Numerical modelling of the effect of the borehole environment on seismic amplitudes measured by fibre-optic distributed acoustic sensors

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SUMMARY

Recent studies use seismic strain amplitudes recorded by distributed fibre-optic acoustic sensors (DAS) to estimate elastic properties of the formation (the stiffer the formation, the smaller the strain). However, borehole DAS response can be affected by borehole environment. We model this effect numerically with 1.5D full wave reflectivity method implemented in OASES software (3D wave propagation in a 1D model). In these simulations, cement, casing and wellbore are represented by infinite vertical layers. For a P-wave with a dominant frequency of 40 Hz propagating parallel to a 10-cm-thick cement layer, the vertical strain amplitude in the cement (with or without a 1 cm thick steel casing) differs from the amplitude away from the well by no more than 5%. The (small) effect of the cement layer extends some 200 m into the formation. The vertical strain in a liquid-filled borehole (modelled by a 10 cm thick liquid layer) is comparable to that in the formation (but can be larger or smaller, depending on the source configuration). However, DAS is not measuring strain in the fluid; it measures strain in an optical fibre or cable immersed in the fluid. Modelling of an optical cable by a 1 cm-thick elastic layer shows that the strain amplitude in that layer is of the same order as (but lower than) both in the formation and in the fluid, and appears to scale with the Poisson's ratio of the 'cable'. The strain in the cable is zero both when 'cable' Poisson's ratio is zero, and when the borehole fluid is replaced with air. The results are consistent with recent laboratory and field studies, and confirm the feasibility of borehole DAS measurements with fibre-optic cables suspended in a borehole liquid (but not gas!) provided the cable has a relatively high Poisson's ratio.

Key words: DAS, coupling, numerical simulations, reflectivity method, borehole.

INTRODUCTION

Distributed acoustic sensors (DAS) measure dynamic strain variations of an optical fibre, and thus these measurements can be affected by the medium in which the fibre is located (Mateeva and Zwartjes, 2017) and the method of its installation (Pevzner et al., 2020b). In particular, recent studies show that seismic strain amplitudes recorded by DAS can be used to estimate elastic properties of the formation: the stiffer the formation, the smaller the strain (Pevzner et al., 2020a; Pevzner et al., 2022). However, the borehole DAS response, and especially strain amplitudes, can also be affected by the borehole environment (Pevzner et al., 2020b). Indeed, the DAS fibre or cable is not located in the formation but can be cemented behind the casing, attached to tubing or simply suspended in the borehole fluid. It is thus important to quantify the effect of the borehole environment and the deployment method on the DAS amplitudes. We explore this effect using full-wave numerical simulations.

MODELLING APPROACH

We model the effect of the borehole environment with 1.5D full wave reflectivity method implemented in the OASES software, which simulates 3D wave propagation in a 1D model, which can contain elastic or fluid layers (Schmidt and Jensen, 1985). In these simulations, cement, casing, wellbore and fibre-optic cable are represented by vertical layers of infinite extent (Figure 1a, b) The simulations are done for a P-wave generated by a point source located 200 m from a borehole wall and 1000 m from the receivers.

RESULTS

The modelling results are shown in Figures 2, 4, 5, and 6 as the root-mean-square (RMS) vertical strain amplitude versus horizontal coordinate. For a 10-cm-thick cement layer, this strain amplitude in the cement (with or without a 1 cm thick steel casing, Figure 1a, b) differs from the amplitude away from the well by no more than 5% (Figure 2). The relatively small effect of the cement layer on the direct-wave amplitude extends some 100 - 200 m into the formation (one to two weavelengths). As is evident from the snapshot (Figure 1c), this effect is the result of interference of the direct P-wave with P- and S-wave reflections from the layer.

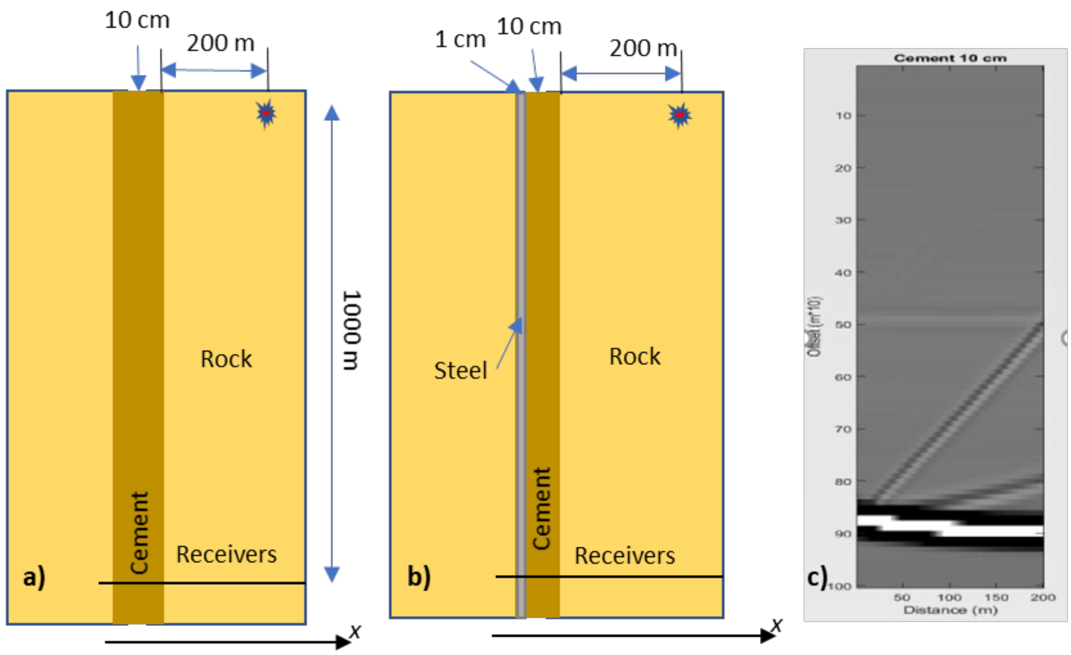

Figure 1 2D layer representation of borehole environments: a) cement layer, b) cement with steel casing; c) snapshot for a) at a time of arrival of the direct P-wave to the receivers.

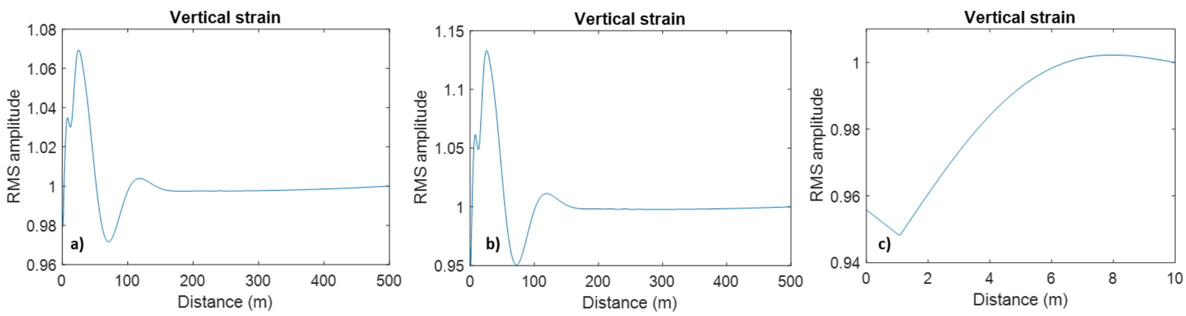

Figure 2 Vertical strain amplitude as a function of lateral coordinate a) for a cement layer; b) for a cement layer with steel casing and c) zoom of b).

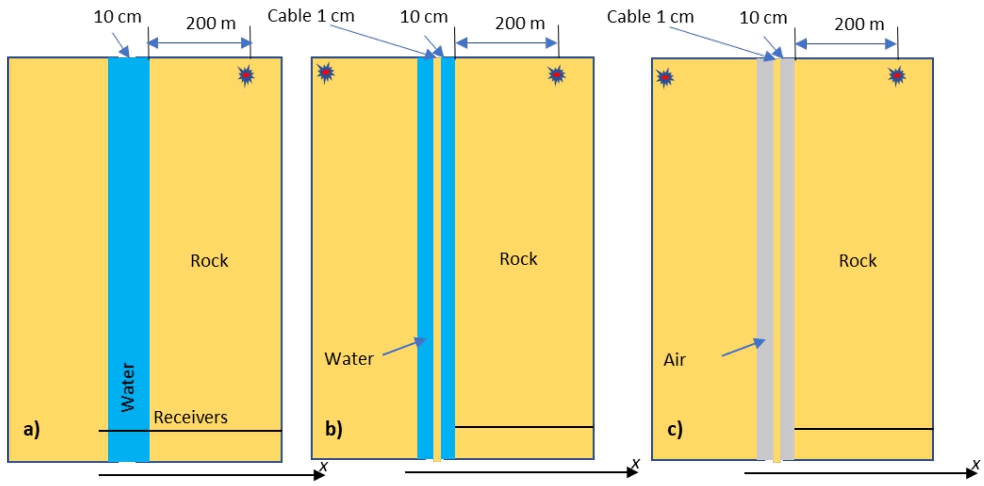

Figure 3 2D layer representation of borehole environments: a) fluid-filled borehole, b) borehole with a cable suspended in water and c) water replaced with air (all modelled as vertical layers).

The vertical strain in a liquid-filled borehole modelled by a 10 cm thick liquid layer (Figure 3a) is comparable to that in the formation, but can be larger or smaller, depending on the source configuration (Figure 4a, b). The strain is even larger when water is replaced with air (Figure 4c). However, DAS does not measure strain in the fluid; it measures strain in an optical fibre or cable immersed in the fluid. Modelling an optical cable by a 1 cm-thick elastic layer (Figure 3b) shows that the strain amplitude in that layer is on the same order as (but lower than) both in the formation and in the fluid (Figure 5a, b) and appears to scale with the Poisson's ratio of the 'cable' (not shown). The strain in the cable is zero when the borehole fluid is replaced with air (Figure 5c).

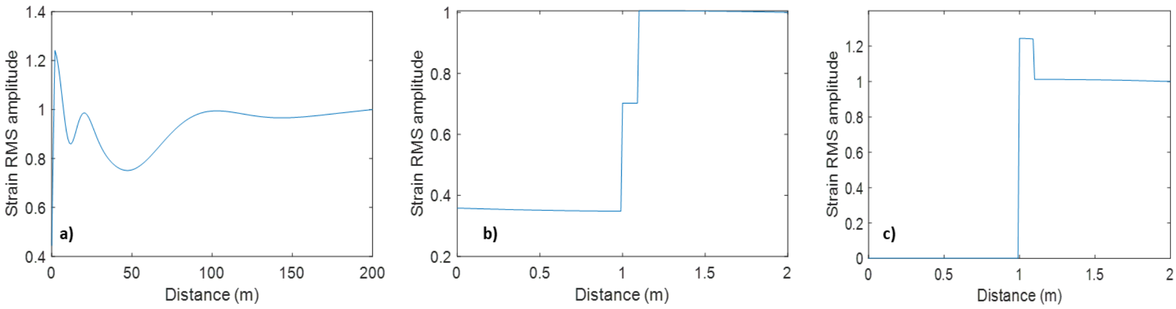

Figure 4 Vertical strain amplitude versus lateral coordinate for a) layer of water (Figure 3a); b) same as in a) but in the vicinity of the layer. c) is the same as in b) but for a layer of air.

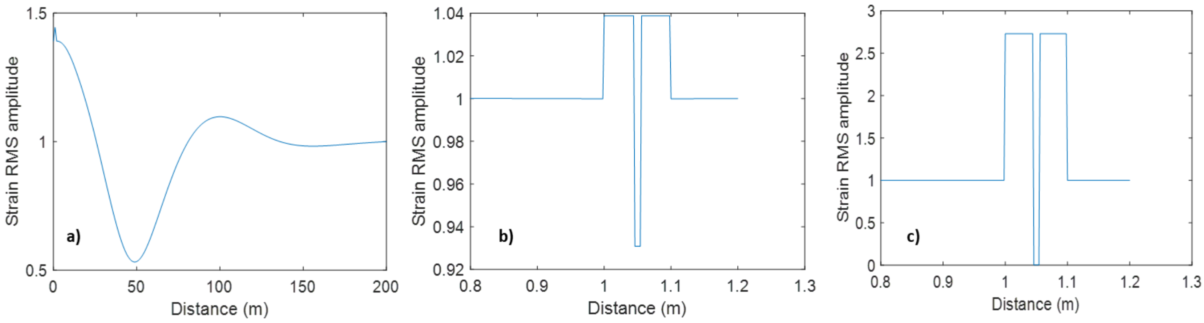

Figure 5 Vertical strain amplitude versus lateral coordinate for a) solid layer (representing a fibre-optic cable) suspended in a layer of water (Figure 3b); b) same as in a) but in the vicinity of the layer. c) is the same as in b) but for water replaced with air (Figure 3c).

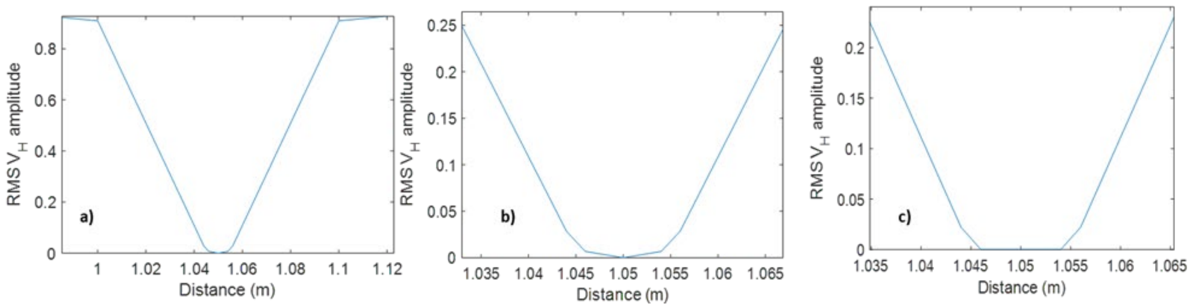

Figure 6 Horizontal particle velocity amplitude versus lateral coordinate for a) solid layer (representing a fibre-optic cable) suspended in a layer of water (Figure 3b); b) same as in a) but within the layer and its immediate vicinity. c) is the same as b) but for water replaced with air (Figure 3c).

DISCUSSION

The observations of the fluid effect on the DAS response are consistent with the physical understanding of the effect of layer properties on wave propagation. Indeed, vertical strain in the `cable' is induced by the horizontal strain through the Poisson-ratio effect. The horizontal strain in the cable is, in turn, induced by the horizontal particle velocity and pressure in the fluid. Thus, for the vertical strain in the cable to be significant, two conditions need to be satisfied:

- The horizonal strain in the cable needs to be significant. The horizontal strain is a lateral derivative of the horizonal particle velocity, which is shown in Figure 6. We see that this derivative is significant when the cable is in water (Figure 6a, b) but zero when it is in air. This is understandable as the transfer of the acoustic energy into air is negligible.
- Cable's Poisson ratio needs to be finite (larger than zero). Materials with a very low Poisson ratio (such as quartz) are best avoided.

CONCLUSIONS

The results are broadly consistent with recent laboratory and field studies and confirm the feasibility of borehole DAS measurements with fibre-optic cables suspended in a borehole liquid (but not gas!), provided the cable has a relatively high Poisson's ratio. However, 2D modelling only provides a very rough proxy for the 3D effects around the borehole. As such, axisymmetric modelling is in order.

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