAS data can help determining this impact in the future. In a first test, we modelled the effect of our survey car on the ground (weight ca. 2.2 t). As the sum of four points of load at the surface, we took into consideration the distances between the right and left wheels of the car (ca. 1.6 m) respectively front and rear wheels (ca. 2.8 m). Assuming a ground density of 2000 kg.m^{-3} and a Poisson ratio of 0.25 (typical for basalts), we used the Flamant–Boussinesq approximation theory describing the static deformation of a point load on the ground surface (Fung, 1965).

The shape of the strain trace with time at one location (Fig. 3) is dependent on the speed and weight of the car, on the distance to the cable, and on the elastic properties of the ground, e.g. P-wave velocity. Whereas the elastic properties influence the absolute strain value recorded along the optical fibre, the velocity changes the duration of the strain anomaly. The measured deformation curve fits best for the model of a car moving at 25 km/h with a sub-surface P-wave velocity of 750 m/s (red line in Fig. 3). In addition to a temporal analysis as shown in Figure 3, data can also be analysed in the spatial domain (several neighbouring traces at the same time) with the same result. Since the match between observations and our simple prediction is surprisingly good, future refined models shall enable a much better impact determination and a simple determination of near surface elastic properties along long profiles.

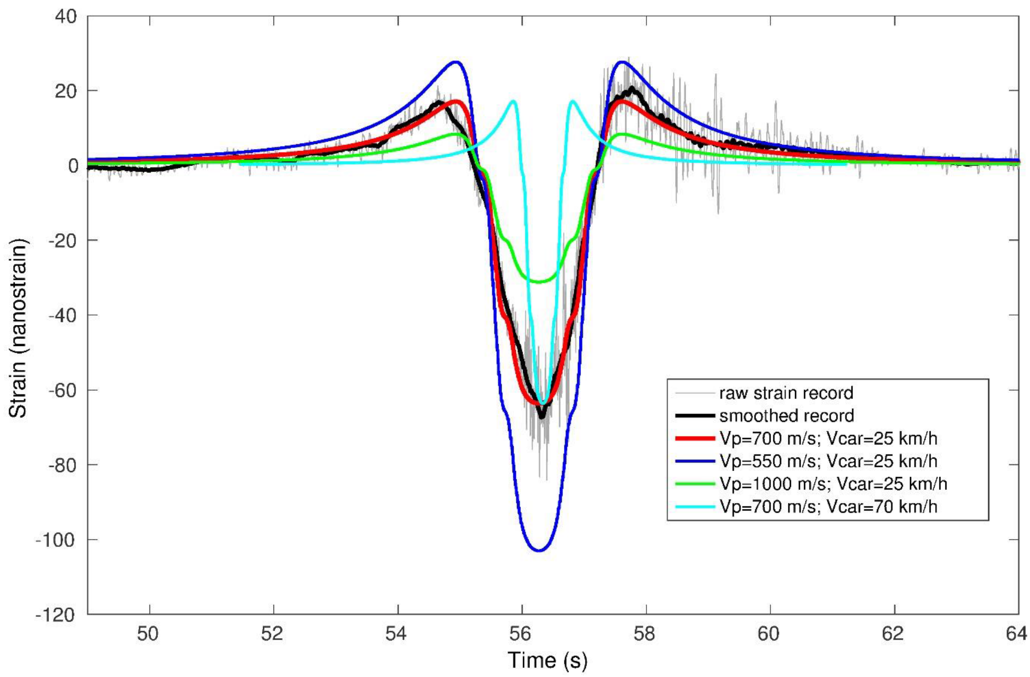

Figure 3 *Deformation of the ground due to a passing car (4WD car, ca. 2.2 t weight). Grey light curve: recorded data; thick black curve: same data but smoothed; colour curves: modelled deformation for a car moving at different speed along a road for various P-wave ground velocities (Jousset et al, 2018).*

Conclusion

We recorded seismic signals from natural and man-made sources with 4-m spacing along a 15-km-long fibre-optic cable layout. Extending recent DAS studies, we provide spatially un-aliased broadband nano-strain data. With unprecedented resolution structural features like normal faults and dykes are identified in the Reykjanes rift system, allowing to infer new fault dynamic processes. If this workflow proved stable, the use of fibre-optic telecommunication networks worldwide would open a new window for Earth exploration.

Outlook

We anticipate that monitoring of underground explosions in the framework of the CTBTO, volcano monitoring, hazard assessment and monitoring, and global seismology using transatlantic cables could benefit from such types of technology. We may also envisage experiments to compare new instrument development in rotational seismology and detailed studies of Rayleigh wave properties. Other applications (regarding e.g., city underground, car traffic, theft protection) will likely develop for further societal benefit.

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