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# DISTRIBUTED FIBER OPTIC MONITORING OF A HIGH-RISE BUILDING PILE-RAFT FOUNDATION: COMMISSIONING CONTROL AND BASELINE ASSESSMENT

# БИІК ҒИМАРАТ ІРГЕТАСЫНЫҢ ТАРАТЫЛҒАН ТАЛШЫҚТЫ-ОПТИКАЛЫҚ МОНИТОРИНГІ: ІСКЕ ҚОСУДЫ БАҚЫЛАУ ЖӘНЕ БАСТАПҚЫ ПАРАМЕТРЛЕРДІ БАҒАЛАУ

# РАСПРЕДЕЛЕННЫЙ ВОЛОКОННО-ОПТИЧЕСКИЙ МОНИТОРИНГ ФУНДАМЕНТА ВЫСОТНОГО ЗДАНИЯ: КОНТРОЛЬ ВВОДА В ЭКСПЛУАТАЦИЮ И ОЦЕНКА ИСХОДНЫХ ПАРАМЕТРОВ

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**Keywords:**
fiber optic sensing, BOTDA, pile-raft foundation, baseline monitoring, commissioning control, high-rise building, structural diagnostics.

**ABSTRACT**

The structural monitoring of high-rise building foundations requires measurement systems that can register spatially distributed deformation and temperature effects during construction and at the early stage of service. This paper presents a field case study of a distributed fiber optic sensing (DFOS) system installed in the raft foundation of a high-rise building complex. The study is focused not on general crack detection, but on the practical commissioning of the sensing line, interpretation of initial measurements, and preparation of a reference dataset for subsequent long-term observation.

The monitoring object is the raft foundation beneath Block R of Abu Dhabi Plaza in Astana, Kazakhstan. Measurements were obtained along the same horizontal sensing route using Brillouin Optical Time Domain Analysis (BOTDA). Two commissioning stages were compared in order to evaluate the repeatability of the installed system and to separate temporary construction-stage influences from the stable response of the foundation slab.

The analysis showed that signal variability during the first measurement stage was mainly associated with ongoing construction operations, including concrete casting and related thermal-mechanical disturbances. In the second stage, after the completion of active works on the monitored section, the measured strain and temperature responses became significantly more stable.

The proposed approach demonstrates how DFOS data can be converted from raw distributed measurements into a practical monitoring basis for reinforced concrete substructures. The results are relevant for commissioning control, baseline formation, diagnostic comparison of future measurements.

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**Түйінді сөздер:**
Талшықты-оптикалық мониторинг, BOTDA, плиталық іргетас, базалық мониторинг, іске қосу-баптау бақылауы, биік ғимарат, құрылымдық диагностика.

**ТҮЙІНДЕМЕ**

Биік ғимараттар іргетастарының құрылымдық мониторингі пайдалану кезеңінің бастапқы сатысында кеңістікте таралған деформациялық және температуралық әсерлерді тіркей алатын өлшеу жүйелерін қажет етеді. Бұл мақалада биік ғимараттар кешенінің плиталық іргетасына орнатылған таратылған талшықты-оптикалық датчиктер жүйесінің далалық зерттеу нәтижелері ұсынылады. Зерттеудің негізгі бағыты жалпы жарықшақтарды анықтау мәселесіне емес, өлшеу желісін тәжірибелік іске қосуға, бастапқы өлшемдерді түсіндіруге және кейінгі ұзақ мерзімді бақылау үшін эталондық деректер жиынтығын қалыптастыруға бағытталған.

Мониторинг нысаны ретінде Қазақстан Республикасы, Астана қаласындағы Abu Dhabi Plaza кешенінің R блогы астындағы плиталық іргетас қарастырылды. Өлшемдер бірдей көлденең сезімталдық бағыты бойынша Бриллюэндік оптикалық уақыттық домендік талдау әдісімен (BOTDA) алынды. Орнатылған жүйенің қайталанғыштығын бағалау және құрылыс кезеңіндегі уақытша әсерлерді іргетас плитасының тұрақты жауап беру сипатынан ажырату мақсатында іске қосу кезеңіндегі екі өлшеу сатысы салыстырылды.

Талдау нәтижелері бірінші өлшеу сатысындағы сигнал өзгергіштігі негізінен құрылыс жұмыстарының жалғасуымен, оның ішінде бетон құю және соған байланысты жылу-механикалық әсерлермен байланысты екенін көрсетті. Екінші сатыда, бақыланатын аймақта белсенді жұмыстар аяқталғаннан кейін, өлшенген деформациялық және температуралық жауаптар едәуір тұрақты сипат алды.

Ұсынылған тәсіл таратылған талшықты-оптикалық өлшемдердің бастапқы деректерін темірбетонды жерасты құрылымдарын практикалық мониторингтеу негізіне қалай түрлендіруге болатынын көрсетеді. Алынған нәтижелер іске қосу бақылауы, бастапқы деңгей қалыптастыру, болашақ өлшемдерді диагностикалық салыстыру үшін өзекті болып табылады.

**Ключевые слова:**
Волоконно-оптический мониторинг, BOTDA, плитный фундамент, базовый мониторинг, пусконаладочный контроль, высотное здание, структурная диагностика.

**АННОТАЦИЯ**

Структурный мониторинг фундаментов высотных зданий требует применения измерительных систем, способных регистрировать пространственно распределённые деформационные и температурные воздействия уже на ранней стадии эксплуатации. В данной статье представлен полевой пример применения системы распределённого волоконно-оптического мониторинга (DFOS), установленной в плитном фундаменте комплекса высотных зданий. Исследование сосредоточено не на общем выявлении трещин, а на практическом вводе измерительной линии в эксплуатацию, интерпретации первичных измерений и формировании опорного набора данных для последующего долгосрочного наблюдения.

Объектом мониторинга является плитный фундамент под блоком R комплекса Abu Dhabi Plaza в городе Астана, Казахстан. Измерения были получены вдоль одного и того же горизонтального измерительного маршрута с использованием метода бриллюэновского оптического анализа во временной области (BOTDA). Для оценки повторяемости установленной системы и отделения временных воздействий строительного этапа от устойчивой реакции фундаментной плиты были сопоставлены два этапа пусконаладочных измерений.

Анализ показал, что изменчивость сигнала на первом этапе измерений в основном была связана с продолжающимися строительными

работами, включая бетонирование и сопутствующие термомеханические возмущения. На втором этапе, после завершения активных работ на контролируемом участке, измеренные деформационные и температурные отклики стали значительно более стабильными. Предложенный подход демонстрирует, каким образом данные DFOS могут быть преобразованы из исходных распределённых измерений в практическую основу мониторинга железобетонных подземных конструкций. Полученные результаты актуальны для пусконаладочного контроля, формирования базового уровня, диагностического сравнения будущих измерений.

**INTRODUCTION**

The construction of high-rise buildings in dense urban areas is associated with increased requirements for the reliability, serviceability, and long-term safety of foundation systems. In such structures, the foundation is not only a load-transfer element, but also a critical structural component that controls the interaction between the building, the pile system, the raft slab, and the surrounding soil mass. For high-rise buildings constructed under complex geotechnical conditions, including heterogeneous soil layers, groundwater influence, and water-saturated deposits, the stress-strain state of the foundation may develop unevenly during construction and early operation. Therefore, the use of monitoring systems capable of registering deformation changes directly within the foundation becomes an important engineering task.

Pile-raft foundations are widely used for high-rise buildings because they allow the vertical loads from the superstructure to be transferred jointly through the raft and piles. However, the structural response of such systems is difficult to evaluate only by conventional inspection methods. The distribution of stresses and strains in the raft may be affected by the stiffness contrast of soil layers, pile arrangement, construction sequence, concrete casting stages, temperature changes, and the gradual increase of load from the building. These factors can cause local variations in deformation that are not always visible on the surface and may remain undetected by discrete measuring instruments. As a result, the development of a spatially distributed monitoring approach is particularly relevant for pile-raft foundations of high-rise buildings (Katzenbach, et al. 2015; Katzenbach, et al. 2022).

Traditional geodetic and point-based monitoring methods, such as settlement marks, inclinometers, strain gauges, or local temperature sensors, provide valuable information about the behavior of the structure. Nevertheless, these methods usually register data only at selected points. For large reinforced concrete foundation slabs, this may be insufficient, because the deformation field can vary along the foundation area and along the structural zones located near columns, walls, pile heads, and expansion joints. In this context, distributed fiber optic sensing (DFOS) offers an important advantage, as it enables continuous measurements along the installed sensing cable and provides information about strain and temperature changes over an extended monitoring route (Bado, et al., 2021; Glišić, et al., 2007).

Among DFOS technologies, Brillouin Optical Time Domain Analysis (BOTDA) is widely applied for structural health monitoring because it allows distributed measurement of strain and temperature along optical fibers. When a sensing cable is embedded in or attached to a reinforced concrete structure, BOTDA measurements can be used to identify spatial changes in the structural response. For foundation monitoring, this capability is especially valuable because the method can support the detection of zones with increased deformation, comparison of repeated measurements, and formation of a baseline dataset for long-term structural diagnostics. However, the practical application of DFOS in foundation systems requires careful interpretation of the initial measurements, since the commissioning stage may be affected by construction activities, thermal fluctuations, concrete curing, and

temporary mechanical disturbances (Nordin, et al., 2020; Kishida, et al., 2005; Merklein, et al., 2022).

For this reason, the commissioning stage of a DFOS monitoring system should not be considered only as a technical check of the cable and measuring equipment. It is also an important stage for evaluating the quality of the installed sensing line, identifying unstable measurement conditions, and defining the initial reference state of the monitored structure. In high-rise construction, the baseline condition should preferably be established after the completion of active works in the monitored section, when the measured strain and temperature responses become more stable. Such a baseline can later be used for diagnostic comparison with future monitoring data during the service life of the building.

This paper presents a field case study of a distributed fiber optic monitoring system installed in the raft foundation of a high-rise building complex. The monitored object is the raft foundation beneath Block R of Abu Dhabi Plaza in Astana, Kazakhstan. The building is supported by a pile-raft foundation constructed under complex geotechnical conditions typical for high-rise development in the region. The study focuses on the practical use of BOTDA-based DFOS measurements for commissioning control, interpretation of initial strain and temperature data, and formation of an engineering baseline for further long-term monitoring.

The main objective of the study is to demonstrate the applicability of distributed fiber optic sensing for monitoring the early behavior of a pile-raft foundation in a high-rise building. Special attention is given to the comparison of two commissioning measurement stages performed along the same horizontal sensing route. This comparison makes it possible to distinguish temporary construction-stage disturbances from a more stable foundation response and to justify the use of the second measurement stage as a reference condition for future structural diagnostics.

The scientific contribution of this study lies in a commissioning-based methodology for selecting an engineering baseline for DFOS monitoring of a high-rise pile-raft foundation. The novelty is not the development of a new BOTDA technique, but the field demonstration that the first available measurement should not automatically be adopted as the reference state. Instead, the baseline is selected after stabilization of distributed strain- and temperature-related responses and reduction of construction-stage disturbances. Unlike many previous DFOS studies focused on bridges, tunnels, laboratory concrete specimens, or general sensing performance, the present work concentrates on commissioning control of a large reinforced concrete raft foundation and links the selection of the reference condition to the construction and geotechnical context. This provides a reproducible engineering logic for subsequent diagnostic comparison during long-term monitoring.

The aim of this study is to develop and demonstrate a commissioning-based approach for DFOS monitoring of a high-rise building raft foundation. The specific objectives are: to describe the field installation conditions of the sensing system; to compare two commissioning measurement stages along the same cable route; to identify the main sources of early signal variability; and to define the measurement state that can be used as a baseline for future structural health monitoring.

## MATERIALS AND METHODS

### Monitored object and foundation system.

The monitored object is the raft foundation beneath Block R of the Abu Dhabi Plaza high-rise building complex located in Astana, Kazakhstan. Block R is a high-rise residential tower, where the foundation system is subjected to significant vertical loads transferred from the superstructure to the underground structural system and soil mass.

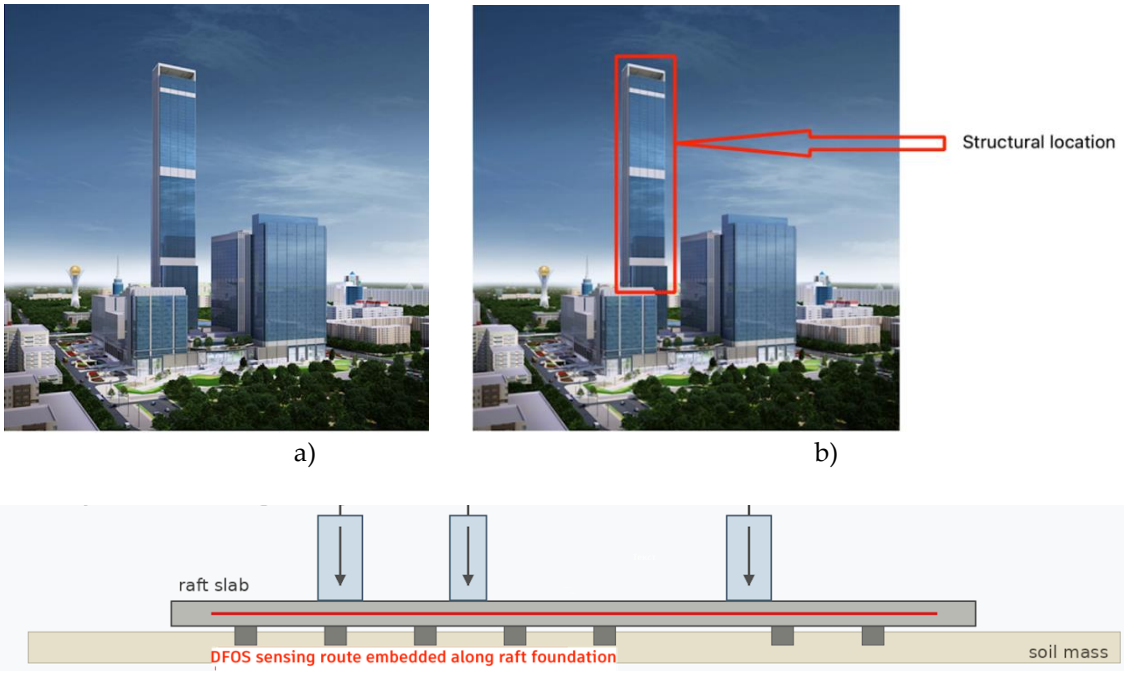



**Figure 1.** General view and structural location of Block R in the Abu Dhabi Plaza high-rise building complex: a) general view; b) structural location; c) simplified monitoring concept at foundation level

*Note – compiled by the authors based on project visualization materials*

The foundation of the monitored block is designed as a pile-raft system. In this type of foundation, the raft slab and piles work together to transfer loads to the underlying soil layers.

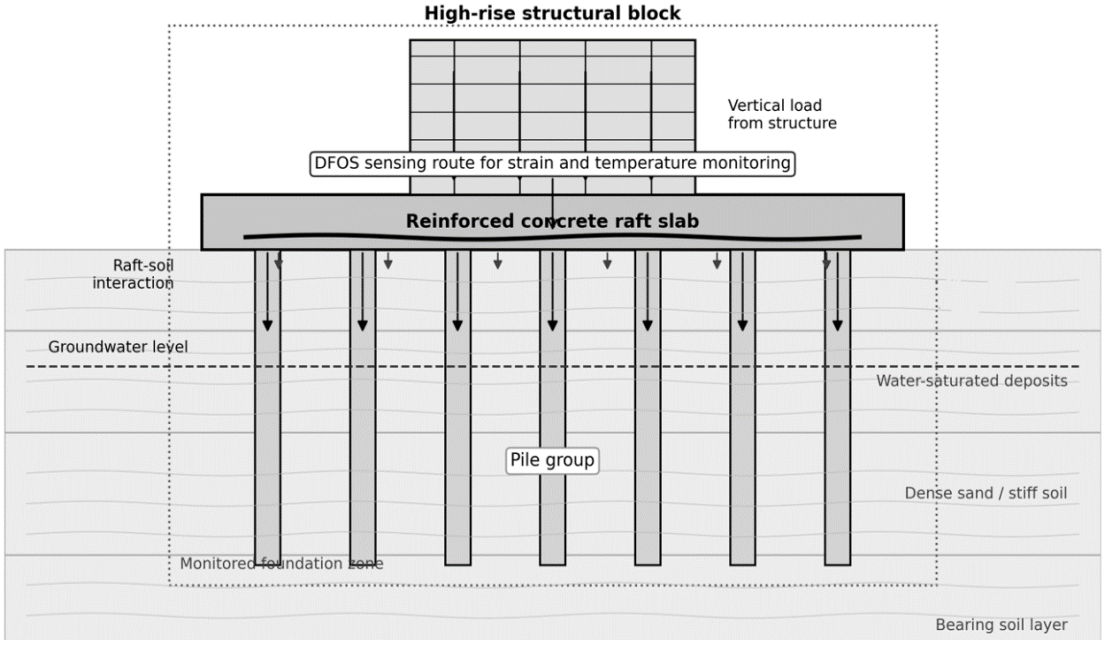



**Figure 2.** Conceptual scheme of the pile-raft foundation system and load transfer mechanism

*Note – adapted by the authors based on engineering-geological survey materials*

The raft distributes the loads from columns and reinforced concrete walls, while the piles reduce settlements and provide additional load-bearing capacity. Such foundation systems are commonly used for high-rise buildings constructed under complex geotechnical conditions, where the interaction between the structure, raft, piles, and soil can lead to non-uniform deformation patterns.

The monitored foundation zone is located at the basement level of the building. The sensing route was arranged along the raft foundation slab in the horizontal direction. The selected monitoring line passed through structurally important zones where deformation changes were expected to be relevant for long-term observation. These zones included areas near load-bearing reinforced concrete walls, columns, pile heads, and other foundation regions influenced by load transfer from the superstructure.

The purpose of selecting this object was not to evaluate the bearing capacity of the foundation, but to investigate the practical application of distributed fiber optic sensing for monitoring the early strain and temperature response of a large reinforced concrete raft foundation.

**Distributed fiber optic sensing system**

A distributed fiber optic sensing system was installed to monitor strain and temperature changes along the raft foundation. The system was based on Brillouin Optical Time Domain Analysis, commonly referred to as BOTDA. This method allows distributed measurements along an optical fiber by analysing the Brillouin frequency shift, which is sensitive to strain and temperature variations (Nordin, et al., 2020; Kishida, et al., 2005).

The main advantage of BOTDA for foundation monitoring is that the optical fiber acts as a continuous sensing element. Unlike point sensors, which provide data only at selected locations, the distributed optical fiber can register changes along the entire sensing route. This is particularly important for large reinforced concrete foundation slabs, where deformation may not be uniform and local changes can occur near columns, walls, pile heads, or construction joints (Bado, et al., 2021; Glišić, et al., 2007; Inaudi, et al., 2005).

The monitoring system included two functional sensing lines:

1. a strain-sensitive fiber optic cable intended to register deformation changes in the foundation slab;
2. a temperature-sensitive fiber optic cable used to evaluate thermal effects and support interpretation of strain measurements.

The combination of strain and temperature information is important because Brillouin-based measurements are affected by both mechanical deformation and temperature variation. Therefore, temperature data were used to distinguish thermal effects from deformation-related changes where possible.

The fiber optic sensing cable was installed along the horizontal monitoring route within the raft foundation zone. The route was selected to provide coverage of structurally significant areas of the foundation slab. Special attention was given to the continuity of the sensing line, protection of the cable during construction, and reduction of potential damage during concrete works.

During installation, the cable route was arranged to avoid excessive bending, sharp turns, and direct interference with reinforcement placement. The minimum bending radius of the cable was maintained according to the technical requirements of the sensing system. In zones where the cable exited the concrete or passed through construction areas, protective measures were used to reduce the risk of mechanical damage.

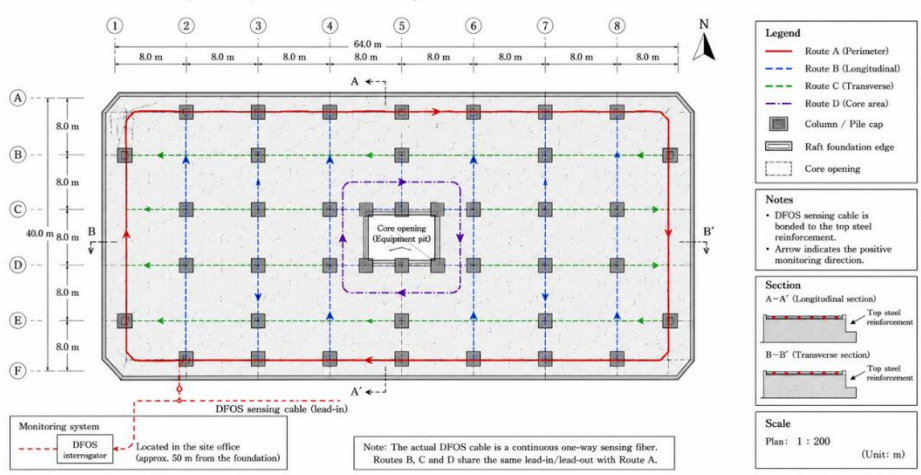



**Figure 3.** Layout of the DFOS sensing route in the raft foundation slab
*Note – compiled by the authors*

The installation approach was aimed at ensuring stable mechanical contact between the sensing cable and the reinforced concrete foundation. This condition is essential for the correct transfer of strain from the structure to the optical fiber. At the same time, the cable had to remain protected during concreting, reinforcement works, and other construction operations (Buranbayeva, 2025).

The installed sensing line was later used for repeated commissioning measurements. Since the same horizontal route was measured at different stages, the obtained data allowed point-by-point comparison of strain and temperature responses along the foundation.

**BOTDA measurement procedure**

The measurements were performed using BOTDA technology along the installed fiber optic route. The method provides distributed information on Brillouin frequency shift, which can be converted into strain- and temperature-related responses. The measurement data were recorded as functions of distance along the sensing cable (Nordin, et al., 2020; Garus, et al., 1996). Both commissioning stages used the same installed route and the same measurement principle, enabling direct spatial comparison of the resulting profiles. The available commissioning documentation used for this study did not provide a sufficiently complete and independently verifiable set of instrument acquisition settings (including spatial resolution, sampling interval, and gauge length); therefore, values not supported by the source documentation are not introduced here. The analysis consequently focuses on repeatability and relative spatial variability under the documented field conditions.

Two commissioning measurement stages were analysed in this study. Both stages were performed along the same horizontal sensing route, which made it possible to compare the measurement results directly.

The first commissioning stage was carried out during active construction works in the monitored foundation zone. At this stage, concrete casting and other construction operations were still influencing the measured section. Therefore, the obtained signal contained not only the response of the foundation slab, but also temporary disturbances related to construction activity, thermal effects, and mechanical interaction during works.

The second commissioning stage was performed after the completion of active works in the monitored section. By this time, the construction-related disturbances had decreased, and the strain and temperature responses became more stable. This stage was considered more suitable for defining an engineering baseline for future monitoring.

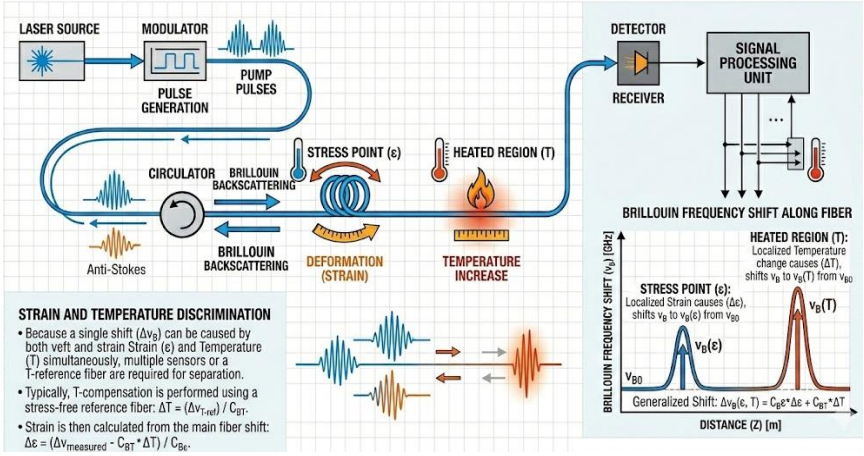



**Figure 4.** Principle of BOTDA-based distributed strain and temperature measurement
*Note – adapted by the authors based on engineering-geological survey materials.*

The comparison of the two stages was used to evaluate:
- repeatability of the installed sensing line;
- stability of distributed strain and temperature measurements;
- influence of construction-stage disturbances;
- suitability of the second measurement stage for baseline formation.

**Data processing and interpretation**

The BOTDA measurement results were processed as distributed profiles along the sensing route using a consistent workflow. First, the recorded profiles were referenced to the distance coordinate along the fiber optic cable. Second, strain-sensitive and temperature-sensitive responses were considered separately along the same route. Third, spatial variability and local deviations were examined for each commissioning stage. Fourth, the two stages were compared under their documented construction conditions. Finally, the more stable measurement state was evaluated against explicit baseline-selection criteria and retained as the engineering reference condition for subsequent monitoring. This workflow allowed zones of higher variability and zones of more stable behaviour to be identified without introducing unsupported corrections to the original field data.

The interpretation was based on direct comparison between the two commissioning stages. The first stage was treated as a construction-influenced measurement condition, whereas the second stage was interpreted as a candidate reference condition after active works had been completed. Temperature-sensitive measurements were used for temperature-informed interpretation of the strain-related response and to identify sections where temporary thermal effects could plausibly contribute to signal variability. A separate mathematical temperature-compensation procedure was not applied in the present analysis; therefore, the manuscript does not interpret the temperature line as a fully compensated mechanical-strain solution.

The following parameters were considered during data analysis:
- spatial distribution of strain-related response along the sensing cable;
- spatial distribution of temperature-related response;
- variability of the measured signal during construction activity;
- stability of repeated measurements after completion of active works;
- suitability of the obtained profiles for future diagnostic comparison.

The baseline was defined not as an absolutely undeformed state of the foundation, but as a practical engineering reference state obtained after stabilization of construction-stage

influences. The baseline-selection criteria adopted in this study were: reduced local signal variability; a lower and more uniform standard-deviation profile; stabilization of the temperature-related response; completion of active construction operations in the monitored section; and improved consistency of repeated distributed measurements along the same route. On this basis, the second commissioning stage was selected as the engineering baseline for future diagnostic comparison (Katzenbach, et al., 2015; Abdel-Azim, et al., 2020).

**Monitoring logic adopted in the study**

The methodology of the study was based on the principle that the commissioning stage of a DFOS system is a key part of structural monitoring. It is not limited to checking the operability of the optical cable and measurement equipment. It also provides information about the early behaviour of the monitored structure and helps to establish a reference dataset for future diagnostics.

The adopted monitoring logic included the following steps:

1. selection of a structurally important monitoring route within the raft foundation;
2. installation and protection of the fiber optic sensing cable;
3. performance of commissioning measurements along the same route;
4. comparison of measurement stages under different construction conditions;
5. identification of the more stable response state;
6. formation of a baseline profile for future long-term monitoring;
7. preparation of the data for possible integration into BIM-based or digital twin monitoring workflows.

This methodology allows the raw distributed measurements to be transformed into a practical monitoring basis for reinforced concrete substructures. The proposed approach is especially relevant for high-rise buildings where the foundation response may develop gradually and non-uniformly during construction and early operation.

## RESULTS AND DISCUSSION

**General behavior of the monitored foundation during commissioning**

The results of the field measurements confirmed that the commissioning stage of a distributed fiber optic sensing system provides important information not only about the operability of the sensing cable, but also about the early response of the monitored foundation. In the present study, two commissioning measurement stages were compared along the same horizontal sensing route installed in the raft foundation of Block R. This approach made it possible to evaluate the stability of the installed DFOS line and to distinguish temporary construction-related disturbances from a more stable foundation response.

The first measurement stage was performed during active construction works in the monitored zone. At this stage, the measured signal was influenced by several temporary factors, including concrete casting, movement of construction equipment, thermal effects related to fresh concrete, and mechanical interaction with reinforcement and construction operations. As a result, the distributed response along the sensing cable showed higher variability. This variability should not be interpreted directly as a permanent deformation pattern of the foundation slab, because the measurement conditions were still unstable.

The second measurement stage was carried out after the completion of active works in the monitored section. Compared with the first stage, the distributed strain and temperature profiles became more stable. The reduction in signal variability indicates that the construction-stage disturbances decreased and that the measured response became more representative of the initial condition of the foundation slab. Therefore, the second measurement stage can be considered more suitable for baseline formation and future diagnostic comparison.

These results show that commissioning measurements should be treated as a separate and important part of the monitoring process. If the first available measurement is automatically accepted as a baseline, the reference dataset may include temporary disturbances caused by construction activities. For this reason, several repeated measurements under different construction conditions are necessary before defining a reliable baseline for long-term monitoring.

**Interpretation of strain-related response**

The distributed strain-related response obtained from the BOTDA measurements reflected the spatial behavior of the monitored raft foundation along the installed sensing route. Since the fiber optic cable was installed horizontally within the foundation zone, the measured profile provided information about deformation changes along an extended part of the reinforced concrete slab rather than at isolated points.

During the first commissioning stage, the strain-related profile showed a less stable pattern. Local variations were observed along the sensing route, which can be associated with construction-stage influences rather than with the permanent structural behavior of the foundation. In particular, ongoing concrete works and temporary thermal-mechanical effects could produce short-term changes in the strain signal. Such variations are typical for early-stage monitoring of reinforced concrete structures, where the measured response is affected by both structural and construction-related factors.

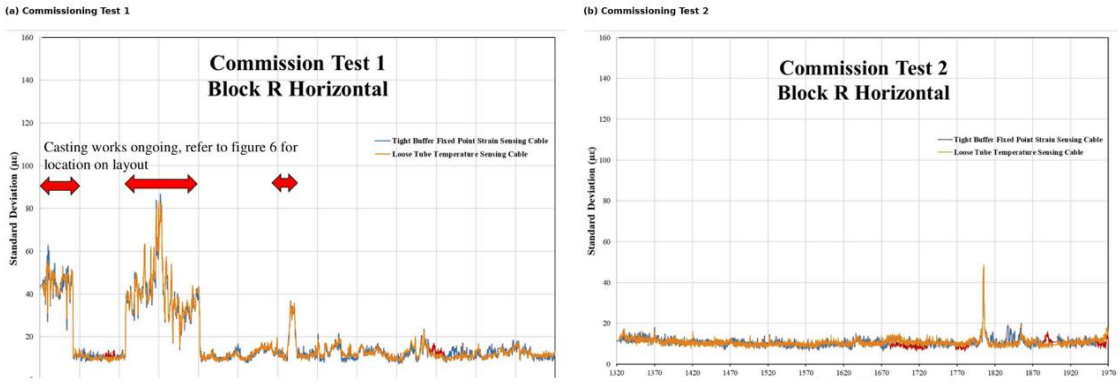



**Figure 5.** Comparison of distributed standard deviation profiles obtained during the first and second commissioning tests along the Block R horizontal sensing route

*Note – compiled by authors based on the Commissioning test report*

As shown in Figure 5, the first commissioning test was characterized by higher local peaks and greater variability along the sensing route. In contrast, the second test demonstrated a lower and more uniform standard deviation profile. This confirms that the second measurement stage was less affected by temporary construction-related disturbances and is more suitable for baseline formation. The comparison is interpreted using the relative spatial pattern and variability visible in the source commissioning profiles; unsupported numerical reductions are not inferred where the underlying report does not provide validated summary statistics.

In the second commissioning stage, the strain-related response became more consistent along the route. The decrease in irregular signal variations suggests that the sensing line had reached a more stable measurement condition. This does not mean that the foundation was completely free from deformation; rather, it indicates that the measured strain profile can be used as a practical engineering reference state. In monitoring practice, such a reference state is necessary for identifying future changes in the foundation behavior.

The comparison of the two stages demonstrates that the interpretation of DFOS strain data should always consider the construction context. Distributed strain measurements are sensitive to local effects, and this sensitivity is an advantage when monitoring large foundation slabs. However, without proper commissioning analysis, temporary effects may be incorrectly interpreted as structural anomalies. Therefore, the baseline should be selected only after the measurement profiles show sufficient stability.

**Interpretation of temperature-related response**

Temperature effects are especially important in Brillouin-based distributed sensing because the Brillouin frequency shift depends on both strain and temperature. For this reason, temperature-related measurements were considered together with strain-related data during the analysis of the commissioning stages.

At the first stage, the temperature-related response was affected by active construction processes. Concrete casting, hydration heat, ambient conditions at the basement level, and local construction-related thermal disturbances contributed to the non-uniform temperature response observed along the sensing route.

Figure 6 shows that the temperature-related response also became more stable during the second commissioning stage. This confirms that part of the variability observed during the first stage was associated with temporary thermal effects rather than only mechanical deformation of the foundation slab.

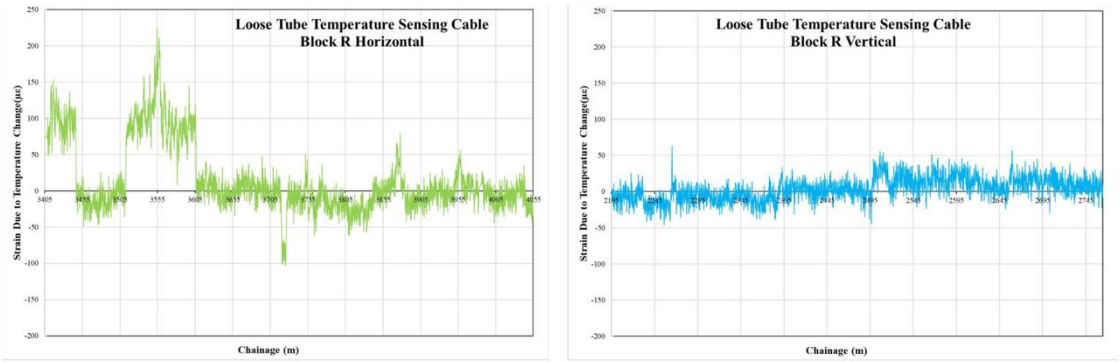



**Figure 6.** Comparison of distributed standard deviation profiles for strain and temperature sensing cables during commissioning tests

*Note – compiled by the authors based on the Commissioning Test Report*

At the second stage, the temperature distribution became more stable. This stabilization is important for the reliability of baseline monitoring because a stable thermal state reduces uncertainty in the interpretation of strain-related changes. In the present study, the temperature-sensitive line was used for temperature-informed interpretation rather than for a separate mathematical compensation of strain. This distinction avoids overestimating mechanically induced deformation when part of the observed response may be thermal.

The obtained results confirm that temperature monitoring should not be treated as an auxiliary task only. In DFOS-based foundation monitoring, temperature data are required for correct interpretation of the structural response. They help to distinguish between thermal disturbances and deformation-related changes and improve the diagnostic value of the monitoring system.

**Baseline formation for long-term monitoring**

One of the main outcomes of the commissioning measurements was the identification of a suitable baseline condition for future monitoring. In this study, the baseline was not defined as

the theoretical initial state of the foundation before loading. Instead, it was defined as a practical engineering reference state obtained after the reduction of construction-stage disturbances.

This approach is more appropriate for real construction projects, where the installation of monitoring systems often takes place during ongoing works. In such conditions, the first measurement may be affected by temporary factors and may not represent a stable condition of the structure. Therefore, baseline formation should be based on repeated measurements and comparison of their stability.

The second commissioning stage showed a more stable strain and temperature response and can therefore be used as the initial reference dataset for subsequent inspections. The proposed diagnostic workflow is: future distributed measurement → comparison with the Stage 2 baseline → evaluation of changes in strain- and temperature-related profiles (Δresponse) → identification of spatial anomalies → trend analysis over repeated campaigns → engineering assessment in conjunction with geotechnical and construction information. This procedure is intended to support the detection of strain redistribution, unusual thermal behaviour, and persistent deviations from the established reference condition during operation of the building.

**Diagnostic significance of DFOS monitoring for pile-raft foundations**

The results demonstrate that DFOS monitoring is especially useful for pile-raft foundations of high-rise buildings because such systems may develop complex and non-uniform deformation patterns. The raft foundation interacts with piles, soil layers, reinforced concrete walls, columns, and other structural elements. As a result, deformation changes may occur locally and may not be detected by conventional point-based monitoring methods.

The distributed nature of the fiber optic system provides a significant advantage in this context. Instead of measuring deformation only at selected points, DFOS allows the response to be recorded continuously along the sensing route. This makes it possible to identify spatial variations and compare different zones of the foundation slab. For large reinforced concrete foundations, this capability is essential for early-stage diagnostics.

The use of BOTDA measurements also provides an opportunity to monitor both strain and temperature effects. This is particularly relevant for basement and foundation structures, where temperature conditions may vary due to concrete curing, seasonal changes, ventilation, contact with soil, and thermal properties of reinforced concrete elements. The combined interpretation of strain and temperature data increases the reliability of structural diagnostics.

From a practical engineering point of view, the monitoring system can be used for:

- checking the operability and continuity of the sensing line after installation;
- evaluating the influence of construction activities on measured data;
- forming a baseline profile for long-term monitoring;
- comparing future measurements with the reference condition;
- identifying zones with increased deformation or unusual thermal behavior;
- supporting decision-making during maintenance and structural assessment.

Thus, the DFOS system should be considered not only as a measurement tool, but also as part of a broader structural diagnostic framework.

The obtained findings are consistent with previous studies showing that distributed optical fiber sensing provides a significant advantage over point-based instrumentation because it enables continuous strain and temperature measurement along extended structural elements. Similar conclusions were reported in review studies on DFOS applications in structural and civil engineering, where the ability to detect spatially distributed changes was identified as one of the main benefits of fiber optic monitoring systems (Bado, et al., 2021; Glišić, et al., 2007; Weisbrich, 2023). However, unlike many studies focused on bridges, tunnels, or laboratory concrete

specimens, the present work emphasizes the commissioning stage of a high-rise building foundation and the formation of a baseline dataset for future diagnostics.

**Influence of geotechnical and construction conditions on monitoring interpretation**

The monitored foundation was constructed under complex geotechnical conditions, including heterogeneous soil layers and groundwater influence. These conditions are important for understanding why distributed monitoring is required for such structures. However, the results of the present study show that during the commissioning stage, construction-related factors may have a stronger immediate effect on the measured signal than long-term geotechnical behavior.

This is especially visible in the comparison between the first and second measurement stages. The higher variability observed during the first stage was mainly related to active construction processes rather than to stable foundation deformation. After the completion of active works, the measured profiles became more stable. This confirms that the interpretation of early DFOS measurements must include both geotechnical and construction context.

For pile-raft foundations, geotechnical conditions may influence long-term settlement, load redistribution between the raft and piles, and local deformation patterns in the slab. Therefore, future monitoring results should be interpreted together with available information about the soil profile, groundwater conditions, pile layout, structural load transfer, and construction history. The baseline formed during commissioning provides the starting point for such interpretation.

In this sense, the role of geotechnical information in the article is not to replace monitoring data, but to support their interpretation. The combination of DFOS measurements and engineering-geological context allows a more reliable assessment of the foundation behavior during long-term operation.

Previous studies on combined pile-raft foundations confirm that the behavior of such systems is governed by soil-structure interaction, load redistribution between raft and piles, and settlement control. In this context, the present study complements geotechnical investigations by introducing a distributed monitoring layer that can be used to observe the early structural response of the raft foundation during commissioning and subsequent operation (Katzenbach, et al., 2015; Leppla, et al., 2025;).

**Limitations of the study**

Although the obtained results demonstrate the practical applicability of DFOS monitoring for raft foundation commissioning and baseline formation, several limitations should be noted. First, the analysis was based on two commissioning measurement stages. A larger number of repeated measurements would allow a more detailed evaluation of measurement repeatability and long-term stability.

Second, the study focused on one horizontal sensing route within the foundation slab. Although this route covered structurally significant zones, a more extensive monitoring network could provide a more complete understanding of the spatial behavior of the entire raft foundation.

Third, the interpretation of Brillouin-based measurements is influenced by the combined effects of strain and temperature. In the present work, the temperature-sensitive line supported temperature-informed interpretation, but a separate mathematical temperature-compensation procedure was not applied. In addition, independent reference measurements and a complete set of independently verifiable BOTDA acquisition parameters were not available within the source documentation used for this analysis. Future studies should therefore include detailed temperature compensation, instrument calibration and uncertainty assessment, and correlation with independent geodetic or point-sensor measurements where possible.

Finally, the present study focused on commissioning and baseline formation rather than long-term operational monitoring. Further observations during the service life of the building are required to evaluate the long-term diagnostic performance of the installed DFOS system.

**Summary of discussion**

The results of the study confirm that distributed fiber optic sensing can provide valuable information during the commissioning stage of foundation monitoring systems. The comparison of two measurement stages showed that the first stage was affected by temporary construction-related disturbances, while the second stage provided a more stable strain and temperature response. Therefore, the second stage can be used as an engineering baseline for future monitoring.

The study also shows that baseline formation is a critical step in DFOS-based structural diagnostics. The methodological principle demonstrated here is that the first available commissioning measurement should not automatically be accepted as the baseline; the reference condition should be selected only after distributed strain- and temperature-related responses have stabilized and construction-stage disturbances have decreased. Without such a reliable baseline, future changes in foundation behavior may be difficult to interpret correctly. The proposed monitoring logic transforms raw distributed measurements into a practical diagnostic framework for reinforced concrete pile-raft foundations of high-rise buildings.

Overall, the results support the use of BOTDA-based DFOS systems for commissioning control, baseline assessment, and long-term structural monitoring of high-rise building foundations constructed under complex geotechnical conditions.

**CONCLUSION**

This study presented a field case of distributed fiber optic monitoring applied to the pile-raft foundation of a high-rise building constructed under complex geotechnical conditions. The main focus of the research was not the general detection of cracks, but the practical use of BOTDA-based DFOS measurements for commissioning control, interpretation of initial strain and temperature responses, and formation of an engineering baseline for future long-term monitoring.

The results showed that the commissioning stage plays a critical role in the reliability of a DFOS monitoring system. The first measurement stage was influenced by active construction operations, including concrete casting and related thermal-mechanical disturbances. Therefore, the obtained signal demonstrated higher variability and could not be directly used as a stable reference condition. In contrast, the second measurement stage, performed after the completion of active works in the monitored section, showed a more stable strain and temperature response. This stage can be considered suitable for baseline formation and future diagnostic comparison.

The study confirmed that distributed fiber optic sensing provides important advantages for monitoring large reinforced concrete foundation slabs. Unlike point-based sensors, DFOS allows the registration of strain and temperature changes along an extended sensing route. This makes it possible to identify spatial variations in the foundation response and to compare future measurements with the initial stable condition. For pile-raft foundations of high-rise buildings, where deformation may develop non-uniformly due to soil-structure interaction, load redistribution, groundwater influence, and construction sequence, such distributed information is especially valuable.

The obtained results also demonstrate the importance of combined interpretation of strain and temperature data. Since Brillouin-based measurements are sensitive to both mechanical deformation and temperature effects, temperature monitoring should be considered an essential part of the diagnostic process. The comparison of the two commissioning stages showed that

thermal and construction-related influences can significantly affect the initial measurement profiles. Therefore, baseline assessment should be performed only after stabilization of the monitored section.

The proposed commissioning-based monitoring approach transforms raw distributed measurements into a practical engineering dataset for further structural diagnostics. Its principal methodological contribution is the selection of the baseline after stabilization of the monitored section rather than automatic use of the first available measurement. The stable Stage 2 profile can subsequently serve as a reference for repeated comparison, identification of spatial anomalies, trend analysis, and engineering assessment of the long-term behavior of the foundation. The approach therefore provides a practical link between DFOS commissioning control and long-term structural diagnostics of high-rise pile-raft foundations.

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**REFERENCES**

Abdel-Azim, O. A., El-Sherbiny, R. M., & El-Mossallamy, Y. M. (2020). Numerical investigation of optimized piled raft foundation for high-rise buildings. *Innovative Infrastructure Solutions, 5*, 1–13. https://doi.org/10.1007/s41062-019-0258-4

Bado, M. F., & Casas, J. R. (2021). A review of recent distributed optical fiber sensors applications for civil engineering structural health monitoring. *Sensors, 21*(5), 1818. https://doi.org/10.3390/s21051818

Buranbayeva, A. M., Zhumadilov, I. T., Tee, B. P., et al. (2025). Performance evaluation of fixed-point DFOS cables for structural monitoring of reinforced concrete elements. *Infrastructures, 10*(12), 349. https://doi.org/10.3390/infrastructures10120349

Garus, D., Krebber, K., Schliep, F., & Gogolla, T. (1996). Distributed sensing technique based on Brillouin optical-fiber frequency-domain analysis. *Optics Letters, 21*(17), 1402–1404. https://doi.org/10.1364/OL.21.001402

Glišić, B., & Inaudi, D. (2007). *Fibre optic methods for structural health monitoring*. John Wiley & Sons. https://doi.org/10.1002/9780470517819

Inaudi, D., & Glisic, B. (2005). Application of distributed fiber optic sensory for SHM. In *Proceedings of the International Conference on Structural Health Monitoring and Intelligent Infrastructure*. https://smartec.ch/wp-content/uploads/2017/03/c130.pdf

Katzenbach, R. (2022). Reducing carbon emissions by combined pile-raft foundations. In *Sustainable construction and building materials*. IntechOpen. https://doi.org/10.5772/intechopen.102819

Katzenbach, R., & Choudhury, D. (2013). *Combined pile-raft foundation guideline*. ISSMGE Technical Committee.

Katzenbach, R., Leppla, S., & Ramm, H. (2015). Realistic modelling of soil-structure interaction for high-rise buildings. *Procedia Engineering, 120*, 136–139. https://doi.org/10.1016/j.proeng.2015.08.597

Kishida, K., Li, C. H., & Nishiguchi, K. (2005). Pulse pre-pump method for cm-order spatial resolution of BOTDA. *Proceedings of SPIE, 5855*, 559–562. https://doi.org/10.1117/12.624259

Leppla, S., Katzenbach, R., & Piro, A. (2025). Design and numerical analysis of a combined pile-raft foundation for a high-rise in a sensitive urban environment. *Buildings, 15*(16), 2933. https://doi.org/10.3390/buildings15162933

Merklein, M., Vu, K., Madden, S. J., & Eggleton, B. J. (2022). 100 years of Brillouin scattering: Historical and future perspectives. *APL Photonics, 7*(8), 080901. https://doi.org/10.1063/5.0095871

Nordin, N. D., Zan, M. S. D., & Abdullah, F. (2020). Comparative analysis on the deployment of machine learning algorithms in the distributed Brillouin optical time domain analysis (BOTDA) fiber sensor. *Photonics, 7*(4), 79. https://doi.org/10.3390/photonics7040079

Wang, S., Wu, T., & Yi, T. H. (2024). Distributed fiber optic sensing for internal strain monitoring of concrete structures. *Engineering Structures, 314*, 118329. https://doi.org/10.1016/j.engstruct.2024.118329

Weisbrich, M., Holschemacher, K., & Bier, T. A. (2023). The challenges and advantages of distributed fiber optic strain measurement in reinforced concrete structures. *Sensors, 23*(24), 9791. https://doi.org/10.3390/s23249791

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