

Application of conventional and fibre optical sensor technology on bored piles in Dubai (U.A.E.)

Thomas Wolff¹, Karl Josef Witt², Aidroos Hassan³

1 Abstract

An accurate prediction of the load-settlement behaviour of deep foundations is essential in the design phases for exposed structures with regard to the serviceability of the total structure, especially under extreme boundary conditions.

Within the scope of a high-rise building project in the United Arab Emirates readings and measurements were carried out from the Bauhaus University in Weimar in cooperation with the Middle East Foundation Group L.L.C. These measurements were taken on bored piles for the purpose of researching the load bearing behaviour and the deformation behaviour of foundation piles under the special subsoil conditions in Dubai. Two different measurement methods were used to survey the relevant parameters for the load bearing and the deformation behaviour. Results from interferometrical measurements of strain were compared with the measurements determined with the conventional vibrating wire strain gages. With the recursive determined input parameters for the design of the pile foundations, it is one of the goals of the research, to inspect and verify the design assumptions and to optimise the calculation. The present report gives an overview of the deployed sensors with regards to the fields of application and the handling under extreme field conditions as well as an exemplary comparison of the design parameters recalculated from the measurements.

¹ scientific Ass., department of geotechnical engineering, Faculty of Civil Engineering, Bauhaus University Weimar

² Prof. Dr.-Ing., professorship Geotechnical Engineering, Faculty of Civil Engineering, Bauhaus University Weimar

³ Managing Director, Middle East Foundations Group L.L.C., Dubai, V.A.E.

2 Introduction

From the cultivation of dates to an international trade centre, Dubai is mentioned in one breath with Singapore and Hong Kong at present. The structural engineering as an indicator of development and economical growth is booming in the emirates not only since the last few years and set architects and civil engineers in a mood of gold diggers.

Buildings with heights between 70 and 250 m rank among the usual residential and business buildings of the expanding Emirate and represent for there understanding no special challenge of construction (Figure 2.1). Only for remarkable constructional and geotechnical structures, detailed subsoil investigations and experimental measurements are presently made. For the design and execution of deep foundations, generally one relies on experiments from different international standards. Considering that and motivated by the question of the local special foundation engineering company about the real bearing behaviour of deep foundation under the specific subsoil conditions large scaled test piles were carried out within the scope of a high rise project. The test results are used to analyse the specific subsoil conditions and the load settlement behaviour of cast in place bored piles.

As a sub goal of the work two physically different measurement methods were comparatively tested to determine the mobilised pile resistance. Statements regarding the magnitude of the single pile resistances and the distribution of the mobilised skin friction can be given if the axial load gradient of the pile is known. As the development of the axial load of the pile is not directly measurable, it is determined reflexive, with knowledge of geometry and material properties of the pile, from its longitudinal deformation. There are various common methods for sectionwise, discrete or continuous measurement of the changes in length. Below, only one test should be exemplary described, were vibrating wire strain gages (VW) as conventional measuring technique and phase modulated fibre optical sensors (SOFO standard sensor) based on the principle of interferometry as an innovative measuring technique were used to measure the concrete strain of the test pile during loading.



Figure 2.1: Skyline, Trade centre of Dubai

3 Test description

3.1 Fabrication of the pile

The pile with a diameter of $D = 75$ cm and a length of $L = 11.18$ m was installed at the place of an earlier soil investigation exploration drilling. Thereby the pile penetrates the upper sand layer and was bond 5.56 m in the calcareous, weak sandstone. The hole was drilled Bentonit supported under use of a drilling bucket. Using a three arm caliper the shape of the drilled hole was measured by an average diameter over the depth (see). With the tremie method the pile was poured in place with concrete class C 100 ($f_{ck} = 100$ N/mm²) and reinforced with reinforcement steel „grad 50“(tensile strength: $f_{u,k} = 460$ N/mm²). The nominal dimension of the concrete cover was defined with $c_{nom} = 5$ cm. The bore hole was not cleaned before concreting. Hence, it can not be excluded, that a deposit of loose material or drill cuttings were placed under the pile base.

To inspect the integrity of the pile after concrete hardening, the low-strain and ultra sonic method were used. No indications of discontinuities could be found from the results. The loading facility (kentledge) was realised after the recommendations of DGGT AK 2.1 (1998) and ASTM D1143 (1994) by using steel beams and concrete blocks as dead weight as depict in Figure 3.1.



Figure 3.1: Kentledge (concrete blocks as dead load) of the single pile, $D = 75$ cm

3.2 Monitoring systems

An extensive monitoring program, consist of vibrating wire strain gauges, fibre optical sensors and the appropriate data acquisition equipment was developed in order to get measurements from both methods simultaneously. The measuring techniques installed on the reinforcement cage are displayed in Figure 3.2a. Four (4) measuring cross sections were installed to acquire the axial strain, change of length and the horizontal agent stresses of the pile shaft, whereas the horizontal stresses were measured selectively only on three (3) measuring points. Figure 3.2b shows the arrangement of the sensors over the cross section. The fibre optical sensors divided the pile accordingly their length into five (5) imaginary cells (Figure 3.2a). The length of the sensors is equal to their measuring basis and lied in between 1.30 m and 2.60 m. Hence, that in comparison to the vibrating wire strain gauges with a measuring basis of 15 cm the strains have not been measured selectively, but integral over the single pile cells.

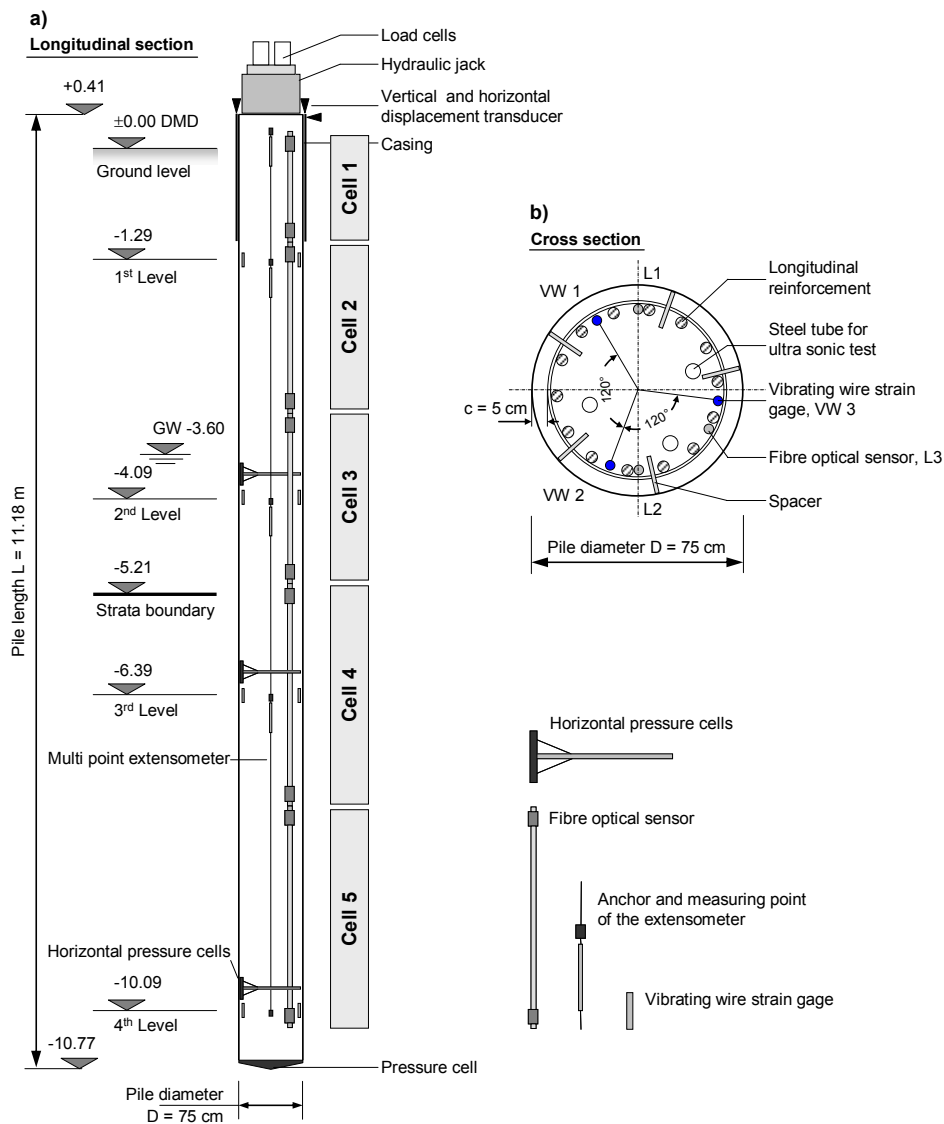


Figure 3.2: Schematic of Test 1 „single pile“

The arrangement of the fibre optical sensors is shown in more detail at Figure 3.3. In order to detect possible load eccentricity at the pile head respectively at the pile base, three instead of two standard deformation sensors were used. Both sensors types were installed as near as possible to each other as depict in Figure 3.2b to get a good comparison in the measured deformation. For Cell 3 and 4 the VW strain gauges were set in the middle (half length) of the fibre optical sensors (Figure 3.2a). To complete the monitoring systems the sensors were connected with the appropriate data acquisition systems. The VW strain gauges were merge with a data logger system whereas all fibre optical sensors were connected to a SOFO 12 channel reading unit (Figure 3.4) consist of optical source, mobile mirror, photo detector and related electronics. Each sensor system was linked to separate computer.

Figure 3.5 depict exemplary the applied measuring technique to the rebar cage at the pile base range. Beside the pressure cell on the pile base and the two (2) different types of sensors the variable distance between the sensors and the pile base can be recognised.

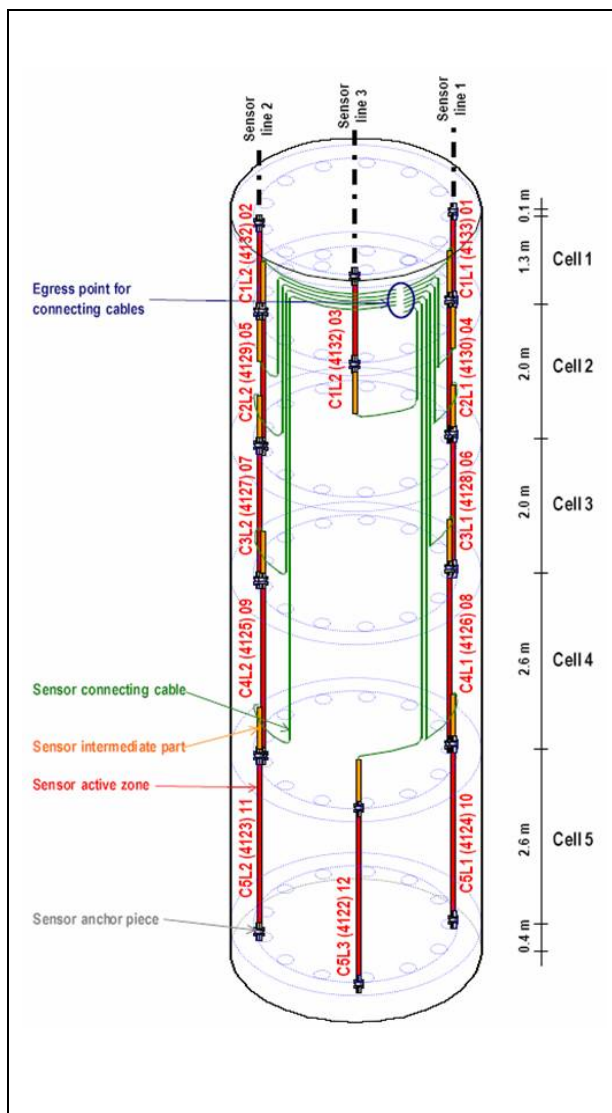


Figure 3.3: Detailed arrangement of the fibre optical Sensors

According to the ASTM D1143 (1994) and DGGT AK 2.1 (1998) three (3) vertical and two (2) horizontal displacement transducer were installed at the pile head to measure the total displacements of the entire pile. A load pressure cell was additionally installed at the pile base in order to register the mobilised base resistance and to get good reproducibility of the development and transfer of the pile axial load.



Figure 3.4: SOFO reading unit

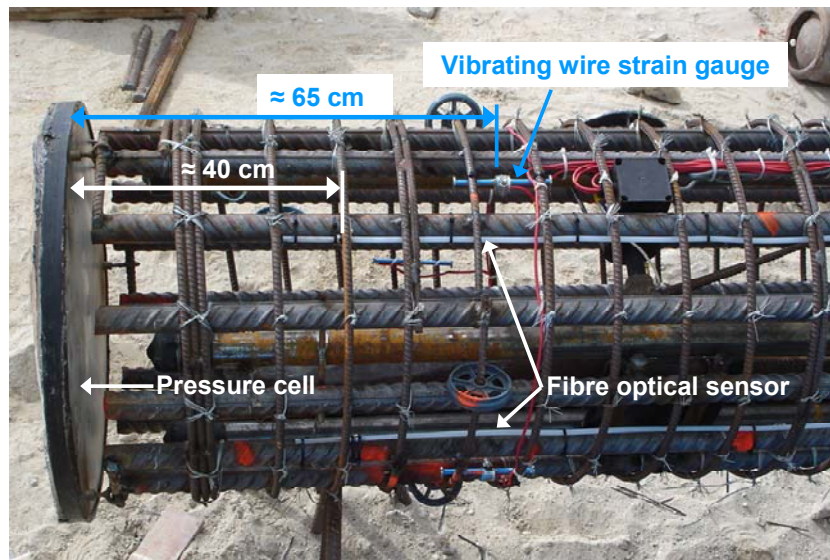


Figure 3.5: Bottom range of the rebar cage with different sensor types (D = 75 cm)

3.3 Principles of the used measuring technique

Vibrating wire strain gauges

For the discrete registration of the strain, electronic strain gauges are recommended e.g. vibrating wire strain gauges, which are connected directly to the pile reinforcement or applied on separate measurement bars. The change in frequency of a prestressed, inductive energised wire is a function of the deformation and exposure the change in strain of the concrete. Figure 3.6 depicts exemplarily a used strain gage based on the principles of a vibrating wire and the arrangement at the pile section. For a reliable registration of the axial changes in length by strain gauges, it is necessary to embed the gauges totally in the pile material and to install them at locations which are representative for the strain behaviour. The system of these vibrating wire strain gauges is relatively insensitive against environmental and mechanical influences. Depending on the aim of measuring, the resolution and the measuring ranges can lie at $< 1.0 \mu\text{m/m}$ and between 300 and 3000 $\mu\text{m/m}$ respectively.

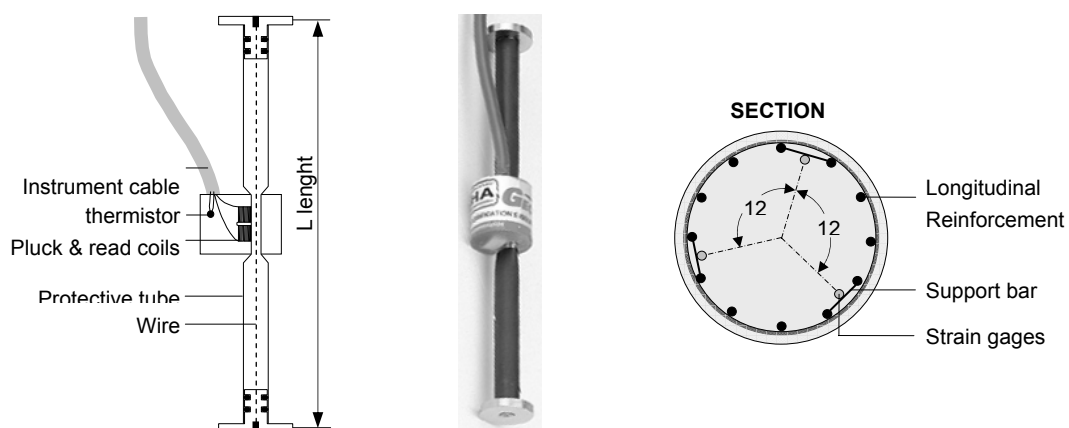


Figure 3.6: Vibrating wire strain gauges and the arrangement at the cross section

Fibre optical sensors

With the use of the SOFO Sensors for the deformation measurement of piles, these sensors divide the pile into individual elements, the so-called cells. Several sensors can be applied in one cell, depending on the aim of measurement (strain or curvature). The sensors will be connected to the reinforcement by anchor points and consist of two optical fibres called the measuring fibre and the reference fibre (Figure 3.7b). The measuring fibre is coupled with the host material and follows the deformation of the structure. The reference fibre is in the same protection tube, but, compared to the measuring fibre, loose and therefore independent. A mirror, placed at the end of each fibre reflects the slight (signal) back to the coupler, which connects both light waves and returns them back to the reading unit. The intensity of the both overlaid partial waves, as a function of the difference in way, gives exposure to the change in length of each cell. The sensors with length between 0.25 m and 10 m can be installed quickly, fulfil high environmental and instrumentation requirements, with measuring ranges of 1 % for tensile strain, 0.5 % for compressive strains and a resolution of $<2/1000$ mm.

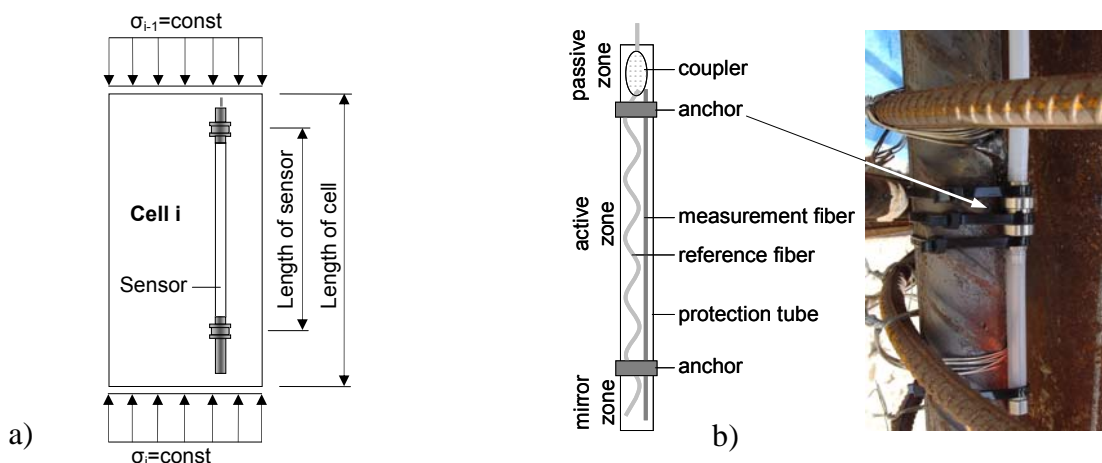


Figure 3.7: Application of SOFO Sensors

3.4 Execution of the test

Corresponding to the test program, the pile was loaded (load controlled) with four (4) load cycles 1.50 MN, 4.50 MN, 9.0 MN and failure. After the recommendations given by FELLENIUS (1980) the single load increments were maintained constant for half an hour in each case. Therewith, the demands to maintain each load increment until the rate of settlement is not greater than 0.1 mm/5 min, DGGT AK 2.1 (1998), respectively 0.25 mm/hour, ASTM D1143 (1994), were fulfilled. The measurements were recorded by the described data logger systems in intervals of 1 for the VW gauges and 2 minutes for the fibre optical sensors. The measurements were online supervised and partial evaluated. Figure 3.8 shows exemplary some result from the online analysis of the SOFO fibre optical sensors at the site.

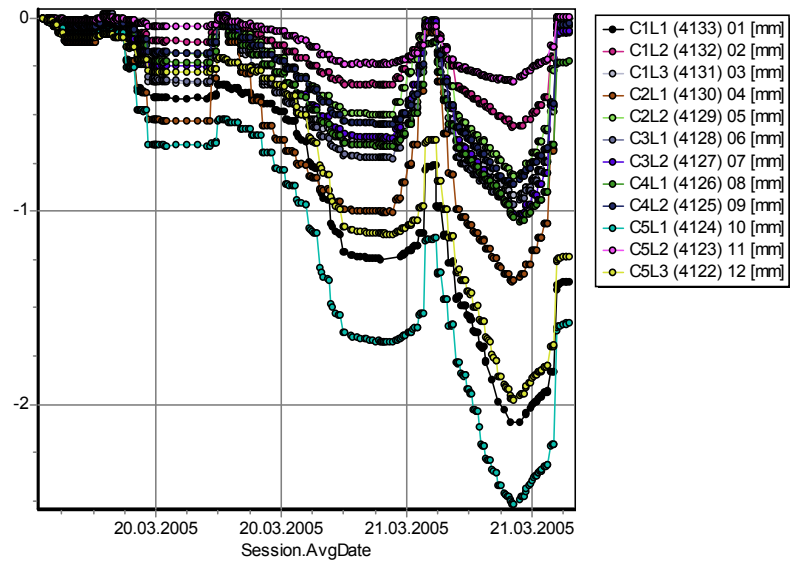


Figure 3.8: Example of online analysis of SOFO fibre optical sensors.

The single load steps and load cycles as well as the position of the sensors along the pile shaft respective the detected change in section (cell) length can be clearly recognised.

The reference system was monitored against possible deformation by using an independent levelling with regard to different benchmarks. At a load of 13.5 MN and a pile head settlement of 140 mm the maximum travel of the hydraulic jack was reached and the test had to be terminated.

4 Evaluation and analysis of the measurements

The full presentation and discussion of the different measured parameter largely exceeds the scope of this paper, therefore only some selected results are presented.

In contrast to the direct load measurement with load cells, the quantity and the progression of the normal axial pile load can only be calculated indirectly from the measured axial strain of the pile concrete. Under the assumption of linear elastic material behaviour, the validity of the hypothesis by Bernoulli and total bonding between the concrete and the longitudinal reinforcement, the normal axial pile load F_i on point i can be calculated by equation (4.1).

$$(4.1) \quad F_i = (A_{S,i} \cdot E_{S,i} + A_{C,i} \cdot E_{C,i}) \cdot \varepsilon_{z,i}$$

In order to eliminate the bending part of the state of strain, the average values of the measured strain per cross section were used for the recalculated axial load. Strains measured with different methods versus depth and the recalculated axial forces are exemplified for the load steps 4.50 MN and 9.0 MN in Figure 4.1.

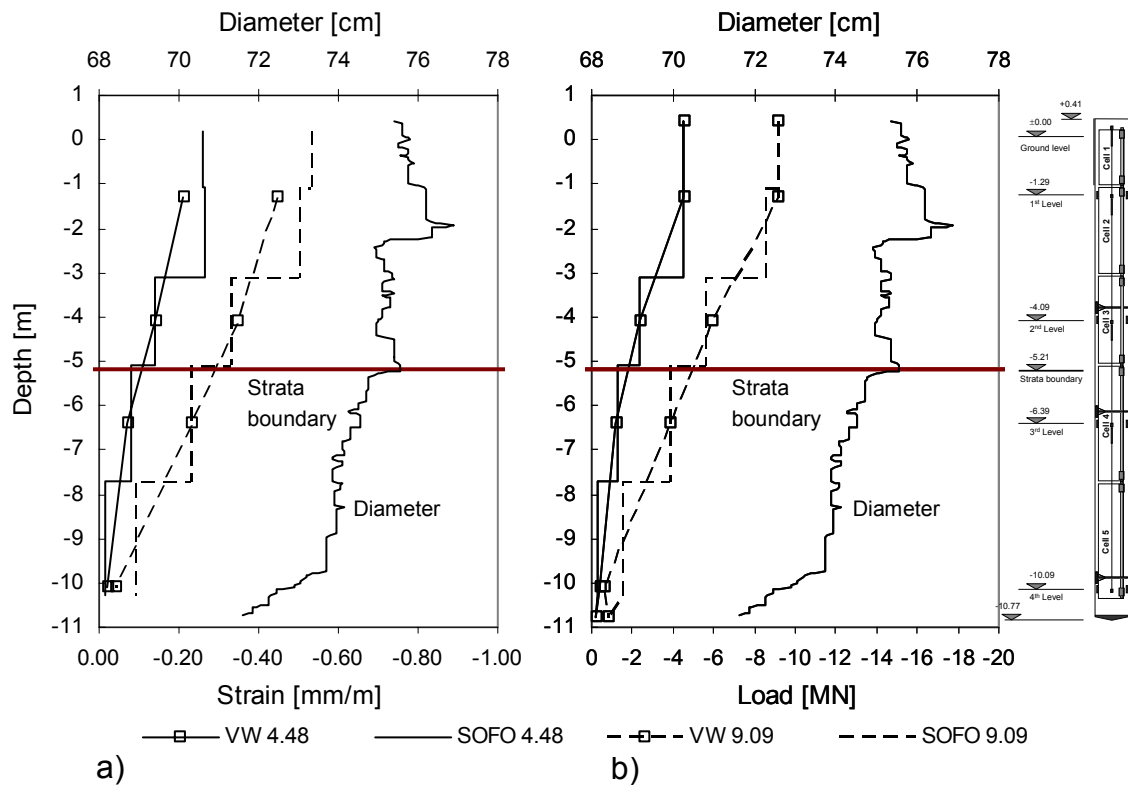


Figure 4.1: a) measured strains, b) recalculated axial force

An excellent conformance can be recognised in the range of the pile cells 3 and 4, where the VW gauges were installed in the middle of the fibre optical sensors. The differences at the top and the base range of the pile are the results of varying in application as well as development of the pile diameter over depth.

The measurement uncertainty of the strain measured with the VW strain gauges results to ± 0.015 mm/m, while the strain, measured with the optical sensors, 2/1000 of the respective measured value result as measurement uncertainty. Despite a larger measuring basis, the precision of the fibre optical sensors is higher compared with those of the vibrating wire strain gages. Under the assumption of linear elastic material behaviour of the concrete, this effect is propagated also for the axial pile force.

5 Comparison of measuring technique

One of the most important factors to be considered in any embedded sensor is the interfacial bonding between the fibre and the surrounding host. Similar to the vibrating wire strain gages (Figure 3.6) the bonding of the fibre optical sensors was realised with anchor points, which were fixed on the longitudinal reinforcement bars (Figure 3.7). The two optical mono mode fibres as well as coupler element are protected by a small tube ($d = 8 \text{ mm}$) against mechanical effects.

Regarding the application of the fibre optical sensors, it would be a mistake due to the comparatively robust construction of the VW strain gauges to assume a smaller expenditure of time for the installation. In the direct comparison of the different measuring methods, rather an advantage in time is to be seen with the fibre optical sensors during careful experimental design (prefabricated sensors) and handling.

For the comparison of the measurement values of both sensor types, the measured strain values are plotted with respect to the loads, as shown in Figure 5.1. Where the vibrating wire strain gages were installed in the middle of the fibre optical sensors (-4.09 m - Cell 3 and -6.39 m Cell 4), the maximum deviation results only between 2 to 10 %. In the ranges where the VW strain gauges were arranged respectively at the end or at the beginning of an optical sensor, the differences arise with 25 % to 40 %. This large difference results from the different measuring basis and measuring length as already described above.

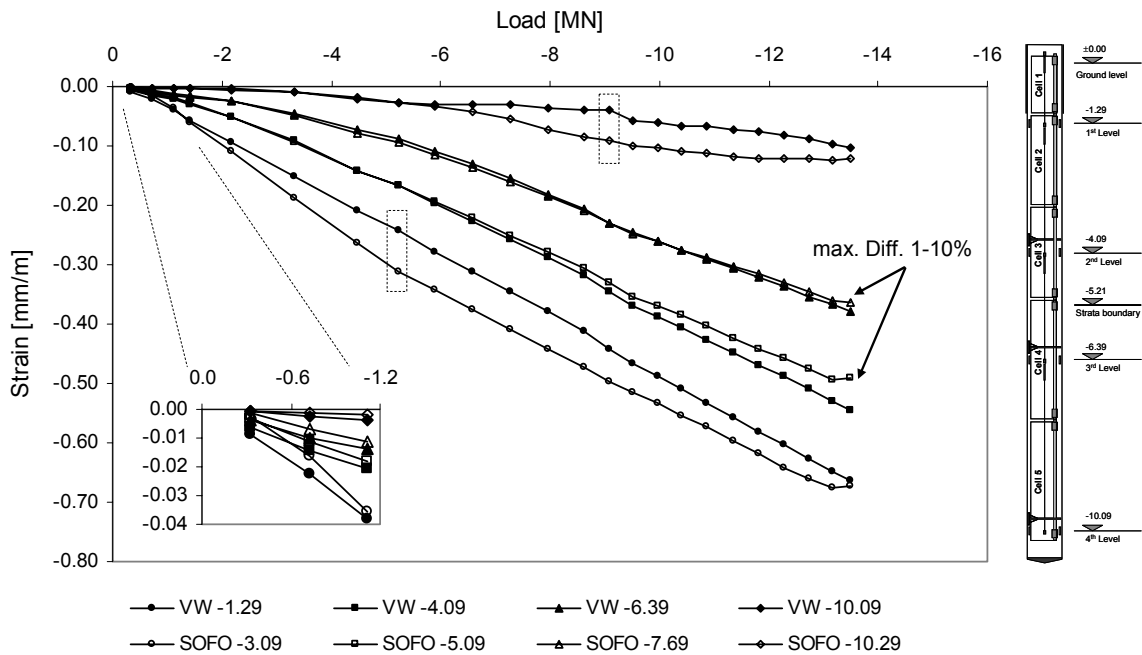


Figure 5.1: Comparison of strain values

Especially for small loadings this influence can be recognised. With small loadings and increasing pile depth the integral development of the elastical strains of the concrete will diminish relatively fast. According to the arrangement, the VW strain gauges will detect almost punctual values, e.g. maximum strain, whereas the fibre optical sensors measure an average value over their length because of the integral measurement method. The measurement results of the VW strain gauges provide therefore useful punctual strains, whereas large or extreme strains are measured more smeared due to the integral measurement over great length.

6 Conclusion

One of the most substantial aims of the strain measurement are statements about the development of the axial force during loading. These can be calculated from the measured strains on the already specified assumption. The distribution of the axial loads agrees very well for both measurement systems. The maximum differences change according to the load and lie between 2 and 5 %. With the measured values of the vibrating wire strain gages usually larger values for the axial forces were calculated than with those of the optical sensors.

In summary, it can be stated that the vibrating wire strain gages simulate a higher accuracy because of the almost punctual strain measurement than the integral measurement of the optical sensors. As far as the measuring basis demands, thus with large strains, integral measurements are even more accurate, as local discontinuities will be compensated. An assumption for a realistic interpretation of the results is a quasi linear development of the strains, with the relative large segmentation here.

The two measuring systems are comparable regarding to their precision and stability. A crucial advantage resulted for the fibre optical sensors with regards to building monitoring (long – term monitoring), due to the absolute measurements and the insensitivity in relation to temperature influences (LIENHART (2005)). With this measurement system a zero off set can not occur during discontinuous measurements, whereas for vibrating wire strain gages discontinuous measurement would lead to a reference loss. Advantages and disadvantages of the installed SOFO Sensors are summarised in Table 6.1.

Table 6.1: Advantages and disadvantages of the used fibre optical sensors

Advantage	Comment
Immunity in relation to electromagnetic fields	Application in the surrounding filed of high voltage and nuclear power
High intrinsic safety, as no electricity at the sensor	Application in lightning and highly combustible environments
Resistant against extreme environmental influences	Chemically aggressive environment, extreme Temp.
Small in dimension and weight	No backflash to the object of measurement, good integrable in the different materials
Large distances between measuring points and evaluation unit are possible	Good adjustment to the local conditions, extensive and expanded monitoring, creation of sensor net.
Disadvantage	Comment
Complex signal conversion	complex evaluation
Ambiguity of the measurement signals	
Smaller robustness in relation to the site conditions	Careful handling with the installation, technical personnel necessarily

References

- ASTM D1143 (1994), „Standard Test Method for Piles under Static Axial Compressive Load“
- CASANOVA, N. (1998), “Verformungsmessungen mit optischen Glasfasersensoren”, *Messen in der Geotechnik '98*, Mitteilung des Instituts für Grundbau und Bodenmechanik TU Braunschweig Heft 55, ISBN 3-927 610-45-3, Seite 387-399
- DGGT AK 2.1 (1998), “Empfehlungen für statische und dynamische Pfahlgründungen“, DGGT Arbeitskreis 2.1 (1998), ISBN: 3-927 610-48-8
- FECKER, E. (1997), „Geotechnische Messgeräte und Feldversuche im Fels“, Ferdinand Enke Verlag Stuttgart, ISBN: 3-432-29911-7
- FELLENIUS, B.H. (1980), “The analysis of results from routine pile load tests”, *Ground engineer*, London, Vol.13, No 6, pp.19-13
- GLISIC, B., INAUDI, D., NAN, C. (2002), “Piles monitoring during the axial compression, pullout and flexure test using fiber optic sensors”, *81st Annual Meetgin of the Transportation Research Board (TRB)*, www.smartec.ch
- HABEL, W.R. (2004), „Faseroptische Messverfahren für die Überwachung von Bauwerken – überblickt der potenzielle Anwender die Vielfalt der Angebote?“, In *Interdisziplinäre Messaufgaben im Bauwesen – Weimar 2004*, Schriftenreihe des DVW, Band 4, Seiten 57 – 76

- KATZENBACH, R., MOORMANN, CH. (2003), „Instrumentation and Monitoring of combined piled rafts (CPRF): State-of-The-Art report, FMFM-Symposium, Sept. 200, Oslo
- LIENHART, W. (2005), „Experimental Investigation of the Performance of the SOFO Measurement System”, *Proc. 5th International Workshop on Structural Health Monitoring*, Stanford, USA, pp. 1131-1138
- MEYERHOF, G.G. (1976 a), „Bearing capacity and settlement of pile foundation”, *Journal Geot. Eng. Div. ASCE*, GT 3, p.197-228
- PELLS, P.J.N., TURNER, R.M. (1980), „Endbearing on rock with particular reference of sandstone” *Proc. International conf. on Structural Foundation on Rock*, Sydney, Australia, pp. 181-190
- POULOS, H.G., (1989), “Pile behaviour – theory and application”, *Géotechnique* 39, No. 3, 365-415
- POULOS, H.G., DAVIDS, A.J. (2005), “Foundation design for the Emirates Twin Towers, Dubai”, *Canadian Geotechnical Journal*, 42, 716-730
- ROSENBERG, P, JOURNEAUX, N.L. (1976), „Friction and end bearing tests on bedrock for high capacity socket design“, *Canadian Geotechnical Journal*, 13, 324-333
- SCHALLERT, M., KREBBER, K., HOFMANN, D., HABEL, W.R., STAHLMANN, J. (2004), „Auswahl geeigneter Fasersensorprinzipien für Anwendungen in der Geotechnik“, *Messen in der Geotechnik 2004*. Braunschweig: Mitteilung des Institutes für Grundbau und Bodenmechanik TU Braunschweig Heft 77, Seiten 309 – 328.
- SCHWARZ, W. (1995), „Vermessungsverfahren im Maschinen- und Anlagenbau“, Wittwer Verlag Stuttgart, ISBN: 3-87919-183-2
- TOMLINSON, M. J. (2001), „Pile Design and Construction Practice“, Fourth edition, TJ International Ltd., Padstow, Cornwall, ISBN: 0130-31180-4
- TOMLINSON, M. J. (2004), „Foundation Design and Construction“, Seventh edition, Spon Press, London and New York, ISBN: 0-419-18450-3
- TOUMA, F.T., REESE, L.C. (1974), „Behaviour of bored piles in Sand“, *Journal Geot. Eng. Div. ASCE* (100), GT 7, p.749-761
- VESIC, A.S. (1977), „Design of pile foundations”, NCHRP Synthesis 42 Transportation Research Board, Washington, D.C., ISBN: 0-309-02544-3
- WILLIAMS, A.F., PELLIS, P.J.N. (1981), “Side resistance rock socket in sandstone, mudstone and shale”, *Canadian Geotechnical Journal*, 18, pp.502-513
- WITT, K.J., BLINDE, A. (1980), “Tragfähigkeit von Zugpfählen und Zugankern”, BMFT-Forschungsbericht, Informationszentrum Raum + Bau, Stuttgart

WOLFF, TH., WITT, K.J., HASSAN, A. (2005), „Anwendung konventioneller und faseroptischer Sensorik am Beispiel eines Pfahltests in Dubai“, 3. Symposium „Experimentelle Untersuchung von Baukonstruktionen“ Dresden

WYLLIE, D.C. (1999), „Foundation on rock“, 2nd edition, E & FN Spon, ISBN: 0-419-232109-9