IPA News Letter

Volume 6, Issue 2 June 2021

Directors' research and development activities

Smart Pile, Smart foundation and Smart infrastructure?

Kenichi Soga

Chancellor's Professor, Donald H. McLaughlin Chair in Mineral Engineering
University of California, Berkeley

One of the greatest challenges facing civil engineers in the 21st century is the stewardship of aging infrastructure along with the creation of new infrastructure that society demands. The existing infrastructure requires monitoring and remedial interventions when new infrastructure is created nearby, and the high cost of replacement often leads to a desire to extend the asset's life. Furthermore, existing infrastructure is placed under increased load and usage than they were originally designed. Another challenge is developing response strategies when a catastrophic event occurs (e.g., an earthquake). Infrastructure systems face a multitude of hazards that must be assessed, communicated, and managed appropriately. Future-proofing existing and new infrastructure has become a constant theme in government and industry discussions.

The critical deterioration of civil infrastructure has driven the search for new methods of rehabilitation and repair by incorporating sensors and developing remote systems that would allow monitoring and diagnosis of possible problems occurring. It is envisaged that structures will eventually be able to monitor themselves and inform owners of their state. These smart infrastructures have unusual abilities: they can sense a change in temperature, pressure, or strain; diagnose a problem; and initiate an appropriate action to preserve their integrity and continue to perform their intended functions. Sensors measure the state of the actual ambient conditions. If the sensor signals differ from the nominal conditions, rehabilitation action can be taken. Smart infrastructure, therefore, adapts to changing environments and demands. In geotechnical construction, the performance of geotechnical structures is monitored during construction due to uncertainty in soil-structure interaction. Although monitoring after construction has been limited up to now, the use of low-cost sensors allows us to make a new step toward the development of a 'smart foundation'.

There are several benefits to smart foundation technologies; the most obvious one is the increased safety levels they can provide to cope with adjacent new constructions and natural disasters such as climate change, flood warnings and earthquakes. Furthermore, the data can be used to reduce costs associated with end-of-life structures. The concept of smart foundations allows their performance to be monitored during their working lives. For example, the average working life of a building is about 25-40 years. In urban areas, possible locations for foundations are often constrained by the underground infrastructure. With the ground becoming more congested, there is a significant risk that there will come the point at which there is no room for new foundations, inhibiting new development and reducing economic sustainability. The solution is for a new development to reuse as much of the existing foundations as possible. Reuse also has a considerable environmental benefit as the new development will require fewer raw materials and less disposal of topsoil and have reduced energy consumption during construction. The additional economic benefits of reuse include time savings in the construction process. However, to exploit this technology, there is a need to know how load develops, how it is distributed and what factors need to be understood in unloading structures.

There has been a rapid development in the area of smart infrastructure over the last decade thanks to innovation in sensor/actuator design and fabrication, fiber optics, micro-electro-mechanical sensors (MEMS) and other electronic devices, signal processing and control, and wireless sensors and sensor networks (Soga and Schooling, 2016). For example, structural integration of fiber optic sensing systems represents a new branch of engineering which involves the unique marriage of: fiber optics, optoelectronics and composite material science. Optical fiber sensors have a number of advantages over their electrical counterparts. The transmission of light down an optical fiber is an established technique in optical communications for carrying information and is the primary candidate for resident sensing systems.

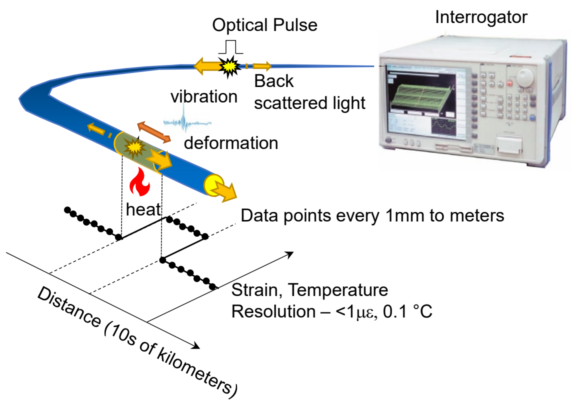
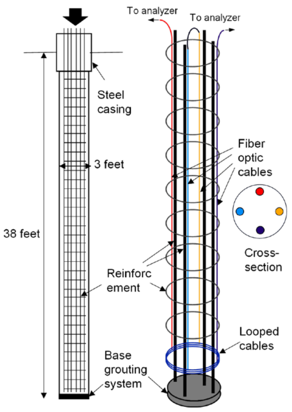


Fig. 1. Distributed fiber optic sensing technology that measures strain/temperature/vibration continuously along the fiber optic sensing cable.

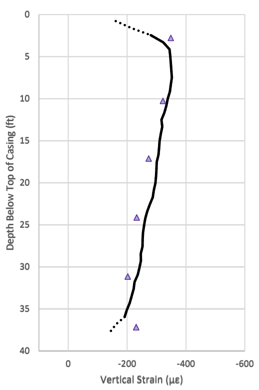
In the past 15 years, our research at the University of Cambridge and the University of California, Berkeley, has focused on investigating the feasibility of distributed fiber optic strain sensing technology in creating smart geotechnical structures. The novel aspect of this technology lies in the fact that tens of kilometers of fiber optic cable can be sensed at once for continuous distributed strain measurement, as shown in Fig. 1. The system utilizes standard low-cost fiber optic cables and the strain resolution can go down to 2 micro strains. The sensing material itself (silica) is relatively inert and can be ideal for long-term monitoring of many decades by embedding the fiber optic cable inside structures. The distributed measurement nature of this technology clearly differentiates it from the other discrete point-wise strain measurement technologies. Such features can potentially provide a relatively cheap but highly effective monitoring system for both the short and long term. Further details of the technology can be found in Kechavarzi et al. (2016) and Soga and Luo (2018).

Fig. 2 shows an example of strain measurements made on a 38 feet (11.6 m) long concrete test pile. The diameter is 3 feet (0.9 m). The aim of the project was to examine the effect of different base grouting methods on pile performance and a series of pile loading tests was conducted for the investigation. The pile had conventional vibration wire strain gauges (VWSGs) at six levels, and each level had four strain gauges, providing a total of 24 strain datasets with 24 cables coming out from the instrumented pile. Four distributed fiber optic strain sensing (DFOS) cables were also installed longitudinally next to the strain gauges, as shown in Fig. 2(a). The DFOS analyzer provided strain data every 0.25 m along the cables, giving a total of 180 datasets from the four cables coming out of the pile. Fig. 2(c) shows the strain data recorded from the two measurement systems when a vertical load of 7.8MN was applied. The strain data at each level are the average value of the four strain values, and the two data sets match well, providing confidence in both datasets. Moreover, the 'almost' continuous strain data from the DFOS system gives a clear trend of a gradual decrease in strain with depth. And the gradient of the strain profile at each location is related to the shaft friction developing at that location. Instead of plotting the averaged data, Fig. 2(d) shows the actual strain data of 24 VWSGs and the 4 DFOS cables. At a given level, VWSG data are scattered. If only such data were to be provided, a data interpreter would start wondering whether some of the data are true or not. The DFOS data, on the other hand, show apparent variation in strain profile among different positions of the pile. There is a significant strain difference between the red and purple lines, indicating that the pile is actually bending. By examining the datasets carefully, one will note that the bending changes its direction from the upper section to the lower section. The DFOS data gives a clearer picture of the soil-pile interaction behavior and, in this case, a picture beyond what we conventionally think when designing a vertically loaded pile (i.e., no bending).

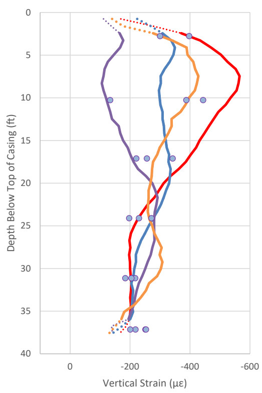


(a) Instrumented pile

(b) photo of pile installation



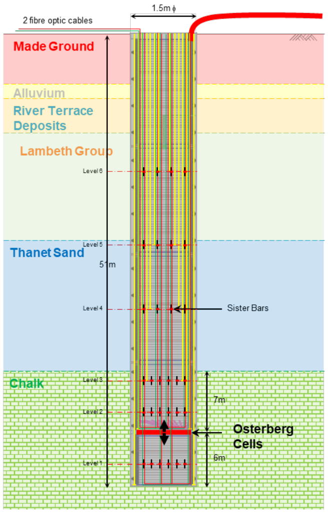
(d) Averaged data (triangles – VWSG, Line - DFOS)



(c) Actual data sets (circles – VWSG, Lines- DFOS)

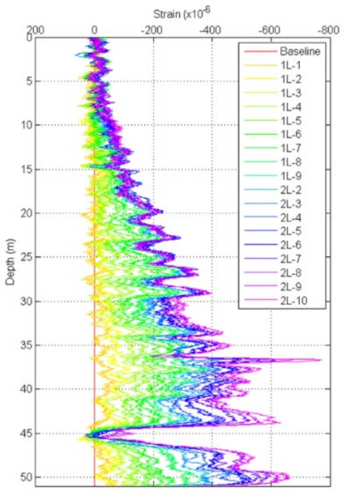
Fig. 2. Load testing of a base grouted pile

Fig. 3 shows another data set of a concrete pile loading test. The length of the pile is 51 m, whereas the diameter is 1.5 m. The loading was applied using a bi-directional Osterberg cell installed at 6 m above the pile bottom, as shown in Fig. 3(a). Again, four DFOS cables were installed in the longitudinal direction. Fig. 3(c) shows the variation in the averaged strain profile at different loads applied by the load cell. The strain is the largest at the load cell location and decreases to zero at the ground surface, indicating the development of shaft friction. As the applied load increases (yellow, green, blue and then to purple lines in the figure), the strain gradient increases, which in turn indicates mobilization of shaft friction with applied load. Pelecanos et al. (2017) analyzed this dataset and derived the t-z relations of different soil layers as shown in Fig. 3(d). Such field-derived soil-pipe interaction relations can be useful for future pile designs in similar ground conditions (Pelecanos et al., 2018). Compared to the smooth trend in strain data shown in Figs. 2(c) and (d), the strain profiles (data every 0.05 m and hence about 1000 data points per line) shown in Fig. 3(c) are very much fluctuating. When each DFOS data at a given load (25.7MN) are plotted, the locations of the variations are very similar among the four cable datasets, as shown in Fig. 3(e). This suggests that the variations recorded are real and not due to the errors of the measurement system. The instrumented pile also had DFOS temperature cables installed next to the strain cables and change in temperature was measured during the curing process of the concrete immediately after Tremie pour. Thermal integrity testing of the installed pile was conducted, and the temperature data was used to estimate the shape of the pile, as shown in Fig. 3(f) (Rui et al., 2016). The spatial variation in pile shape can be linked to the strain variation shown in Fig. 3(c) and the t-z curves shown in Fig. 3(d).

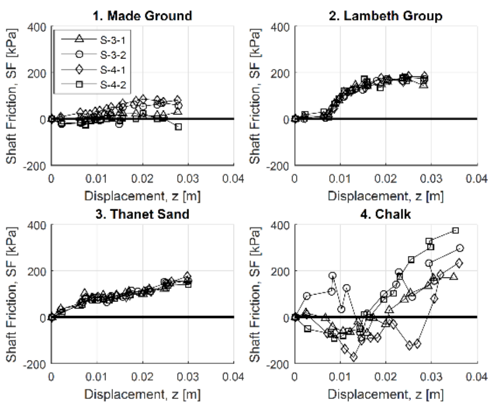


(a) DFOS Instrumented pile

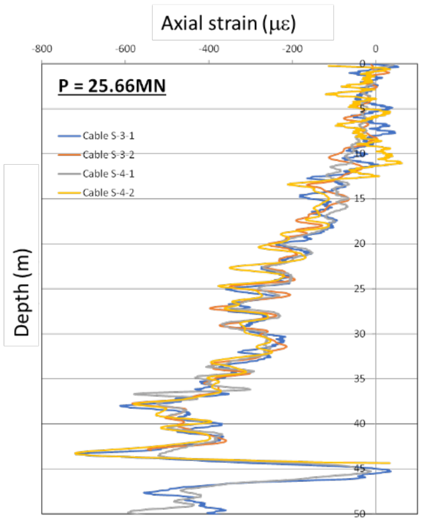
(b) Photo of pile installation



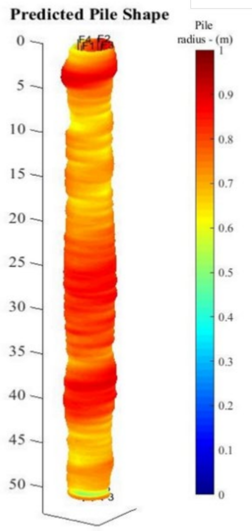
(c) DFOS strain profiles at different loads



(d) Derived t-z curves from DFOS data



(e) Strain profiles from four cables



(f) Estimated pile shape

Fig. 3. Load testing of a large diameter long pile

Design limits are frequently based on strain developing in the structure. Although strain measurement is well established, current practice has until recently been restricted to the measurement of point-wise strains by means of vibrating wire (VWSG) or metal foil strain gauges. When instrumenting building components such as columns or beams where the strain distribution is merely a function of the end conditions and applied loading, point sensors can be suitable to define the complete strain profile. However, where structures interact with soil, (e.g., underground infrastructure such as foundations, tunnels or pipelines) or indeed in the case of a soil structure (dam or embankments), the state of the structure is not fully understood unless the complete in situ strain regime is known. In the context of monitoring strain in piled foundations, capturing the continuous strain profile cab be invaluable to pinpoint localized problem areas such as joint rotations, deformations and non-uniformly distributed soil-structure interaction loads.

The case studies presented in this note show possible application of DFOS technology for smart piles (i) to conduct quality control/assessment of pile installation (e.g., a sensor embedded pile communicating with construction machine during installation), (ii) to measure the actual pile performance (axial and bending) during actual loading from a building or the surrounding soil and (iii) to future proof the pile against a future hazard such as earthquake or nearby construction. Such initiative can potentially lead to making a step-change in the civil engineering industry by providing innovative solutions to realize smart foundation systems that has 'intelligence for life'.

REFERENCES

Kechavarzi, C., K. Soga, N. de Battista, L. Pelecanos, M. Elshafie and R.J. Mair (2016) Distributed Optical Fibre Sensing for Monitoring Civil Infrastructure - A Practical Guide, ICE Publishing, 264p.

Pelecanos, L., K. Soga, M.P.M. Chunge, Y. Ouyang, V. Kwan, C. Kechavarzi and D. Nicholson (2017) "Distributed Fibre-Optic Monitoring of an Osterberg-Cell Pile Test in London," Géotechnique Letters, June 2017, Vol. 7, No. 2, pp. 152-160.

Pelecanos, L., K. Soga, M. Elshafie, N. de Battista, C. Kechavarzi, C.Y. Gue, Y. Ouyang and H. Seo (2018) "Distributed Fibre Optic Sensing of Axially Loaded Bored Piles," Journal of Geotechnical and Geoenvironmental Engineering, American Society of Civil Engineers, March 2018, Vol. 144, No. 3, pp. 1-16, doi: 10.1061/(ASCE) GT.1943-5606.0001843.

Rui, Y., C. Kechavarzi, F. O'Leary, C. Barker, D. Nicholson and K. Soga (2017) "Integrity Testing of Pile Cover Using Distributed Fibre Optic Sensing," Sensors 2017, December 2017, Vol. 17, No. 12, 2949. https://doi.org/10.3390/s17122949

Soga, K. and L. Luo (2018) "Distributed Fiber Optics Sensors for Civil Engineering Infrastructure Sensing," Journal of Structural Integrity and Maintenance, February 2018, Vol. 3, No. 1, pp. 1-21.

Soga, K. and J. Schooling (2016) "Infrastructure Sensing," Interface Focus, Royal Society Publishing, Vol. 6, No. 4, 20160023 http://doi.org/10.1098/rsfs.2016.0023

◆ A brief CV of Prof. Kenichi Soga

Kenichi Soga is the Donald H. McLaughlin Professor and a Chancellor's Professor at the University of California, Berkeley. He is also a faculty scientist at Lawrence Berkeley National Laboratory. He obtained his BEng and MEng from Kyoto University in Japan and PhD from the University of California at Berkeley. He was Professor of Civil Engineering at the University of Cambridge before joining UC Berkeley in 2016. His current research activities are infrastructure sensing, performance based design and maintenance of infrastructure, energy geotechnics, and geomechanics. He is a Fellow of the UK Royal Academy of Engineering, the Institution of Civil Engineers (ICE) and American Society of Civil Engineers (ASCE). He is a Bakar Fellow of UC Berkeley, promoting commercialization of smart infrastructure technologies.