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Monitoring the performance of cast in-situ retaining walls using distributed fibre optic sensing.

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ABSTRACT: Cast in-situ retaining walls are often used for the construction of deep basements, cuttings and shafts. Their design takes into account both geotechnical conditions and construction sequences, including excavation methods, temporary propping and permanent support systems. These complexities provide an opportunity for monitoring systems to be used to verify design performance and optimise construction. A common technique for monitoring the performance of retaining walls is with an inclinometer, either used periodically or left in place. Distributed fibre optic sensing can also be used to provide comparable measurements of wall movement and performance. Distributed fibre optic sensing is a technique which can either supplement an inclinometer or be used to provide an independent measurement. This paper discusses the use of fibre optic monitoring in retaining walls, and through recent case studies and theoretical examples presents the practical and technical considerations needed to plan an efficient monitoring solution, install the system and process the data. Consideration is given to the advantages of each system alongside a systematic review of the sources of error in each measurement.

KEYWORDS: Fibre Optic Sensing, Retaining Walls.

1 INTRODUCTION

Deep excavations serve many purposes in the built environment. They can provide increased space for residential and commercial buildings through multi-level basements. They can enable access to subterranean facilities such as underground train stations and utility tunnels as well as generally retain and reshape the ground surface. Their design needs to account for both the ground in which they are formed and the methods used to construct them. Aside from providing bearing capacity, they must also be capable of supporting the excavation at different stages of its construction, provide the space in which the excavation can be efficiently carried out and prevent damaging ground movements to adjacent structures. This level of complexity increases both risk and opportunity for a contractor, with monitoring often employed to mitigate and realise both.

The most basic observation of a wall's performance is its deflection. This can be an indication of its performance with respect to design expectations and a guarantor of limiting the impact on surrounding structures. Consequently, measurements of wall deflection are often the primary requirement of a monitoring system. However, the driving forces behind the deflection of a wall are the bending moments resulting from ground forces. To verify that these are in line with design expectations monitoring may also be used. Bending moments cannot usually be measured directly, however, they can be calculated from observations of the movement of the wall, provided that its stiffness is known or can be estimated. A combination of both deflection and bending moments can be used to assess the performance of a wall.

Whilst a number of technologies are available for wall monitoring, the most common method for detailed observation is the inclinometer. However, alongside this technology, distributed fibre optic sensing (DFOS) has also been deployed. Both Li et al, (2018) and Nejjar et al, (2023) describe the use of DFOS and inclinometers in diaphragm walls used to form station boxes in London and Paris. Schwamb and Soga, (2015) present the details of monitoring installation in an 80m deep utility shaft, formed by diaphragm walling and in which both inclinometers and DFOS are used. Mohamad et al, (2011) present the example of their use in a secant piled mini pile wall, 22.5m deep. These case studies, though relatively few, demonstrate the importance of monitoring in complex retaining walls and show the potential of DFOS as a technique to measure both deflection and bending moments. In these case studies, the focus is on how the two systems can be used effectively together, rather than viewing one as a replacement for the other.

When designing such a monitoring solution, it is important to recognize the differences between the measurement technologies, in particular the specific parameters that they measure and how the associated accuracies will influence how the data can be used.

2 THEORETICAL CONSIDERATIONS

2.1 *Calculation of Parameters – DFOS*

A full description of the methods of obtaining strain measurements from reinforced concrete structures using DFOS is provided in Kechavarzi et al, (2017). In order to use the measured values of strain, ε, to calculate deflection, Δx, and curvature, κ, the following procedure may be followed.

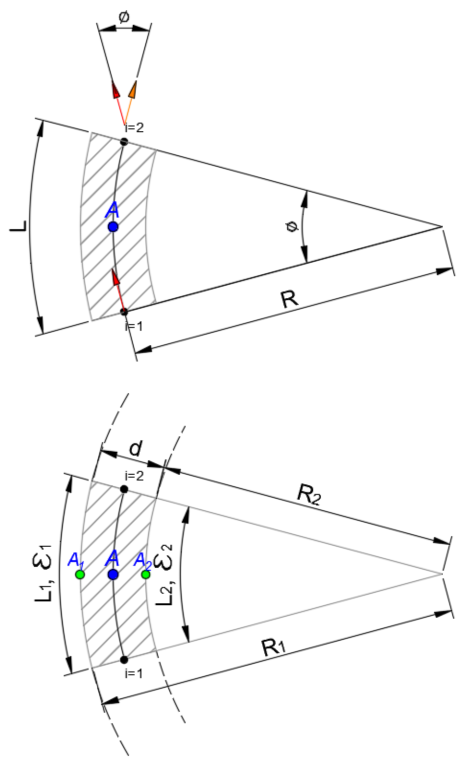

Figure 1. Illustration of a segment of a wall with a constant curvature.

Figure 1 illustrates a theoretical segment of a wall of length, L with a uniform curvature and a central neutral axis at radius R. The theoretical strains at radial positions R_1 and R_2, the front and back of the wall, can be calculated from the difference in their positions from R using equation (1), derived as follows.

$$\varepsilon_n = \frac{L_n - L}{L} = \frac{\frac{\emptyset}{2\pi}2\pi R_n - \frac{\emptyset}{2\pi}2\pi R}{\frac{\emptyset}{2\pi}2\pi R} = \frac{R_n - R}{R} \quad (1)$$

From measurement observations of strain at A_1 and A_2, also presented in Figure 1, and using equation (1), the curvature of a segment can be calculated using equation (2), derived as follows.

$$\varepsilon_1 - \varepsilon_2 = \frac{R_1 - R}{R} - \frac{R_2 - R}{R} = \frac{1}{R}(R_1 - R_2) = \kappa d$$

$$\kappa = \frac{1}{d}(\varepsilon_1 - \varepsilon_2) \quad (2)$$

This equation is stated in Mohammed et al, (2018). Knowing the distance, L, the spacing between measurement points along the length of the wall, the angle, $\emptyset$, can be calculated using equation (3), derived as follows.

$$\frac{\emptyset}{2\pi} = \frac{L}{2\pi R}$$

$$\emptyset = \frac{1}{R}L = \kappa L \quad (3)$$

Where $\emptyset$ is the change in inclination of the wall from point $i = 1$ to point i= 2. This equation is also stated in Mohammed et al, (2018).

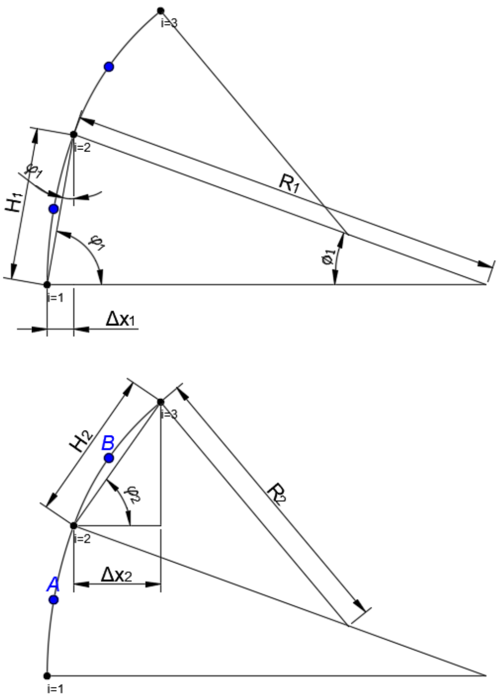

Figure 2. Illustration of a wall, discretized as a series of segments.

Considering a retaining wall as a series of segments (where n is the total number of segments and j is used to incrementally denote each segment), as presented in Figure 2, the horizontal deflection, Δx_j over each segment can be calculated using Equation (4).

$$\Delta x_j = H_j sin(\varphi_j) \quad (4)$$

Where

$$H_i = 2R_j \sin\frac{\emptyset_j}{2} \quad \text{and} \quad \varphi_j = \left(\frac{\emptyset_j}{2} + \sum_{m=1}^{m=j-1} \emptyset_m + B\right)$$

B = any initial rotation of the wall from vertical at the point $i = 1$. φ_j = the inclination of the wall at each segment.

The cumulative horizontal deflection of a wall with n segments, written in terms of the fundamental observations in equations (2) and (3) can be calculated using equation (5).

$$\Delta x = \sum_{j=1}^{j=n}\left[2R_j \sin\frac{\emptyset_j}{2} \sin\left(\frac{\emptyset_j}{2} + \sum_{m=1}^{m=j-1} \emptyset_m + B\right)\right] + A \quad (5)$$

Where A = any horizontal deflection at position $i = 1$.

Equation (5) is not computationally demanding and can be calculated explicitly, however, applying a small angle approximation, it can be written in the form of equation (6) making it equivalent to the expression presented in Mohammed et al, (2018).

$$\Delta x = \sum_{j=1}^{j=n}\left[R_j \emptyset_j \left(\frac{\emptyset_j}{2} + \sum_{m=1}^{m=j-1} \emptyset_m + B\right)\right] + A \quad (6)$$

In the case of constant L and where

$$X_j = \varepsilon_{1j} - \varepsilon_{2j}$$

Equation (6) can be simplified to

$$\Delta x = \frac{L^2}{d}\sum_{j=1}^{j=n}[X_j(n - j + 0.5)] + nLB + A \quad (7)$$

This formulation makes clear the influence of uncertainty in the measurement of L, d and X.

These equations rely on the spacing between observation points being sufficiently small for the curvature to remain constant and, in the case of equation (6), the small angle approximation to be valid. In the case of piled retaining walls where curvatures are at least in the order of $1x10^{-5}$m and observations are made over intervals of less than 1.0m, this is not an unreasonable assumption.

2.2 *Calculation of Parameters - Inclinometer*

A detailed description of the use of inclinometers is provided by Dunnicliff, (1988). Most commercial inclinometer systems can produce an output of horizontal deflection, however, values of sin φ from equation (4) can still be obtained and used in the calculation of curvature by rearranging equation (3).

With the inclination measured and using a small angle approximation and a constat value of L, the total deflection can be written in the form of equation (8). This formulation makes clear the impact of any uncertainty in the determination of L or φ.

$$\Delta x = L\sum_{j=1}^{j=n} \varphi_j + A \quad (8)$$

Alternative approaches for calculation of curvature from deflection profiles, are discussed in detail in Ooi and Ramsey, (2003), who demonstrate the importance of carefully selecting an appropriate method and conclude that cubic polynomials fitted piecewise to deflection (over 5 consecutive points) are often best suited. This is equivalent to fitting a quadratic equation to observations of inclination with depth, z, such that

$$\varphi_j = Mz^2 + Nz + P \qquad (9)$$

The constants in equation (9) can be easily determined in software packages such as Microsoft Excel using the powerful LINEST function. Differentiation of this function with respect to z yields an expression for the curvature.

$$\kappa_j = 2Mz + N \qquad (10)$$

2.3 *Sources of uncertainty*

In addition to the theoretical formulas relating measurements of strain and inclination to curvature and deflection it is important to consider the sources of uncertainty in the measurements themselves and the potential magnitude of errors which can arise as a result. Sources of uncertainty in the measurement of strain and inclination using DFOS and inclinometers are well covered in literature.

For the inclinometer, a typical manufacturer specification for modern Micro Electro-Mechanical Systems (MEMS) derived inclinometers claims an accuracy of 0.004^{o} for the instrument itself (Geosense, 2025). However, as described by Dunnicliff, (1988) and Ridley et al, (2020), there are other sources of uncertainty which also need to be considered and carefully managed. Data from the example presented later in this paper, and from other projects have been used to investigate the magnitude and distribution of this error by examining the deviation of the angular measurements from the average checksum values. From this, it appears that a residual random error remains which is normally distributed and which has standard deviation of around 0.005^{o}. Systemic errors can be managed through instrument calibration, operator training and reverse measurements.

Klar et al, (2006) describe the presence of a normally distributed random error with a standard distribution of $15\mu\varepsilon$ associated with DFOS measurements using the Brillouin Optical Time Domain Reflectometry (BOTDR) method. Whist other technologies such as Brillouin Optical Time Domain Analysis (BOTDA) can reduce this by an order of magnitude (Omnisens, 2017), other error sources such as optical losses at splices, connections and cable miss-alignment will mean the magnitude of the error will not significantly reduce.

Cleary, the presence of any systematic error will be of great significance for determination of deflection and curvature. It is essential, therefore, that the linearity of the fibre optic response is ascertained over the appropriate strain range and suitable calibration factors are used.

A further consideration is the influence of temperature on the measured values. Fibre optic sensors are affected by both strain and temperature. Measurements of strain made in a location where temperature varies between measurements will require a corrective procedure, described by Kechavarzi et al, (2017). Given that this response to temperature is typically linear, calculation of curvature using equation (2) will be unaffected, provided that the temperature remains constant across the section of the wall. However, if axial forces also need to be calculated from the data, temperature variation will need to be taken into account.

3 THEORETICAL EXAMPLE

The influence of these uncertainties can be investigated through a theoretical example. By this method, the true values are calculated from theory, the sources of uncertainty modeled and the potential error quantified. This approach was taken by Klar et al, (2006) in their discussion of using DFOS in piles.

Figure 3 presents the calculated values of curvature and deflection of an embedded cantilever retaining wall, modeled using the fixed earth method. From these calculations, the compatible values of strain and inclination can be determined and are presented in Figure 4. Measurements of strain and inclination from DFOS and inclinometers have been simulated by adopting the size and distribution of error discussed earlier in this paper.

In this example, the retaining wall has been modeled with both A and B equal to zero and so there is no error associated with these inputs.

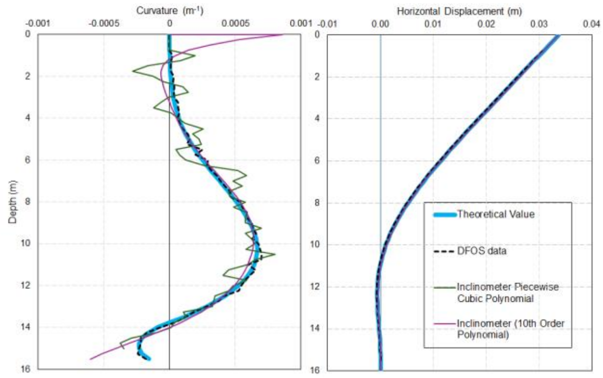

Figure 3. Curvature and deflection of a theoretical retaining wall with simulated measurement data.

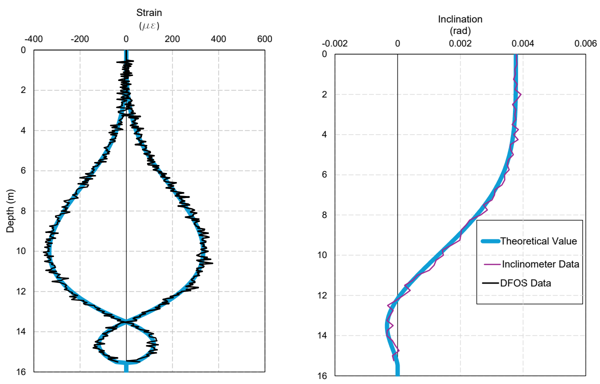

Figure 4. Strain and inclination values for a theoretical retaining wall with simulated measurement data.

3.1 *Discussion*

From this theoretical exercise, several points can be established. Calculations of deflection by both DFOS and inclinometers, are relatively unaffected by the magnitude of errors modeled. The calculation of deflection involves a summation of the measured values using equations (7) and (8) and so zero mean random errors will summate to zero in the final calculus.

For the calculation of curvature, the presence of random errors is significant. From equations (2) and (3) it can be appreciated that the value of curvature is directly proportional to individual measurements of strain or inclination change. For DFOS measurements, the magnitude of the random error is relatively small when compared to the absolute value of strains measured. However, for inclinometer measurements, the change in inclination between data points is very small indeed and so even the high accuracies achieved on a single absolute measurement are significant in the determination of curvature.

The adoption of a high order polynomial for modeling the curvature of a wall from inclinometer measurement has some benefit in reducing the influence of random errors. However, as discussed in Ooi and Ramsey, (2003) it can provide a poor fit for a real example. It is presented in figure Figure 3 and Figure 4 for comparison purposes only.

The presented DFOS data also includes modelling of the effects of spatial resolution which are found to be insignificant to the accuracy of the measurement. Unlike the features discussed by Fisher and Barker, (2025) who use DFOS measurements to identify areas of temperature change within a piled foundation, the changes in strain in a retaining wall occur over distances comparable to or greater than the spatial resolution.

On the basis of this example, both methods provide adequate accuracy for measurement of a theoretical deflection and bending moment. However, the influence of random error on calculated values of curvature is more significant for inclinometer derived measurements. This can be further verified through the presentation of the following project example.

4 PROJECT EXAMPLE

In the following example, DFOS and an inclinometer were installed in a 1.05m diameter, 25m deep rotary bored pile. This pile forms part of a secant piled retaining wall for a multi-story basement in central London. The building was constructed using a top-down sequence and the contractor relied on an observation-based approach to allow for a delay in the installation of some of the temporary propping in order to speed up the excavation. The monitoring was used to measure both the wall's deflection and the bending moments acting on it as the works progressed.

The inclinometer was installed within a steel reservation tube in the core of the pile and on the soil side of the excavation. It was grouted into place with a cement grout with a small addition of bentonite for flexibility and to reduce bleed. It was monitored on a weekly basis using a manual inclinometer probe.

For the DFOS, 3 loops of strain sensing fibre were installed at different radial positions around the cage. This not only provided redundancy but also a means to improve the accuracy of the measurements. This procedure is described in the results section of this paper. A single loop of temperature sensing fibre was installed on the front and rear face of the pile for the purposes of temperature correction. An illustration of the position of these sensors within the reinforcement cage is presented in Figure 5.

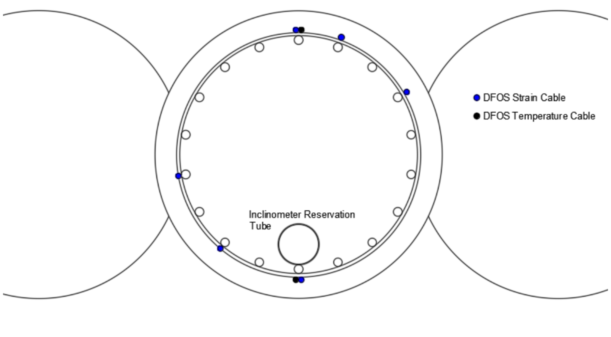

Figure 5. Illustration of pile cross section showing instrumentation locations.

Where the retaining wall was to be broken-out to facilitate the construction of permanent slabs, the fibre optic cables were routed to the sides and rear of the cage. Similar care must be exercised if shuttering or stud walls are to be drilled into the retaining wall and, if possible, these should be designed to avoid those piles containing instrumentation.

The fibres were attached to the outside of the reinforcement, following the route of the main bars and attached with cable ties and tying wire. Pre-straining of the fibre optic cables was not carried out as this has been found to increase the risk of kinks and breaks. Instead, careful note of chainage was made which, along with observations of temperature and excavation depth were used to verify the position of the fibre.

Once installed, the fibre optic cables were then routed through the capping beam to a convenient point for monitoring and terminated with E2000/APC patch cords and housed in an enclosure. Readings were made at intervals ranging from 1 month to 1 week.

4.1 *Results*

Calculation of wall deflection from inclinometer and DFOS measurements are presented in Figure 6. These show reasonable agreement if a common point of equal horizontal displacement is assumed at the toe of the wall although there is a relatively significant difference observed between the maximum deflections calculated.

To calculate B, the initial inclination of the wall, an average value from the bottom 3 inclinometer measurements was taken. The absolute movement of the wall was calculated through the inclusion of optical monitoring data on the capping beam and props, however, this is excluded from Figure 6 for clarity.

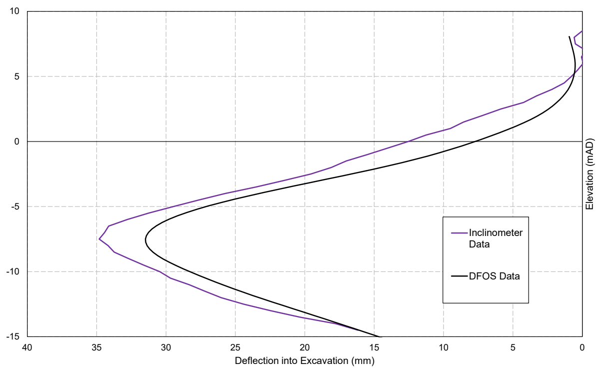

Figure 6. Deflection profiles for the retaining wall.

Calculation of curvature from both DFOS and inclinometer measurements is presented in Figure 7. As for the theoretical example, values of curvature calculated from inclinometer data are presented using a range of fitting methods. To compare the bending of the wall to design values, the calculated curvatures were multiplied by the wall's flexural rigidity, EI, which was reduced to 70% of its initial value in accordance with industry guidance (Gaba et al. 2017). This is presented in Figure 7 which shows reasonable agreement with the design outputs for this construction sequence.

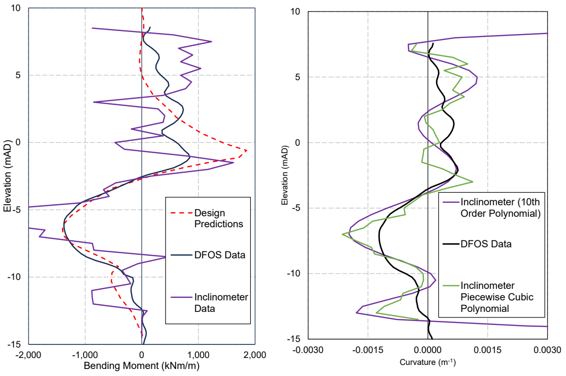

Figure 7. Bending moment and curvature profiles for the retaining wall.

In order to improve the accuracy of the DFOS measurements, data from different points across the section was included in the calculation of curvature. These data points came from the three loops of cable installed within the pile and are presented in Figure 8. Generally, these sections revealed a linear distribution of strain across the section, allowing a best fit line to be calculated and used to determine the most appropriate values of strain to use in equation (2). This approach further reduces the influence of random errors and sensitivity to determination of d.

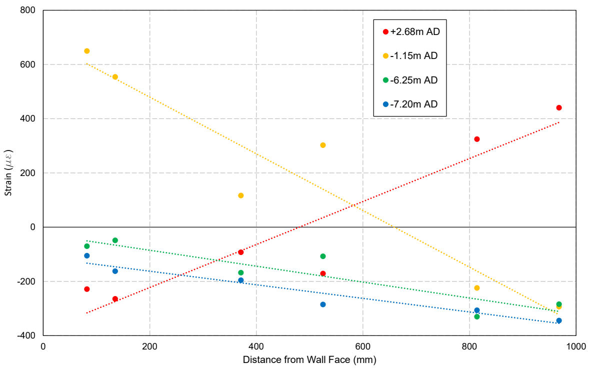

Figure 8. Strain distribution across the section of the wall at various levels.

4.2 *Discussion*

Both DFOS and inclinometer monitoring systems produced comparable and credible results that could be used to calculate values of deflection and curvature. Neither was entirely independent as a means to describe the movement of the wall, the inclinometer relying on optical measurement of displacement at the capping beam and the DFOS also requiring an additional input of inclination, in this case, derived from the inclinometer readings. As an alternative, data from multi-level optical surveys or independent tilt meters could be combined with the DFOS data to provide an independent measure from the inclinometer.

The discrepancies between calculated values of deflection and curvature at -6.0m AD were slightly greater than expected. However, a number of factors may have influenced these results. This includes the complexity of the excavation sequence and the difficulty associated with determining the parameters A and B. The inclinometer was also installed in short sections with low head room and, whilst corrections were made for orientation and spiraling, these may still have resulted in additional sources of error.

With both measurement systems, protection of the installations was very important. For the inclinometer, this included a protective cover to the top of the tube with adequate access maintained throughout the project. For the fibre optic measurements, sensors were spliced together and routed to a convenient point at the site boundary. This proved effective as a means to both protect the cables and maintain access. In fact, this method allows fibre optic cables to be permanently cast into the capping beam and routed around site. In areas where maintaining access is difficult, this is an advantage of the DFOS system as, once installed, no further access is required for measurements or maintenance.

The use of multiple loops of DFOS provided an effective way to verify the section strain from each measurement and therefore should improve the accuracy of the measurement. Furthermore, it provides an insight into the behavior of the cross section over time.

The inclinometer and DFOS monitoring were provided by the same contractor with measurement time on site lasting only 2-3 hours. Consequently, whilst more expensive per visit due to the higher equipment costs, the DFOS method was comparable in cost with inclinometers, particularly when the higher, up-front costs of in place inclinometers was considered.

5 CONCLUSION

DFOS measurement both theoretically and practically has been shown to provide an effective means to measure the deflection and curvature of a retaining wall. For simple solutions where the only requirement is to measure deflection, the advantages of DFOS may only be in locations where maintaining access to the pile head is difficult. However, if a more detailed understanding of the pile's behavior is required, including its response to bending, DFOS offers advantages. The sources of uncertainty are such that calculation of curvature may be more accurate, and the placement of fibres across the section will provide further insight into the behavior of the section.

Klar et al, (2006) discuss the economics of the fibre optic method based on the instrument costs available at the time. Since 2006 there have been many improvements in technology however, the fundamentals have not changed significantly. The measurement instrument associated with fibre optic cables remains an expensive piece of equipment, similar to a 3D laser scanner or other high end survey product. However, considerable advances have been made in the availability and portability of such equipment. If periodic visits are possible rather than constant monitoring, the costs to individual projects can be reduced whilst maintaining sufficient utilization of equipment.

The basic cost of the strain sensing fibre has also been significantly reduced such that the installation costs is similar to an inclinometer (when reservation tubes and grouting are considered), and considerably less than the cost of an in-place inclinometer.

Whilst a DFOS installation is perfectly capable of standing alone as a monitoring tool for a retaining wall, it is more appropriate to consider it as one of many solutions which, should be designed and specified to suit the particular needs of each project. Where there is a benefit to be gained from detailed monitoring, different techniques can be combined to achieve the required accuracy, redundancy and economy of the system. In this way, DFOS should continue to be adopted on new projects and serve to continue the improvement of our understanding and ability to design and predict retaining wall movements into the future.

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