Abstract of Paper No: **XXX**

EXPERIMENTAL STUDY OF A SOIL-EMBEDDED FIBRE OPTIC STRAIN SENSOR CROSSING A SHEAR ZONE

Dominik Hauswirth
ETH Zürich, Switzerland

Michael Iten
ETH Zürich, Switzerland

Alexander M. Puzrin
ETH Zürich, Switzerland

Fibre optic strain sensors embedded in soil can be used for the monitoring of ground movements. In this paper, the strain response of different soil-embedded distributed fibre optic sensors (BOTDA) subjected to controlled soil displacement is investigated within an experimental test setup.

In co-operation with a cable manufacturer, a variety of different robust strain sensing cables for the harsh soil environment was produced. The mechanical properties of these cables with different level of protection, cable surface and longitudinal stiffness were initially tested in tension tests. Afterwards the cables were embedded into a 9.1m long setup consisting of two sand-filled rigid boxes with a moveable shear zone in between. By stepwise shifting one box relatively to the other, controlled soil displacements were applied to the sensors and subsequent strain measurements taken. With this procedure, a situation is simulated, where a fibre optic sensor crosses a boundary between the stable and moving ground. Due to the different mechanical behaviour of the fibre optic cable and the surrounding soil as well as the slippage on their interface, the strain measured in the fibre optic cable differs from the strain present in the soil. In this paper, particular attention is given to the influence of decreasing longitudinal stiffness due to yielding of the outer cable sheath on the strain response of the sensor. Based on the experimental results, the ability of initially stiff cables to localize soil displacements with increasing strain level is demonstrated.

Corresponding author’s email: dominik.hauswirth@igt.baug.ethz.ch

EXPERIMENTAL STUDY OF A SOIL-EMBEDDED FIBRE OPTIC STRAIN SENSOR CROSSING A SHEAR ZONE

Dominik Hauswirth, Michael Iten and Alexander M. Puzrin

Institute for Geotechnical Engineering, ETH Zürich, 8093 Zürich, Switzerland

ABSTRACT: Distributed fibre optic strain sensors can be applied for the monitoring of soil displacements in geotechnical engineering. In order to study the effect of different fibre optic cable layouts and integration concepts, a full scale test setup was applied, where the fibre optic cable was embedded in soil and subjected to controlled soil displacements from various directions. Due to the different mechanical behaviour of the fibre optic cable and the surrounding soil as well as the slippage on their interface, the strain measured in the fibre optic cable may differ from the strain present in the soil. In this paper, in particular the influence of decreasing longitudinal stiffness due to yielding of the outer cable sheath on the strain response of the sensor is discussed. Based on experimental results it is shown, how initially stiff cables are able to localize soil displacement with increasing level of strain.

1 INTRODUCTION

Geotechnical engineering has a large demand for monitoring solutions. Construction sites in urban areas being located close to existing buildings or important infrastructures crossing areas endangered by natural hazards need to be monitored during construction and operating time. Fibre optic sensing technologies offer new monitoring possibilities in this field which could replace and outreach existing monitoring technologies in terms of the amount and accuracy of available data.

2 SOIL-EMBEDDED FIBRE OPTIC STRAIN SENSOR

In order to monitor geotechnical structures and facilities, fiber optic strain sensors can be attached to the endangered structure itself. However, soil displacements should be monitored also in cases where no structure is available for attachment of the sensor, and thus, the fiber optic cable has to be embedded directly in the soil (e.g. for landslide monitoring, Iten et al., 2009). In the recent past, several authors have presented studies where distributed fiber optic sensors were attached to pipes (e.g. Dewynter et al. 2009) or connected to geotextiles (e.g. Villard & Briancon, 2008; Belli et al. 2009; Artières et al. 2010) in order to monitor soil displacements in large scale tests or test applications in the field. A different approach, in which the fiber optic cable is directly embedded in soil, without using a hosting structure such as geotextiles or pipes, is presented in this study.

Table 1. Cable properties, 1με (microstrain) = 10^{-6}

Cable type	V1a	V2	V3	V4
Metallic protection	No	Yes	Yes	Yes
Diameter *d*	2.8mm	2.8 / 5.7mm	6.8mm	3.2mm
Surface	Smooth	Smooth	Corrugated	Smooth
Elastic stiffness *EA*	2.5kN	140kN	500kN	56kN
Yield limit ε_y	-	-	2000 με	6000 με

2.1 Distributed fibre optic measurement technology

Different types of fibre optic sensing technologies have been developed and this development is still ongoing. Each technology has its specific advantages and limitations in terms of sensor length, spatial resolution, strain range and economics. In order to monitor large perimeters, distributed sensors based on stimulated Brillouin scattering, such as Brillouin optical time domain analysis (BOTDA) (Niklès et al. 1996; Niklès 2007) or Brillouin echo distributed sensing (BEDS) (Foaleng Mafang et al. 2009) may be an adequate solution due to its possibility of having large sensor lengths. Conventional BOTDA allows for sensing lengths in the range of tens of kilometers with spatial resolution of 1m, whereas BEDS is applicable up to few kilometers with the advantage of enhanced spatial resolution down to a few centimeters.

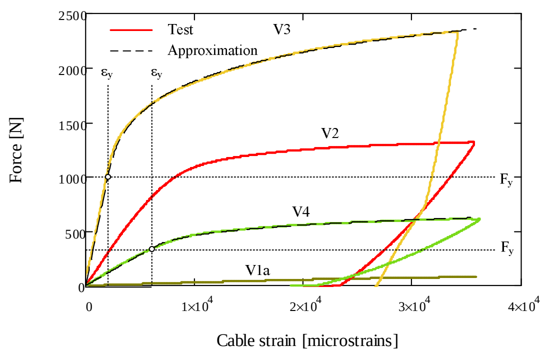

Figure 1. Tension test results, $\dot{\varepsilon}$ =2300με/min.

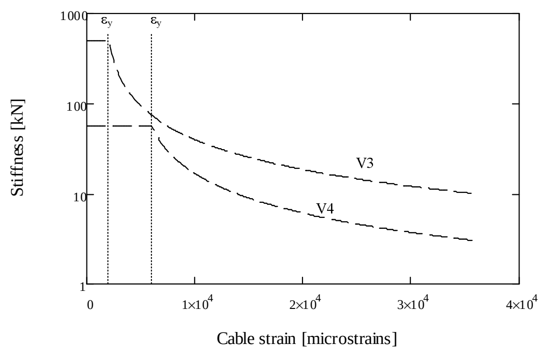

Figure 2. Tangent stiffness for V3 and V4

2.2 Fibre optic cables designed for soil environment

Bringing vulnerable fibre optics into the harsh soil environment requires for special cable designs. First of all, the fibre has to be protected against the rough environment on construction sites during the cable integration process (crushing and folding) and secondly, the cable needs a protection against detrimental effects from soil environment during its operating time (e.g. rodents). In co-operation with a cable manufacturer, a series of cables was produced, which is in particular designed for the application in soil. In this study, four cable versions out of this group are being presented. In order to quantify their mechanical parameters, tension tests of 2.1m long cable specimens were carried out (Figure 1, Table 1).The cables V2-V4 include a thin metallic tube which is hosting the silica fibre and V3 is additionally armoured with metal wires. These metal wires provide on one hand an improved protection, on the other hand they increase longitudinal stiffness in the elastic range, with a clearly decrease of stiffness once the yield limit is reached. The behaviour of the cables V3 and V4 was approximated with an analytical expression consisting of a linear elastic section and a nonlinear logarithmic section for the purpose of measurement evaluation in section 4 of this paper (Figure 1, 2).

3 FULL SCALE TEST

3.1 Motivation

Soil-embedded fibre optic cables may measure strains different from the strain present in surrounding soil due to two reasons. Firstly, a cable consisting from several layers may not transfer the strain applied on the jacket perfectly down to the sensing fibre and, secondly, the sensor can suffer from differential displacements in longitudinal or lateral direction between cable and soil due to limited bond or limited lateral bearing capacity of the cable. In particular thin and stiff cables are prone to lose connection to soil in longitudinal direction and therefore to distribute strains of a local soil displacement over a large length. In order to quantify the performance of several cable designs and integration concepts, a test setup was built, which allows for subjecting the soil-embedded fibre optic strain sensors to controlled soil displacements.

3.2 Test setup

The test setup consists of two sand-filled rigid boxes and a mechanism in between, which allows for a relative translation of one box to the other, without any rotation on a chosen displacement path (Figure 3). In principal any displacement direction α is possible. Of special interest is the sensor response to α being equal to 0° and 90°. The test setup is 9.1m long, with an adaptable width of 0.8m in maximum. The aim of this test setup is to simulate the sensor behaviour in a shear or extension zone, when a cable is for example crossing a boundary from stable to slowly moving ground in a creeping landslide. The applied box displacements were controlled in the points A – F. At both sides of the test setup a possible move-in of the cable was measured. The cables were embedded in compacted moist sand with maximum grain size of 5.6mm at different level of depth. The fibre optic strain measurements were taken on a commercially available BOTDA measurement unit for subsequent displacement steps, with spatial resolution of 1m and a sampling interval of 0.1m.

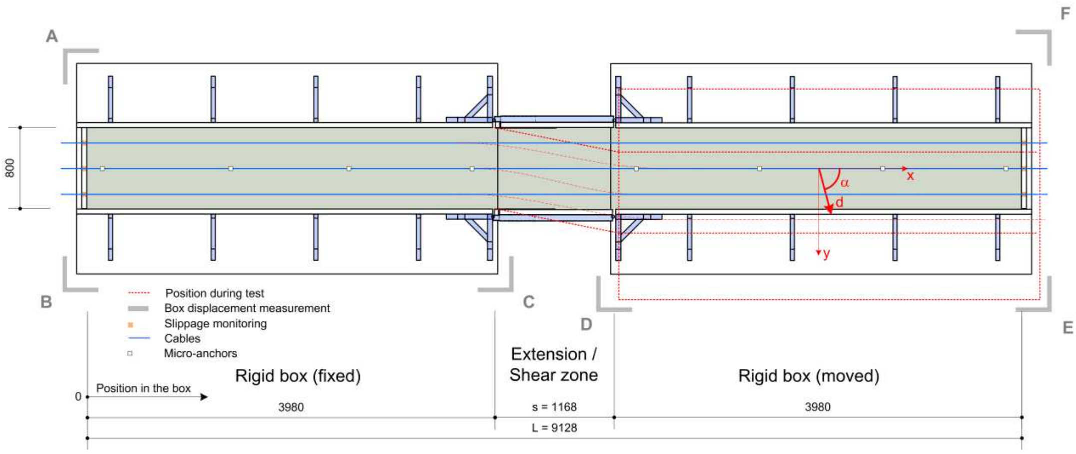

Figure 3. Test setup, dimensions in [mm].

This test setup was applied for a set of experiments with different types of cables and integration concepts (cable corrugation, anchors). The sensors were subjected to displacements from different directions and additionally the effect of the compaction level of the sand was investigated. Based on a part of these tests results, the problem of differential displacements between the cable and soil in longitudinal direction is discussed in this paper, with a particular emphasis on the ability of initially stiff cables to localize soil displacements due to yielding of their metallic protection.

3.3 Measurement results

3.3.1 Differential displacements between the sensor and surrounding soil

The problem of limited connection between the fibre optic strain sensor and soil becomes apparent from Figure 4. In this figure, strain measurements of three subsequent displacement steps are shown for the soft V1a and the stiff V2 cable. Both cables were embedded in a shallow depth of 0.1m in slightly compacted sand. In the case of the soft V1a cable, the strain penetrates from the shear zone (s_1, s_2), where the displacement is applied, with each step deeper into the box. If small block anchors (edge length 40mm) are attached on the same cable type, the strain is fully accumulated between the central pair of anchors, as shown in Figure 4. Up to failure load, the anchors provide a local connection of the cable to surrounding soil. The results of this improved sensor connection to soil show that there exist almost no soil displacements except those applied in the shear zone. The strains in the cable without anchors indicate the length necessary to transfer the longitudinal force of the cable in the shear zone into surrounding soil, but not the strains present in soil. In case of the stiff V2 cable without anchors, this length exceeded the size of this test setup already at very small displacements steps, resulting in slippage of the cable at both box ends with strains in the shear zone being almost equal to zero and no further increase in strain for the later displacement steps.

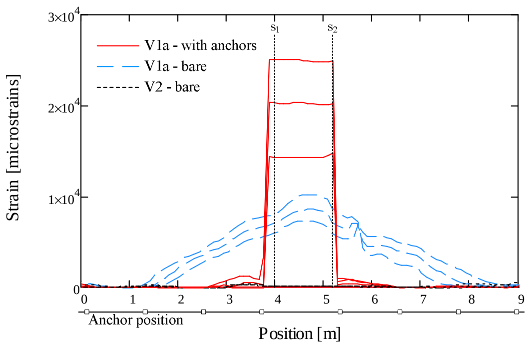

Figure 4. Comparison of V1a / V2 in 0.1m depth

3.3.2 Localization of strains due to yielding in the cable sheath

The connection of the sensor cable to soil can be improved by increasing the shear stress acting on the surface of the cable sheath by means of increasing embedment depth and sand density. Figure 5 – 8 show the strain measurement results of a test, where the box was shifted in longitudinal direction (α = 0°) in 11 steps from 1mm to 39mm and the sand was highly compacted with a vibrating plate. In this condition, the stiff and well protected cable versions V3 and V4 were tested in the depth of 0.5m and 0.7m. In a depth of 0.5m the strain is still propagating in a trapezoidal shape through the whole box, leading to slippage at both box ends in the last step with no further increase in strain. However, the reduction in stiffness of V4 compared to V2 and the increase of shear stress on the cable surface allow at least for certain limitation of the strain propagation. By means of additional 40mm anchors attached on the V4 cable in the same conditions, it is possible to concentrate the strain around the extension zone, as Figure 6 shows. In contradiction to Figure 4, not only the first pair of anchors, but also the second pair was activated, indicating the onset of anchor bearing capacity failure due to the higher stiffness of V4 compared to V1a cable. This behaviour can be prevented with the application of larger anchors. If the V4 cable is even deeper embedded (0.7m, Figure 7), the slope of the trapezoidal distributed strains can be increased, due to higher shear stress acting on the cable surface. Once the yield limit in strain ε_y is exceeded, the stiffness is not distributed uniformly along the cable anymore and the strain starts to accumulate in the section with reduced stiffness. This behaviour becomes apparent from the strains measured in the last step. A measurement after the last step, when the cable was carefully excavated, shows that indeed irreversible strains occurred in the extension zone and that the strain penetration is transient and not caused by cable internal slippage (e.g. Figure 5).

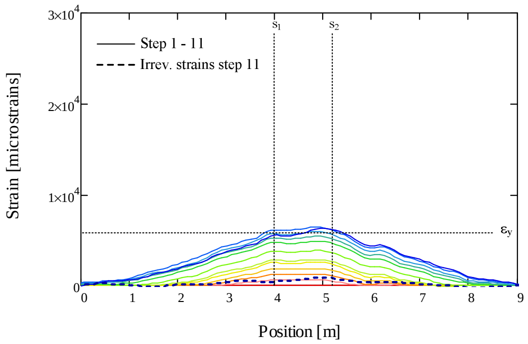

Figure 5. V4 in 0.5m depth.

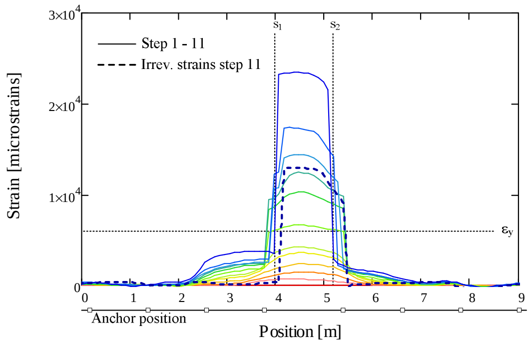

Figure 6. V4 cable with anchors in 0.5m depth.

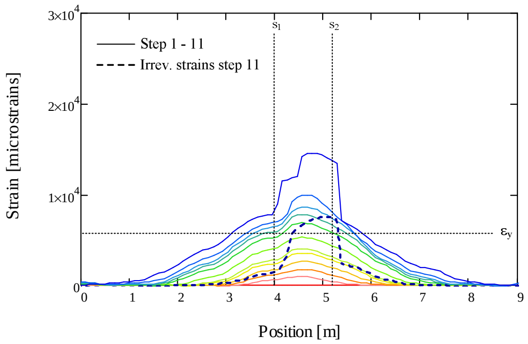

Figure 7. V4 cable in 0.7m depth.

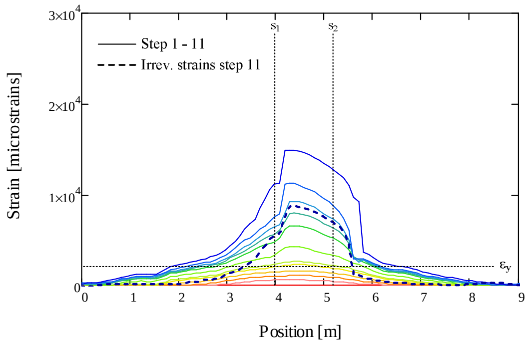

Figure 8. V3 cable in 0.5m depth.

Due to its additional metallic armouring, cable version V3 is in the linear elastic range approximately an order of magnitude stiffer than the version V4 (Figure 2). Its larger diameter and surface corrugation are only partially able to compensate for this, as a comparison of Figures 8 and 5 in the elastic range shows. The metallic protection in the V3 cable experiences at very early stage plastic strains. Therefore the propagation of strain is efficiently reduced after the first few steps in the elastic range. This results in an even stronger localization of strains as observed with the V4 cable in the same depth. However, for many applications an elasto-plastic behaviour of the sensor may be a drawback. In other applications, where the strain level is expected to increase monotonically (e.g. landslides, excavations), it is not. Additionally it should be noted, that these irreversible cable deformations introduce the option of having a sensor with some sort of memory.

4 EVALUATION OF MEASUREMENTS

4.1 Integration of strains along the cable

Even though some cables distribute the strain applied in the extension zone over a certain length, an integration of the strains along the cable should equal the applied displacement as long as no slippage occurred at the box end. Figure 10 and 11 show the "measured cable elongation" (which is the integrated strain over the whole length of the box) for all displacement steps applied and all types of sensors discussed in section 3.3.2 compared to the applied box displacement in *x*-direction. With exception of the last displacement step (39mm), all sensors match the applied displacement within a precision of +- 1mm. Within this band, the deviation of the measured cable elongation from the applied displacement could also be caused by the measurement uncertainty of the applied box displacement. During the last displacement step, as already mentioned, slippage was detected in case of the V4 cable in 0.5m depth; therefore this sensor was not able to indicate the correct displacement.

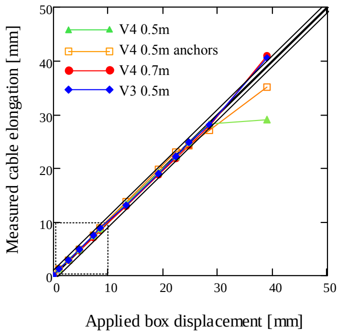

Figure 10. Cable elongation.

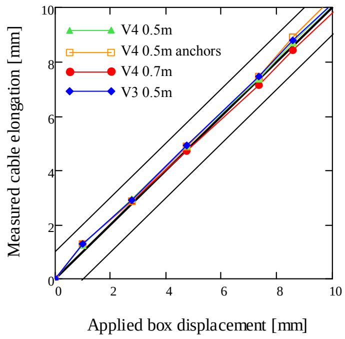

Figure 11. Scale-up of Fig. 10.

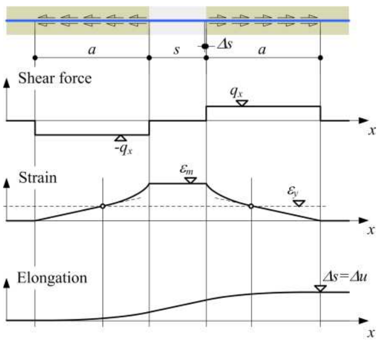

Figure 12. Model assumptions.

4.2 Estimation of the cable response in the extension zone

For the design of soil-embedded fibre optic sensors, it would be advantageous to be able to estimate the sensor response to a certain event in advance in order to assess whether the sensor connection to soil is sufficient. For this purpose, a simple model was applied, which describes the strain distribution along the sensor in an extension zone as a function of the cable stiffness, the shear force per unit length q_x acting on the outer cable sheath and the length of the extension zone *s* where a certain soil displacement Δs is expected. Within this model, the cable is assumed to behave linear elastic up to the yield strain ε_y, followed by an elasto-plastic part, approximated with a logarithmic function for the case of monotonic loading (Figure 1). The interaction between cable and soil is reduced to a shear force per unit length acting on the cable, which is for simplification assumed to be constant and independent from the relative displacement between cable and soil, once a differential displacement occurred. In reality, the shear force may not be constant, as detailed laboratory test results obtained e.g. by Puzrin et al. (2011) suggest. However, for the purpose of this paper, they are assumed to be constant. Furthermore, no deformation of surrounding soil is taken into account. In the extension zone the shear stress is considered to be zero (Figure 12). The application of such simplified model on to the strain measurements for the case of the V3 cable in 0.5m depth is shown in Figure 13. All model parameters except q_x are defined from the test setup or the cable tension test. The shear force per unit length q_x was adjusted to the strain measurement results in Figure 13, and kept constant for all displacement steps. The strain expected by the model in the extension zone ε_m is compared to the average strain measured in the extension zone (s_1, s_2) in Figure 14 for the two cables V3 and V4 in 0.5m depth. By comparing the purely linear elastic to the elasto-plastic solution in Figure 14 it becomes apparent, that the reduction of stiffness due to strain hardening leads to more than two times higher strains in the extension zone for the case of the V3 cable in 0.5m depth.

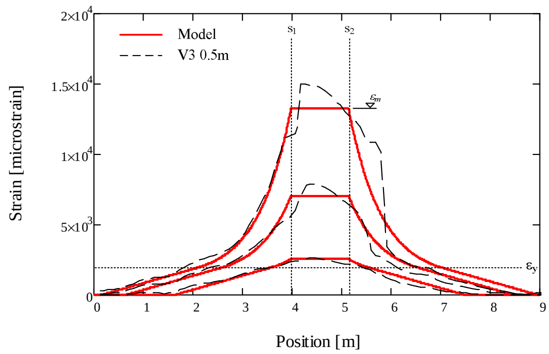

Figure 13. Comparison Model – Test for V3 0.5m.

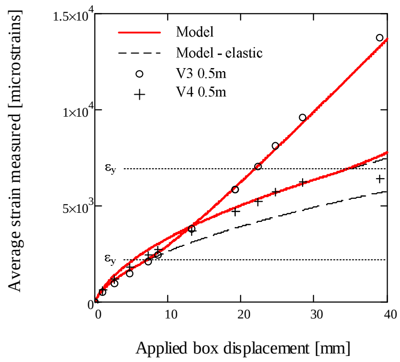

Figure 14. Comparison Model – Test.

5 CONCLUSIONS

Soil-embedded fibre optic cables need a certain protection of the fibre. However, a strong metallic protection can increase their longitudinal stiffness significantly. Due to limited bond between the cable and the surrounding soil, strain induced by a local event can distribute over several meters or even tens of meters, if the cables are too stiff or not embedded adequately in soil. This behaviour complicates the interpretation of the measurement results in field applications, as the increase of strain in the cable for a given displacement is very small and also not clearly localized. By means of cable surface corrugation or even more effectively, by attaching small block anchors on the cable, the propagation of strains into zones without displacement in soil, can be strongly reduced. It should be noted, that this improved connection to soil on the other hand may reduce the sensor lifetime due to reaching earlier the upper limit of the sensor strain range, if large local displacements are expected.

A concentration of strains can also be achieved for stiff and well protected cables, due to their elasto-plastic cable properties, if irreversible strains can be accepted (cases of monotonic loading). Once the yield limit of the metallic cable protection has been overcome, strain accumulates in the zone where yielding occurred due to the reduction in stiffness. The propagation of strains into adjacent zones is limited to a certain amount, dependent on the hardening properties of the cable.

6 ACKNOWLEDGEMENTS

The authors highly appreciate the work of the industry partners Brugg Cables AG (cable development) and Omnisens SA (measurement unit). This project is financially supported by the Swiss Innovation Agency CTI.

7 REFERENCES

Artières, O., Galiana, M., Royet, P., Beck, Y.-L., Cunat, P., Courivaud, J.-R., Fry, J.-J., Faure, Y.H. and Guidoux, C. (2010) Fiber Optics Monitiring Solution for Canal Dykes. *PIANC MMX Congress*, Liverpool, UK, 2010.

Belli, R., Glisic, B., Inaudi, D., Gebreselassie, B. 2009. Smart textiles for SHM of Geostructures and Buildings. *Proc. of the 4th Int. Conference on Structural Health Monitoring of Intelligent Infrastructure*, Zurich.

Dewynter V., Rougeault S., Magne S., Ferdinand P., F. Vallon F., Avallone L., Vacher E., de Broissia M. Ch. Canepa Ch. and Poulain A. (2009). Brillouin optical fiber distributed sensor for settlement monitoring while tunnelling the metro line 3 in Cairo, Egypt. *Proc. of 20th International Conference on Optical Fibre Sensors (Proc. of SPIE Vol. 7503)*.

Foaleng Mafang, S., Beugnot, J.-C. & Thévenaz, L. 2009. "Optimized configuration for high resolution distributed sensing using Brillouin echoes", 20th International Conference on Optical Fibre Sensors, Proc. of SPIE vol. 7503, Edinburgh, UK, pp. C1-C4.

Iten, M., Schmid, A., Hauswirth, D. and Puzrin, A.M. (2009). Defining and monitoring landslide boundaries using fiber optic systems. *Proc. of Prediction and Simulation Methods for Geohazard Mitigation*. pp. 451-456.

Niklès, M., Thévenaz, L., Robert, Ph. A. 1996. Simple distributed fiber sensor based on Brillouin gain spectrum analysis. *Optics Letters, Vol. 21*. pp. 758-760.

Niklès, M. 2007. Fibre optic distributed scattering sensing system: perspectives and challenges for high performance applications. *3rd European Workshop on Optical Fibre Sensors, Proc. of SPIE Vol. 6619*. 66190D.

Puzrin, A. M., Iten, M., Hauswirth, D. 2011. Progressive failure in soil-cable interaction. *Proc. of XV European Conference on Soil Mechanics & Geotechnical Engineering (in press).*

Villard, P. and Briancon, L. (2008). Design of geosynthetic reinforcements for platforms subjected to localized sinkholes. *Can. Geotech. J. 45*, pp. 196-209.