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# The use of distributed fibre-optic strain data to develop finite element models for foundation piles

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## Abstract

Distributed fibre-optic strain sensing using BOTDR or BOTDA is an instrumentation technique that offers a spatially-continuous data. This is superior to more conventional discrete point-based sensors which provided limited monitoring information at pre-specified location points. The availability of a distributed strain regime offers a number of advantages when it comes to studying soil-structure interaction problems such as foundation piles.

Distributed strain profiles from foundation piles are useful in understanding the actual behaviour of these structures and can provide important information to develop relevant computational finite element models. Axial pile strains can be integrated to obtain absolute pile displacements or can be differentiated to get pile shaft friction values.

This paper describes the use of BOTDR/A in monitoring axially-loaded foundation piles and presents recent case studies in London. It also proposes an approach to develop finite-element load-transfer models for future analysis and design of foundation piles.

**Keywords**: fibre-optic strain sensing, piles, finite-element analysis

## 1. Introduction

Pile load tests are conducted to obtain the load-displacement relationship of a pile interacting with the surrounding soil. Useful technical interpretation of the pile-soil interaction can be done from a well-instrumented pile (Bond et al., 1991; Jardine et al., 2013; Bica et al., 2014). Load-transfer curves for axially loaded piles represent the developed shear stress at the pile shaft (t-z) or at the end bearing (q-z) due to the vertical (axial) displacement of the pile relative to the far-field soil. This information which may be obtained from instrumented pile load tests is useful for understanding the deformation and capacity of piles and for future design (Frank & Zhao, 1982; Fahey & Carter, 1993; Honjo et al., 1993; Abchir et al., 2016).

This paper proposes a simple method for estimating the load-transfer curves for axially-loaded piles directly using spatially-continuous FO strain data from a pile load test using the BOTDR technique. The method is computationally very efficient as it does not need a sophisticated and demanding optimisation scheme to match experimental and numerical data using computationally intensive techniques such as neural networks or machine learning. A modified hyperbolic relation is used to define the observed load-transfer curve, and this relation is able to consider both the degradation of stiffness and hardening/softening. The approach is then applied to a set of FO data from a recent pile load test in London. The derived back-analysed curves are subsequently used as input in forward-analyses of the pile load tests and a good comparison is obtained, thus verifying the accuracy of the proposed method.

## 2. Problem definition

The problem under study is shown in Figure 1. A vertically loaded pile load test (a) is conducted in the field for various values of the applied load P. Distributed fibre optic monitoring data are obtained for the distributed strain profiles for each load step (b) and for the pile top load-displacement curve (c). The aim of this study is to use the available monitoring data (b & c) in order to construct appropriate nonlinear load-transfer (for both pile shaft and base: t-z and q-z) curves (e) for simple finite element (FE) beam-spring analysis models (d) that can reproduce the pile behaviour.

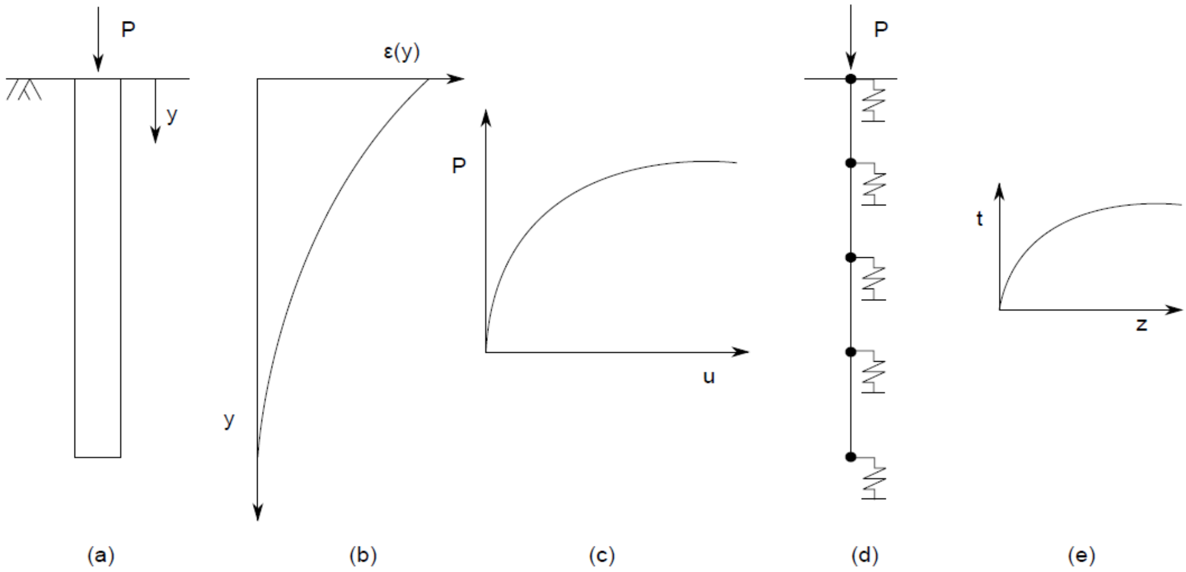



**Figure 1.** Problem definition: (a) axially loaded pile, (b) profiles of axial strain for each load step, (c) pile top load-displacement curve, (d) finite element beam-spring model of the pile-soil interaction and (e) load-transfer curve defining the nonlinear behaviour of a soil spring.

The field monitoring data can be obtained using the Brillouin Optical Time-Domain Relfectometry/Analysis (BOTDR/A) technique. This technique is able to provide spatially-continuous (i.e. distributed) strain data along the entire length of an optical fibre. The relevant background of the physical principle (i.e. theoretical physics, photonics and optics) and the relevant experimental approaches followed for calibration can be found elsewhere (Horiguchi et al. 1995) (Mohamad 2007) (Iten 2011) (Soga 2014) (Soga et al. 2015). A detailed description of the theory of distributed FO strain sensing and its applications in civil and geotechnical infrastructure may be found by Kechavarzi et al. (2016), while examples of application to piles are obtained from Klar et al. (2007), Ouyang et al. (2015) and Pelecanos et al. (2016, 2017a, 2017b). More examples on monitoring soil-structure interaction may be found by Acikgoz et al. (2016, 2017), Cheung et al. (2010) Di Murro (2016), Schwamb et al. (2014) and Soga et al. (2017).

## 3. Development of FE models

### 3.1. Inverse analysis procedure

The proposed load-transfer curve derivation procedure assumes that the following monitoring information from the load test is known:

(i) distributed (from fibre optics) axial strain profiles with depth, y, for each load step (reading), j: εα(y, j).

(ii) top (y=0) load-displacement curve, for each load step, j: P(u(y=0), j).

Then, the following information can be calculated for each load step, j:

(a) Axial force, $F_a$(y,j):

$$F_a(y,j) = EA \cdot \varepsilon_a(y,j) \qquad \text{Equation 1}$$

(b) Shaft friction, SF(y,j):

$$SF(y,j) = \frac{1}{2\pi r}\frac{d}{dy}\left[EA \cdot \varepsilon_a(y,j)\right] \qquad \text{Equation 2}$$

(c) Vertical displacement, z(y,j):

$$z(y,j) = z(y = y_0, j) + \int_0^y \varepsilon_a(y,j)\, dy \qquad \text{Equation 3}$$

where, E, A and r are the Young's modulus, cross-sectional area and radius of the pile. Young's Modulus, E, can be evaluated from the strain and load measured at the top of the pile. It is assumed here that E is constant with depth (i.e. constructed uniformly). In reality, this may not be the case and careful examination of the measured strain profile and the associated soil profile can lead to assessment of the quality of the test pile (Soga, 2014; Pelecanos et al., 2017b).

At each point, i, along the depth of the pile, y=yi, the evolution of shaft friction, SF(y=yi, j), for all loadsteps, j, can be plotted against the externally applied load, P(j), or the experienced vertical displacement at that point, z(y=yi, j). Alternatively, the corresponding values of the axial load transfer, t(y=yi, j), can be plotted against the experienced vertical displacement at each point, u(y=yi,j), along the depth of the pile, thus illustrating the field observed behaviour of load-transfer.

Subsequently, a nonlinear load-transfer (t-z or q-z) model can be calibrated against the field-observed t-z or q-z plots (i.e. the nonlinear model equation fitted in the field data using an appropriate optimisation scheme), thus deriving load-transfer curves for pile analysis from a particular field pile load test. The suitability of the derived load-transfer curves can then be verified by the comparison of the results of a numerical pile analysis which employs the derived load-transfer curves against the observed field data, such as axial force, shaft friction of vertical displacement profiles.

### 3.2. Nonlinear load-transfer model

The nonlinear load-transfer (t-z or q-z) model used in this study is a modified version of the standard Hyperbolic model (Pyke, 1979) that additionally takes into account stiffness degradation and hardening/softening. The Degradation & Hardening Hyperbolic Model (DHHM) (Pelecanos et al., 2017b; Pelecanos & Soga, 2017) has 4 distinct parameters which govern different aspects of the curve and its mathematical description is given by Equation 4.

$$t = \frac{k_m z}{\sqrt[d]{\left(1+\left(\frac{k_m}{t_m}z\right)^{hd}\right)}}$$ Equation 4

where $k_m$ is the maximum stiffness for displacement, z=0 (units: [force/length$^3$]), $t_m$ is the "maximum" value of shear stress, t (maximum only in the case of no hardening/softening, i.e. h=0) (units: [force/length$^2$]), d is the degradation parameter (units: [-]), that governs the degradation of subgrade modulus, k, with displacement, z, and h is the hardening parameter (units: [-]), that mostly governs the model behaviour at large displacements, z.

The load-transfer model is used to describe the behaviour of nonlinear soil-springs in a finite element beam-spring analysis, as shown in Figure 1 (c). These nonlinear springs define the global soil stiffness matrix, $K_s$, which along with the global pile stiffness matrix, $K_p$, and the externally applied load, P, contribute to global equilibrium, as described by Equation 5, in order to obtain global pile displacements, u.

$$\left(\left[\mathrm{K_p}\right] + [K_s]\right) \cdot \{u\} = \{P\}$$ Equation 5

### 3.3. Optimisation scheme

As mentioned earlier the derivation of load-transfer curves involved calibration of the nonlinear model (Equation 4) through model-fitting against the experimental data by employing an optimisation scheme. In this case, the following optimisation scheme was adopted: The optimal set of numerical analysis parameters {$k_m$, $t_m$, d, h} is obtained by minimising the Objective Function (OF). The latter function to be minimised adopts the method of least squares of the difference between the t values of the model and the field data for each value of z, subject to the constraint of the model parameters being positive.

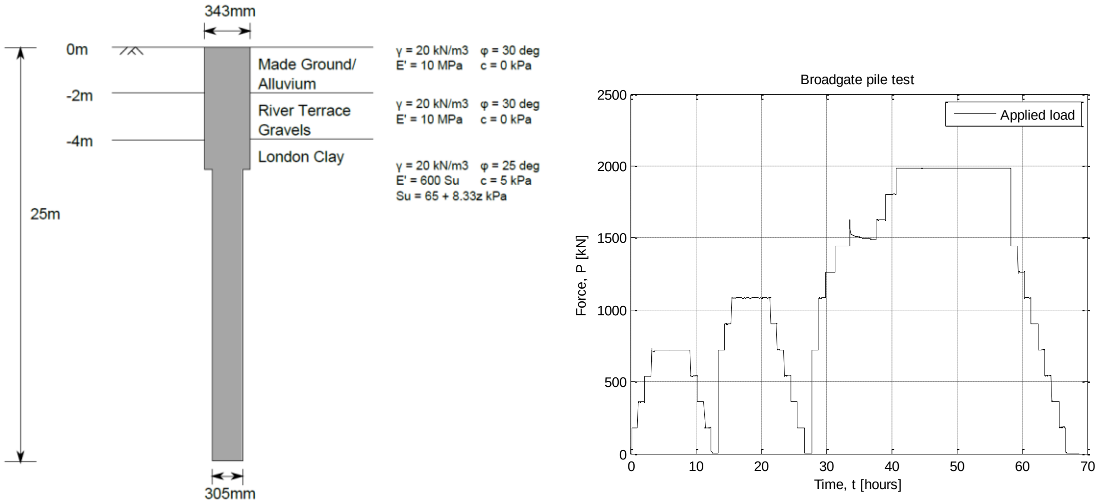
The optimisation problem was solved in this case by using the Levenberg-Marquadt (Levenberg, 1944; Marquadt, 1963) optimisation algorithm, as this is implemented in the commercial numerical software MATLAB. However, other similar algorithms are possible, but it is out of study scope to find the best algorithm for this particular problem. The result of the optimisation problem gives the set of the model parameters that best-fit the field-observed data curve and which is essentially the calibration of the model.

## 4. Application

The proposed method is subsequently applied to a real case of a top-loaded pile load test which was monitored with distributed fibre optic sensing cables and had available data for both the top load-displacement curve and axial strain profiles with pile depth.

### 4.1. Pile test details

This case considers a vertical top-loaded test of a bored pile at a building site in London (Gue et al., 2012). The monitored pile is 25m long with a varying diameter of 343mm for the top 6m and 305mm for the bottom rest 19m. Some basic information regarding the pile test is shown in Figure 2. Local soil stratigraphy comprises of Made Ground, River Terrace Gravels and London Clay where the pile base is founded. The test consists of successive stepped loading-unloading cycles of 720, 1080 and 1985kN total force applied at the top of the pile.




.(a) (b)

**Figure 2:** Pile load test: (a) pile geometry and soil stratigraphy, (b) history of applied load.

## 4.2.Finite element model

The back-analysis approach described earlier is followed in order to derive the load-transfer curves (t-z and q-z) for this pile based on the data from the pile load test. Here, the differentiation of axial strains for the derivation of axial shaft force profiles was done by dividing the pile into 2 different sections (see Table 1). Subsequently, the nonlinear DHHM model relation was fitted in the back-calculated load-transfer curves providing the corresponding load-transfer model parameters. The values obtained from the optimisation procedure are listed in Table 1.

**Table 1.** Back-calculated parameters for the developed load-transfer curves.

| Layer | Depth [m] | $k_m$ [$MN/m^3$] | $k_m/y$ [$MN/m^3/m$] | $t_m$ [$MN/m^2$] | $t_m/y$ [$MN/m^2/m$] | d [-] | h [-] |
|---|---|---|---|---|---|---|---|
| **Based on FO monitoring data** | | | | | | | |
| 1 | 0 – 6 | 9 | 0 | 0.009 | 0 | 2 | 0.8 |
| 2 | 6 – 25 | 10 | 0 | 0.06 | 0.01 | 1.2 | 0.95 |
| Base | 25 | 12 | - | 0.5 | - | 2 | 1 |

Figure 3 shows the back-calculated load-displacement curves. It is shown that the top soil layer exhibits a softer and of lower ultimate strength response than the second layer because the top layer is Made Ground and due to its small depth it has smaller confining pressure. Moreover, the stiffness and strength parameters of the second layer increase with the depth. Finally, the pile base behaves in a nonlinear matter and exhibits a reasonably stiff response.

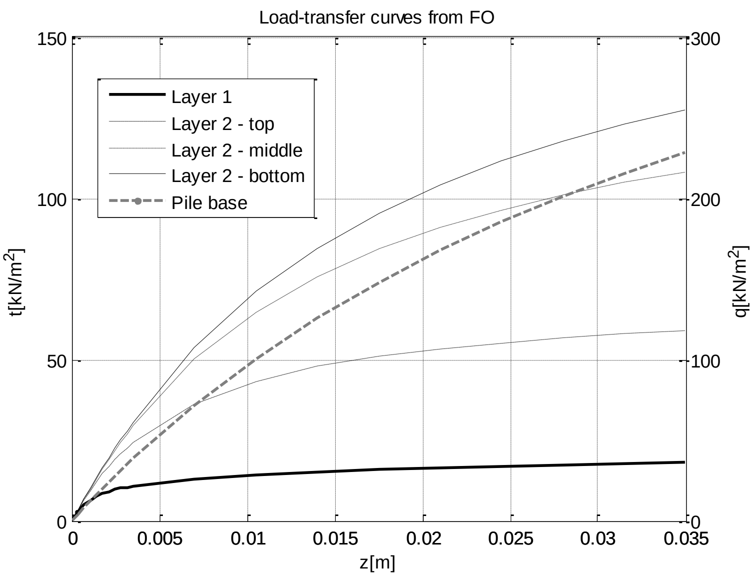
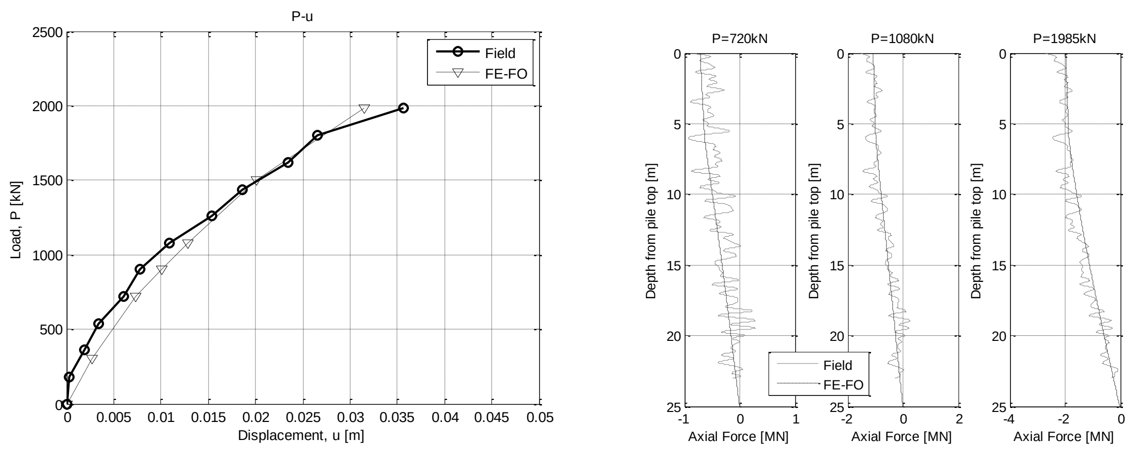


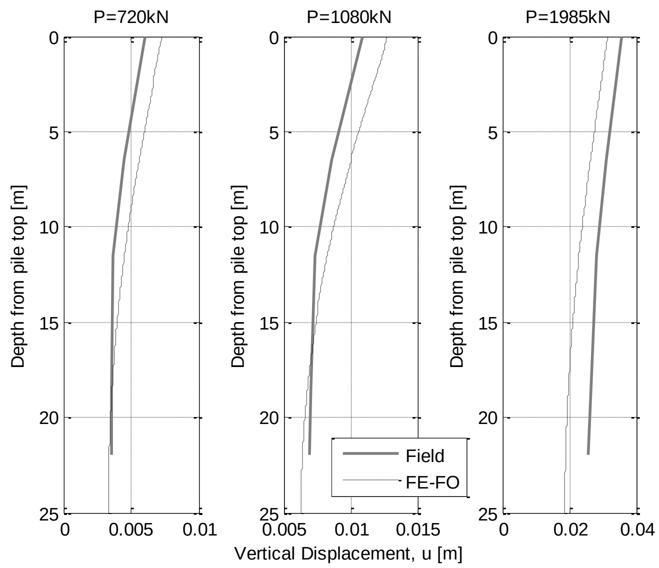

**Figure 3**. Back-calculated load-transfer curves for the soil springs.

## 4.3.Verification of the developed load-transfer curves

Subsequently, in order to verify the results of this back-analysis, numerical FE analysis is run, using as input the load-transfer model parameters obtained (**Error! Reference source not found.**). Figure 4 shows the results of the "forward" numerical analysis and their comparison with the field test results. Top load-displacement and profiles of axial force and vertical displacement are presented. Vertical displacement is calculated directly from the monitoring distributed FO strain data by direct spatial integration (i.e. with respect to depth y), as described by Equation 3. It is shown that a very good agreement is achieved between the model predictions from the FO monitoring data and the field measurements, especially for the top load-displacement curve, thus verifying the validity of the adopted load-transfer curves and hence the applicability of the proposed back-analysis procedure. It may be observed from this figure that the monitored profiles of axial force (which are proportional to the measured axial strain) show a visible waviness which is a characteristic of distributed field measurements and this is within the error expected from this type of instruments. However, as shown here, this wavy profile does not have a major impact on the predicted displacements, as integration of strains leads to a smoother profile of displacements.




.(a) (b)




(c)

**Figure 4.** Comparison of field data and finite element analysis: (a) top load-displacement curve, (b) profiles of axial pile force and (c) profiles of vertical pile displacement.

The verification exercise presented proved that the back-analysis approach presented earlier was able to reproduce to observed field behaviour reasonably well. This therefore means that the proposed approach can be applied to define the actual behaviour of such an axially loaded pile. It is also argued that this approach can be in the future a standard method to post-process distributed fibre optic data and provide the relevant load-transfer curves for piles. If such an approach is followed for every pile load test in the future, the engineering community will be able to build a database of load-transfer curves that can be used in general pile design.

## 5. Conclusions

This paper proposes an approach to develop numerical models using distributed fibre optic data. In particular, it concentrates on defining load-transfer curves for axially-loaded foundation piles using Brillouin Optical Time-Domain Reflectometry/Analysis (BOTDR/A). It initially presents the methodology to be followed and then an application is presented from a recent pile load test in London, where a pile was heavily instrumented with distributed fibre optic sensing. It is shown that spatially-continuous strain data from BOTDR/A can indeed provide valuable information that can directly be used to define computational models. It is envisaged that in the future big data in structural health monitoring can be used for developing computational models.

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