Distributed fibre optic ground deformation sensing

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Abstract

Since the beginning of the century Distributed fibre optic Strain Sensing (DSS) has been an emerging technique for geo and structural deformation monitoring. The technology is continuously evolving with improved cables and fibre optic interrogation techniques.

One of the most challenging applications for DSS measurements, but with high potential, is to measure ground deformations (uplift, settlements, slope creep, faulting, etc.) in the cross-line direction relative a fibre cable installed along the ground surface. The axial strain sensitivity along a DSS cable is high, however measurements of cross-line deformations based on axial strain readings are not trivial and depend on several factors such as cable-soil friction, sensing spatial resolution, shape and direction of the deformations. Novel model tests have been performed by NGI to further investigate the performance and sensitivity of DSS measurements in such conditions.

To measure ground deformations, the DSS cable must have a good mechanical coupling to the soil. Instead of embedding the cable in a backfilled trench, the tests were performed in a long rectangular "sand box" which was filled with sand after placing the test cables inside the box. The bottom of the box could be raised and lowered at different sections by airbags generating smooth slope gradients which are anticipated as more difficult to detect by DSS cables than sharp deformations such as faulting. Several cable configurations were tested utilizing strain readings with high spatial resolution, including different types of micro anchors.

The tests indicate remarkable high sensitivity to small cross-line deformations, applied gradual slope gradients down to 0.01% could be detected with excellent response also for embedded cables without micro anchors. However, the complexity in quantifying cross-line deformations with different shapes and directions along the cable is recognized, thus more tests and large-scale applications with reference measurements are necessary for better interpretation of DSS data and quantification of different types of ground deformations.

Keywords: Distributed fibre optic strain sensing, DSS, Ground deformation, Monitoring, Model tests

1. Introduction

The model tests described in this paper were performed in conjunction with an international research project for monitoring underground CO_2 storage, https://sense-act.eu/. The objective was to investigate the capability of DSS to capture small vertical deformations (uplift) at the surface when CO_2 is injected into porous rock formations for permanent storage. The DSS monitoring approach and test results are, however, applicable for many geotechnical applications where monitoring of ground deformations along long baselines is relevant.

2. Distributed fibre optic strain sensing (DSS)

Distributed fibre-optic sensing (DFOS) is a technology based on backscatters that occurs when light travels through an optical fibre. The scattering is affected by changes in mechanical stress or temperature in the fibre and enables continuous recordings of these parameters with high spatial resolution across several tens of kilometres of fibres. Depending on the measurand, DFOS can be subdivided into distributed (static) strain sensing (DSS), distributed temperature sensing (DTS) and distributed acoustic sensing (DAS).

2.1 Sensing principles

Measurements with DFOS systems are based on spontaneous scattering of a forward propagating optical pulse against impurities or density fluctuations within an optical fibre. Small parts of the scattered light are reflected back to the interrogation unit and analysed for sensing purposes (Figure 1a). As depicted in Figure 1b, the backscattering spectrum can be split into elastic (Rayleigh) and inelastic (Brillouin and Raman) scattering effects. In general, Raman-based systems are only sensitive to temperature, whereas Rayleigh and Brillouin instruments are sensitive to both axial strain and temperature changes. Their capabilities regarding spatial resolution, measurement time, accuracy and range are, however, significantly different.

Rayleigh scattering sensing systems can provide a very high spatial resolution down to sub-millimetres for static measurements with a resolution of about 1 μm⁄m but are limited with respect to the sensing range. The return loss of the Rayleigh backscatter can be measured by optical time or frequency domain-based reflectometers (OTDR or OFDR) and normally used for finding defects in large optical fibre networks. For distributed sensing the most common application is DAS and seismic monitoring. Rayleigh backscatter reflectometry used for static strain measurement refer to a reference fibre inside the interrogator which must be located in stable temperature environment. An initial reference reading is required, and the provided strain values are relative this reading. The measuring fibre is hooked up single ended to the interrogator and preferable terminated with a reflection damper. The Rayleigh frequency shift is negative with increased strain and/or temperature.

Sensing systems based on Brillouin scattering enable measurements over several tens of kilometres but have limited spatial resolution (between 0.1 and 10 m, depending on the sensing range), less precision (about 4–10 μm⁄m) and longer scanning time (static monitoring). The frequency shift of the Brillouin backscatter depends on the axial strain and/or temperature variations in the fibre and often measured by optical time domain-based reflectometers (BOTDR) with single ended connection to the fibre. For instruments based on Brillouin Optical Time-Domain Analysis (BOTDA) and Brillouin Optical Frequency-Domain Analysis (BOFDA) the precision and range for the DSS measurements are significantly improved by means of launching a short continuous wave (CW) pulse from the other end of the cable. The measuring fibre must then be hooked up in a loop configuration to the interrogator. The Brillouin frequency shift is positive with increased strain and/or temperature and the absolute magnitude of these parameters are measured.

The intensity of the Raman backscatter Anti-Stokes spectrum is sensitive to temperature changes, by utilizing the relation between the Stokes and Anti-Stokes spectrums the distributed temperature of the fibre can be measured independent of applied strain. The distance along the cable to each DFOS measuring point is normally determined by the time of flight of the backscattered signals. It should be noted that several other variations for analysing the backscattered signals exist and the different DFOS techniques are continuously being improved.

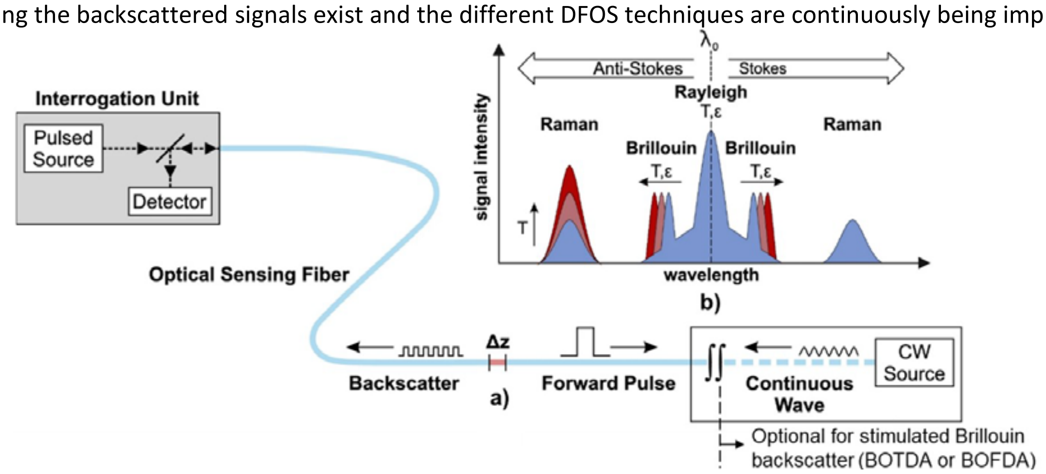

Figure 1. Basic principles of a DFOS system, illustration based on Monsberger (2020)

2.2 DSS sensing cables

For strain measurements based on the described sensing principles, Single Mode (SM) fibres must be used and the cable layers must be interlocked to each other to guarantee a reliable strain transfer from the outer surface to the sensitive glass fibre core. For burial in the ground the robustness of the cable and the shape of the outer surface are important, see examples in Figure 2. Special care must be taken at interfaces between deforming soil and stiffer materials (concrete or rock abutments) and at conditions where large deformations can be expected (tall embankment dams during construction or across faults/cracks), local strain relief and/or sufficient strain range of the DSS cable is then important to avoid fibre breakage. Measuring hysteresis (plastic deformations) of the cable must be limited and for burial in the soil the shape of the outer coating must facilitate direct transfer of the external ground deformations to axial forces in the cable with minimal sliding. Suitable DSS cables must therefore be engineered and fit for purpose.

Figure 2. Example of engineered cables for DSS ground deformation monitoring; a) Solifos V3 grip armoured cable; b) Epsilon composite DSS cable with 4% strain range from Nerve sensors and c) DSST cable from Fibrain

2.3 Temperature and strain discrimination

As described earlier, both the Brillouin and Rayleigh backscatter response are affected by temperature variations. For DSS measurements the temperature sensitivity of the SM fibre is ~20-25 µstrain/deg C (Brillouin) and ~10 µstrain/deg C (Rayleigh), the cable composition (armouring etc.) may also affect the temperature response. For precise strain measurements at varying temperatures, it is therefore necessary to discriminate between temperature and strain induced readings. This can be done by three different approaches:

1. Temperature is measured by independent sensors at some positions near and along the cable
2. The temperature effect is recorded along parts of the DSS cable that not are subjected to strain variations or through a separate sensing fibre located inside a gel filled loose tube minimizing the strain transfer to the fibre
3. Temperature is measured in the fibre by independent methods not affected by strain (Raman backscatter or combined Rayleigh-Brillouin system)

The third option is probably the most accurate, but also most expensive in terms of the interrogator hardware. It should be noted that temperature induced deformation of the media itself (soil, concrete or steel) cannot be discriminated and should be assessed by baseline readings.

3. DSS test set-up with simulated ground deformations

The axial strain sensitivity along a DSS cable can be high (±1.0 µstrain), however measurements of cross-line deformations based on axial strain readings are not trivial and depends on several factors such as cable-soil friction, sensing spatial resolution, shape and direction of the deformations. DSS cables laid out along baselines at the ground surface must have a mechanical coupling to the soil in order to monitor cross-line deformations such as uplift, subsidence, lateral and possible fault movements. The cable must not move due to environmental conditions at the surface, such as currents and/or scour for seabed applications, thus be embedded (trenched down and buried) into the ground which also provides the necessary soil-cable coupling.

Several tests have been performed to investigate the DSS cable sensitivity to cross-line deformations, such as lateral deformations in a hinged test bench with focused angular deformation (Iten 2011) or subsidence induced by added overburden weight at selected locations above buried cables (Nöther 2012 and Amer 2021). These tests may not be representative for several geotechnical ground deformation scenarios. Localised deformations, such as faulting or angular changes will induce high strain concentrations and added overburden weight may increase effective stresses and the friction between the cable and soil. The model tests performed by NGI focus on surface monitoring of smooth ground deformations (uplift) across the DSS cable but are also relevant for subsidence/settlement and slope deformations that may occur without added overburden, see Figure 3.

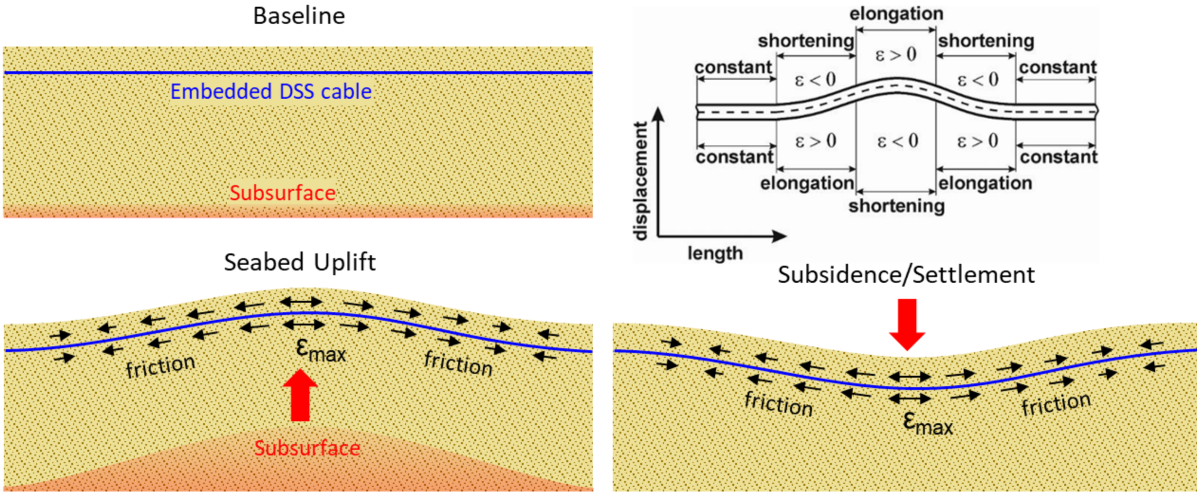

Figure 3. The principles for monitoring vertical ground deformations cross-line an embedded DSS cable

Instead of burying the cable in a trench, the simulated ground deformation tests were performed in a long "sand box", (Figure 4). The bottom could be raised and lowered at three different sections (denoted A, B, C in the results) using airbags beneath 2m long flexible metal sheet plates. The smooth slope gradients generated by the plates are anticipated as representative for simulation of uplift above CO_2 storage or subsidence scenarios, and more difficult to detect by DSS cables compared to sharp deformations such as faulting. The applied uplift was measured by tell-tale rods connected to the lifting plates at the maximum uplift point. The DSS cables were laid out on a 10cm sand layer above the plates and finally covered by another 20cm layer of sand simulating cable embedment. No effort was done to pre-tension the cables, only minor hold back was applied for straight laying of the cables along the sand bed. Utilizing strain readings with high spatial resolution, several cable configurations were tested, including different types of micro anchors. A robust armoured DSS cable, Solifos V3 suitable for embedment in the ground, with corrugated grip surface and a tight buffered single mode fibre protected inside a central metal tube was used for the tests.

As the test setup was scaled down, the strain readings were performed with higher spatial resolution than normally required for full scale applications in the field. To achieve this, Optical Frequency Domain Reflectometry based on Rayleigh backscatter (Luna OBR 4600) was used for the strain measurements. A spatial resolution of a couple of centimetres was applied for post processing of the OBR data, extensive Pythons scripts utilizing the interrogators API were developed specifically for the strain analysis. As the measurements depend on correlation analysis, the results were increasingly influenced by correlation noise when the deviation from the reference reading became large. A running reference method, as suggested by Sæter (2018), was therefore applied to minimize these erroneous effects. Multiple tests were performed, each with several and similar uplift increments at the three lifting points for conformity checks of the measured strain response. The walls of the box and sand surface was vibrated between each test to reconstitute the sand and soil coupling to the DSS cables. The main test objectives were to check the sensitivity of the DSS cables to vertical deformations and establish a correlation between the measured strain and actual uplift.

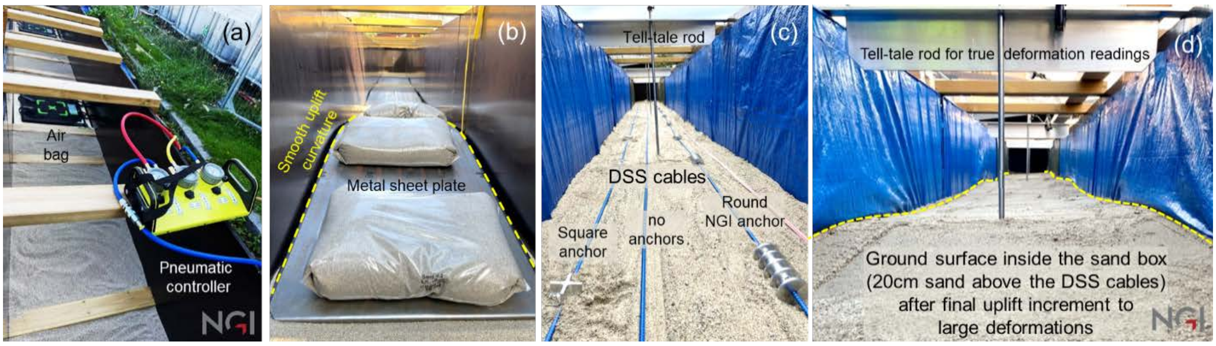

Figure 4. The sand box erected for simulated uplift tests using airbags (a) beneath flexible steel sheet plates (b) covered with sand where DSS cables with different micro anchor configurations were laid out (c) and finally covered with 20cm sand (d)

4. Test results and observations

DSS readings are sensitive to temperature variations, however no compensation was necessary during the test as the temperature was stable within the limited duration of each test. Each test series started with a baseline reading as only relative strain changes can be recorded by the OBR. Typical results from gradually increasing uplift increments are shown in Figure 5. For large uplift the three lifting points (A, B and C) interact and increased axial strain is also generated along the cable sections that remain stationary between the lifting plates.

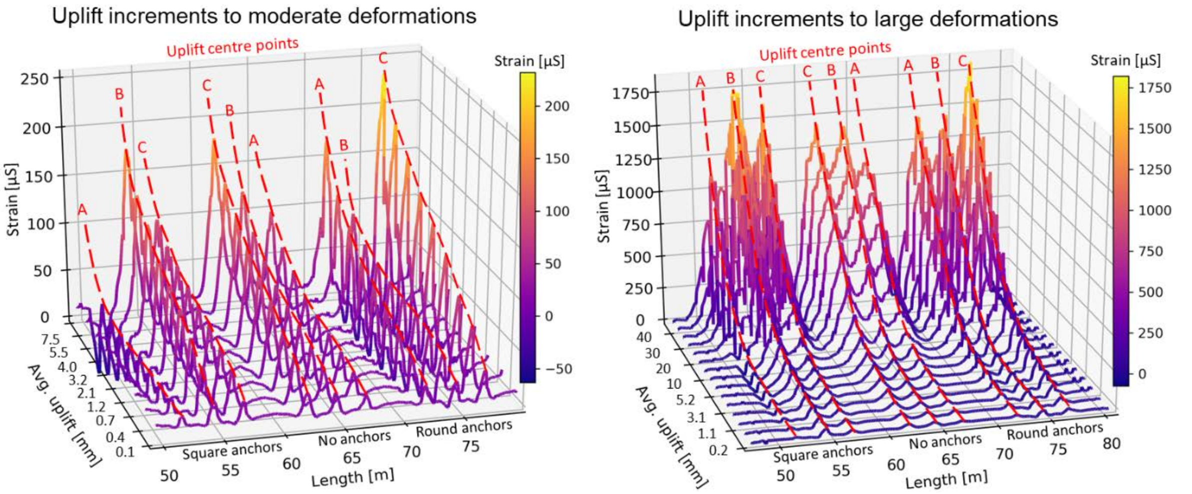

Figure 5. Examples of recorded DSS axial strain response during tests with incremental uplift sequences until moderate (left) and large deformations (right)

For CCS monitoring, high detection sensitivity is of key importance. A recorded example of the strain response to small uplift increments for the DSS cable without micro anchors is shown in Figure 6.

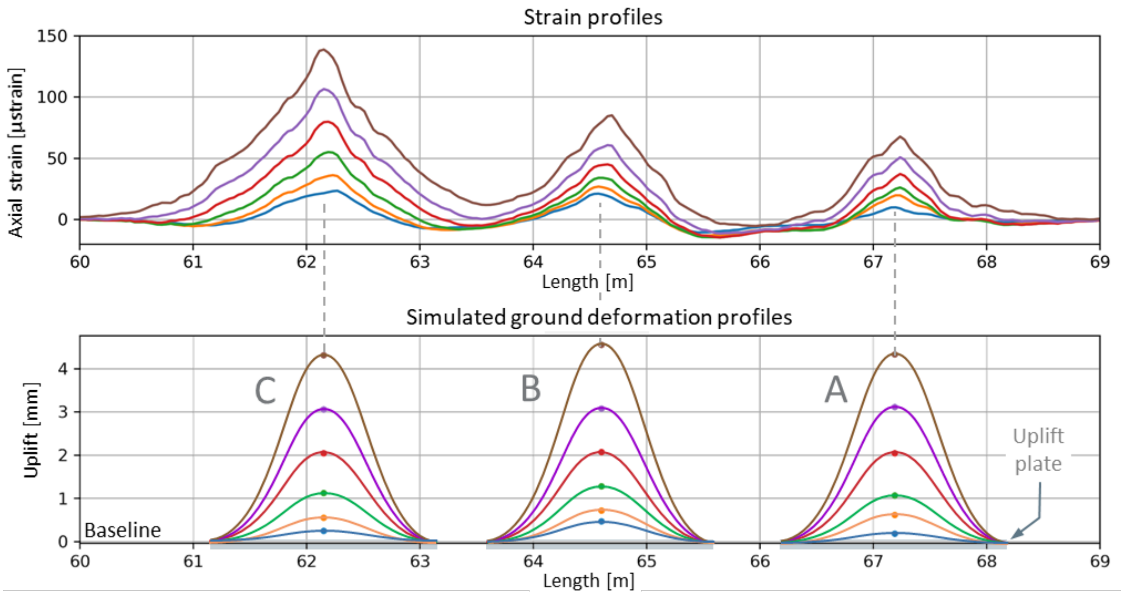

Figure 6. Example of axial strain response to applied uplift profiles for the DSS cable without micro anchors

The strain recorded at the highest uplift points has been compiled for all performed tests and examples are plotted in Figure 7. As indicated in the plots, very high sensitivity is present for the initial small uplift increments. Initial uplift of ~0,1mm over 1m length or a slope gradient of 0.01% (the minimum applicable lift increment) could clearly be detected by the axial strain response in the DSS cable. Cables with micro anchors did not provide significantly higher sensitivity compared to the bare corrugated cable. The round NGI anchor performed better than the square anchors, which are sensitive to axial rotation and must be carefully placed in the sand as rotation affects the axial strain response (less conform data).

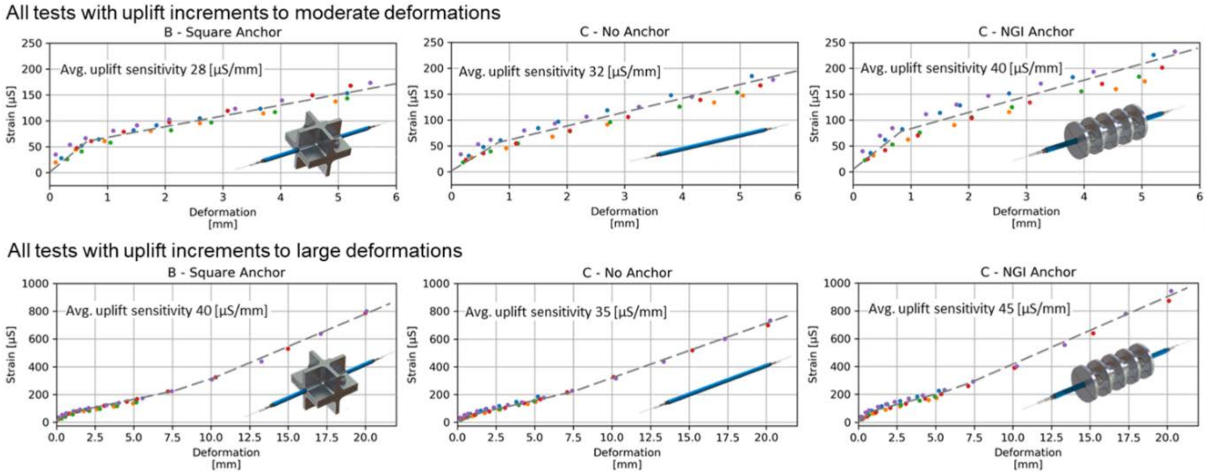

Figure 7. Recorded axial strain versus uplift magnitude at the highest uplift point plotted for lifting increments to moderate (top) and large deformations (bottom), the average sensitivities are indicated by dashed lines

5. Scaling up the in-line length of crossline deformations

Smooth vertical deformations could only be simulated over a limited length (2m) in the sand box. To illustrate how the in-line length of the crossline deformation affects the axial strain response in the cable a simplified 2D finite element model was developed. The axial strain response along a thin plate embedded in sand was simulated when the length of the plate and smooth uplift profile was increased. The theoretical strain derived from this FE model is bigger than the strain measured by the fibre due to losses in the soil-cable coupling and within the cable itself, these effects are analysed in more detail by Zhang et al. (2020). A rough "calibration" of the FE model was therefore made based on the strain readings in the sand box at small vertical deformations. For larger deformations other non-linear effects as direct cable slippage may occur. The FE simulated axial strain response in the DSS cable when the length of the smooth vertical (crossline) deformation profile is increased is shown in Figure 8.

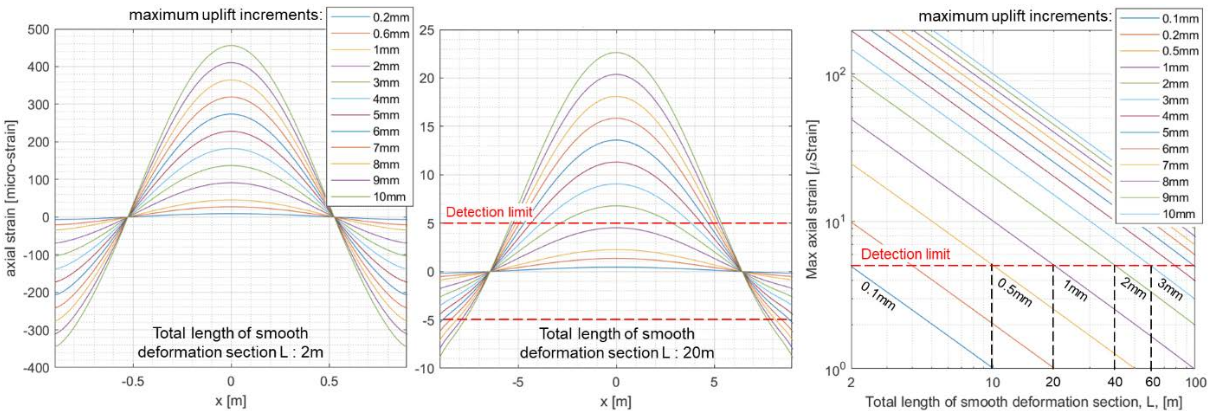

Figure 8. Examples of simulated axial strain response for different lengths of smooth crossline deformations. The summary plot to the right shows simulated maximum axial strain vs length of the smooth deformation for different maximum uplift increments

The compressed sections (negative strain) along the cable are shown in the simulations but less visible in the performed tests. This is most likely because of the confined space in the sandbox and the limited space between the lifting points, the cable is simply pulled from both sides. If we assume a detection limit of +/- 5µstrain change in axial strain, the summary plot shows that the maximum uplift that can be detected is proportional to the increased length of the deformation. This makes sense as the shape of the deformation then is identical, the simulations also indicate that initial slope gradients down to 0.01% can be detected. For ideal shapes of only cross-line deformation the magnitude can probably be assessed based on the axial strain measurements, however deformations occurring in the field are not ideal and seldom occurring in a known direction. In addition, only deformation shapes and not rigid body displacement can be monitored.

6. Shape sensing

The basic principle of shape sensing is the use of minimum three equally spaced SM fibres in the cable, these distributed strain sensors create a tri-core directional bend sensing system. This methodology is already well established within civil engineering applications such as for example lateral pile load testing where bending moments and deformations are measured using multiple strings of strain sensors along the pile shaft and located at diametric opposite positions around the perimeter of the pile. Shape sensing cables based on strain measurements are frequently used for medical and robotic applications but recently also introduced for 3D ground deformation sensing. The deformation of a shape sensing cable in the ground is not affected by the soil-cable interaction and the inline/crossline deformations can be discriminated. However, it should be noted that the measured deformations refer to the cable coordinate system and the cable orientation in the ground must be known for refence to geo coordinates, principles and example are shown in Figure 9.

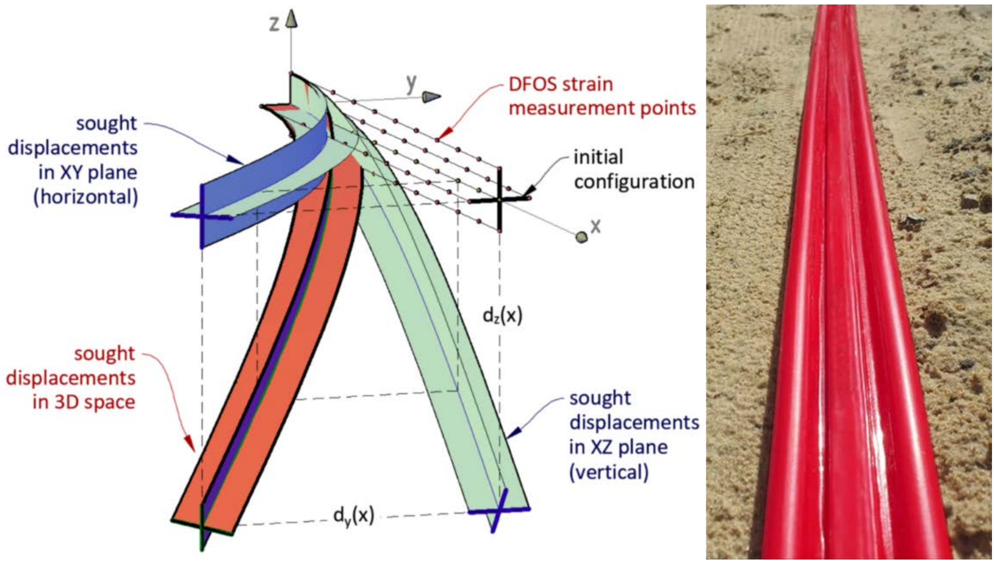

Figure 9. Principles of for shape (3D) DSS cable and cable example (right), illustrations from nerve-sensors.com

7. Conclusions

The ability of embedded DSS cables to register vertical ground deformations with high sensitivity (0.01% slope gradients) has been demonstrated by simulated tests. To prevent influence from the environment and to provide the required coupling to the soil the cables must be trenched and buried in the seabed or ground. To achieve consistent measuring conditions along the cable, the whole trench should be backfilled with the same material (preferably sand) to constant embedment depth. The observed sensitivity to crossline deformations was high using a steel armoured cable with a corrugated outer sleeve and engineered for DSS measurements. Micro anchors did not improve the sensitivity significantly and are evaluated as obsolete. The scaled tests were performed with strain readings at high spatial resolution (some centimetres), however less dense readings can probably be used in the field scale, allowing for other interrogation techniques to be used such as Brillouin DSS that enables measurements over very long distances (several tens of km). Temperature compensation is most likely required for long-term monitoring applications.

Although the tests presented in this paper indicate high sensitivity and reasonable repeatability, the quantification of deformations measured cross-line the DSS cable is complex and depends on several conditions, especially the shape and direction of the deformations. Baseline readings must be made directly after installation of the DSS cable in the ground and the subsequent measured deformations are relative to this baseline. Some fixed reference points that can be surveyed by other methods are recommended along the cable route for "Ground truth" calibration of the DSS based measurements. The direction of cross-line deformations and discrimination of possible inline displacement cannot be determined by strain measurements using only a single fibre. Special shape sensing cables containing multiple DSS fibres at fixed and defined positions within the cable are then required. Burial of the shape sensing cable is necessary to ensure that it follows the deforming ground and for detection of possible inline deformation. For geotechnical applications this technique is presently less exploited and probably costly if long baselines shall be monitored.

The presented tests were executed to investigate the feasibility for detecting very small uplift gradients with a cable installed along the seabed. The promising results strongly support the suitability also for other geotechnical ground deformation monitoring applications such as embankment dams, slope stability, subsidence/settlement, along road and railway embankments, etc. However, more tests and large-scale applications with reference measurements are necessary for better understanding of the axial strain response when the DSS cable is subjected to ground deformations with more complex shapes and different directions relative the cable.

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