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# Numerical analysis and geomonitoring of behaviour of foundation of Abu-Dhabi Plaza in Nur-Sultan

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**Abstract.** In similarity to every civilization in history originated from the riverside, the city of Nur-Sultan, which the new capital of Kazakhstan developed around the Ishim River. During the last 25 years, many high-rise buildings supported by pile foundations are rising in Nur-Sultan. The paper presents the monitoring of development for the unique residential building of 310 m high with 4-story underground parking. The pile raft foundation (for block R) analyses had designed using Geotechnical soft, which can assess in precise of the deformations, occurs in soil. In the paper presents, method monitoring raft foundations for block R, the height of this block R is 320 meters. Design of distributed fibre optic strain sensing system (DFOSS) has been employed for measuring the strain in civil engineering structures for over a decade. It is now harnessed worldwide for monitoring a wide range of structures slab pile foundation. Geotechnical monitoring data of adjacent building and utility systems settlement caused by the construction of presented high-rise buildings were compared to numerical modelling results, predicted, and permissible values.

Finally, the raft foundation recommended for future high-rise buildings constructed of Nur-Sultan city on complex soils.

## 1. Introduction

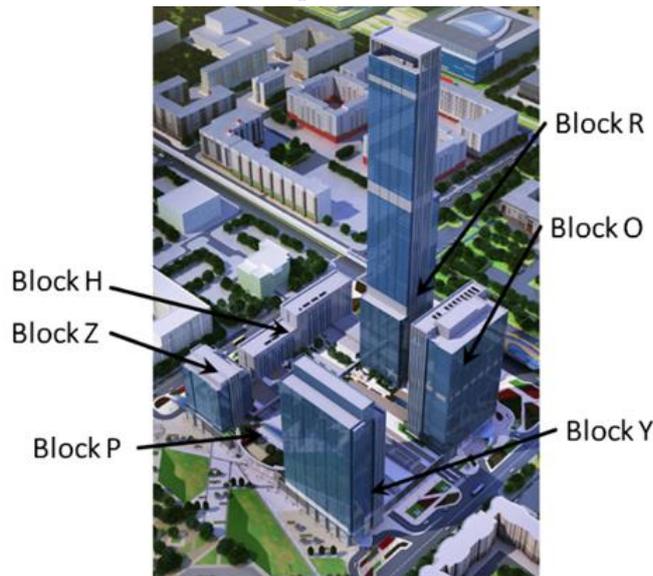
High-rise buildings (buildings with a height of more than 75 m) pose new challenges for engineers, especially in the field of calculations and design of above-ground structures, bases and foundations. Therefore, designers of both above-ground and underground parts of the building are forced to resort to more complex methods of calculation and design. Especially this applies to geotechnicians, who are involved in the design of foundations for high-rise buildings. By complexity, problematic design, erection, operation, impact on the environment and people, high-rises can be attributed to the structures of increased danger and complexity [1-4].

Project ADP (Abu-Dhabi Plaza) is a new 5-hectare development in Nur-Sultan (formerly Astana), Kazakhstan, comprising retail, office, residential and hotel buildings. The development incorporates the tallest tower in the Central Asia at 310 m high and is designed to be a symbolic and commercially important component of the master plan for the new business centre within the city of Nur-Sultan. The architectural concept is shown in figure 2, which represents the construction site - in the centre of which a skyscraper should rise. This grandiose skyscraper will be the fourteenth tallest building in the world. ADP is a High-rise buildings with a retail and leisure podium and a hotel cluster at the base that rises to form a series of office and residential towers to the north - creating a new landmark on Nur-Sultan's skyline.

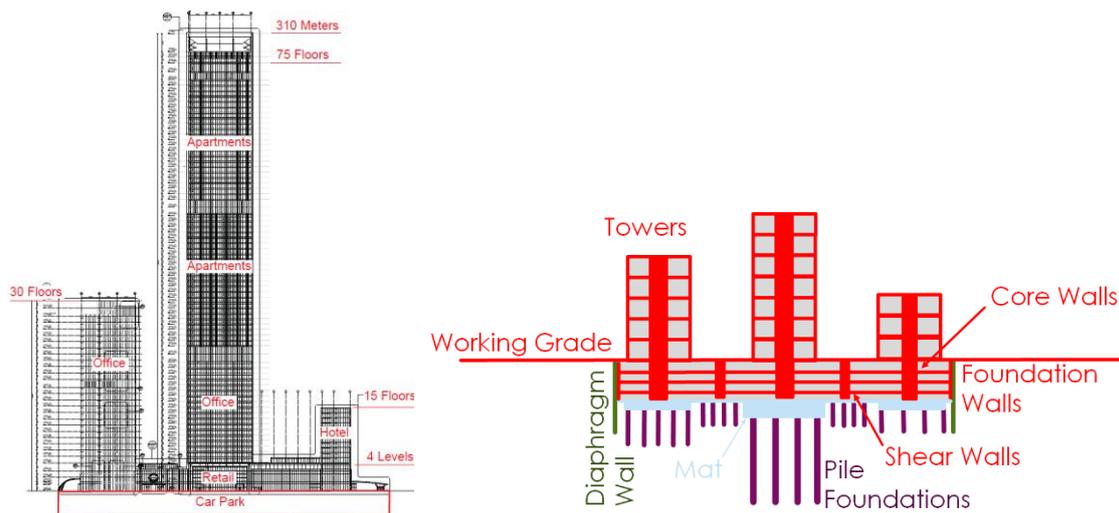


Before you start laying the foundation, you need to decide on its technology and depth. It depends on the expected load on it and the features of the natural conditions, namely the type of soil and the depth of the groundwater. ADP residential skyscraper consists of 5 main towers (see figure 1):

- Block R- offices and living quarters (75-Storey, Mixed Use 450 Apts 69,000 sqm, Office 37,000 sqm);
- Block O- office building (30-storey, Office 69,000 sqm. see figure 2);
- Block H- hotel and furnished rooms (15-Storey Hotel, 190 Guest Rooms, 100 Serviced Apts, 32,000 sqm);
- Block Y- offices of class «A» (2-Storey, Podium Retail, 50,000 sqm);
- Block Z-residential apartments (17-Storey Residential 20,000 sqm).



**Figure 1.** Project ADP in New Capital of Kazakhstan.



**Figure 2.** Cross section High-rise buildings project ADP.

The features of high-rise buildings present high requirements to the results of the EGS (engineering and geotechnical survey) and should solve the following main tasks in their implementation [1-5]:

- study of the geological structure of the soil massif with large volume (up to 60 m in depth and at least 2 foundation widths beyond its contour) (see Table 1)

- reliable assessment of the hydrogeological and hydro chemical conditions of both the compressible soil massif, and in the excavation zone and adjacent territory with the establishment of their corrosive aggressiveness, in time;
- determination of deformation and strength properties of dispersed and rocky soils at large ranges of voltage changes;
- instrumental observation and monitoring of deformations of the soil massif of the basement foundation and the adjacent territory under static effects.

Abu Dhabi Plaza Pile Raft Foundations parameters: Auger Cast Piles 1,125m; Diameter boring piles in from 1.2 to 1.5 meters; Length of piles from 13 to 25 m and Concrete with Severe Exposure Durability - 40 MPa.

**Table 1.** Geotechnical soil parameters for project ADP [5].

Soil	Clay / Loam	Sand and Gravel	Loam and Clay	Rock Debris	Sandstone	Hard Sandstone
Thickness (m)	4.0	4.5	5.5	1.5	2.0	Below
Natural Unit Weight $\gamma$ (kN/m <sup>3</sup> )	18.5	19	18.5	20.5	23.5	24.0
Internal Friction Angle $\phi'$ (°)	25	35	26	35	38	38
Cohesion $c'$ (kN/m <sup>2</sup> )	1	1	30	1	40	50
Modulus of Elasticity E (MPa)	15	25	30	50	65	100

## 2. Analysis of base deformation using of FEM

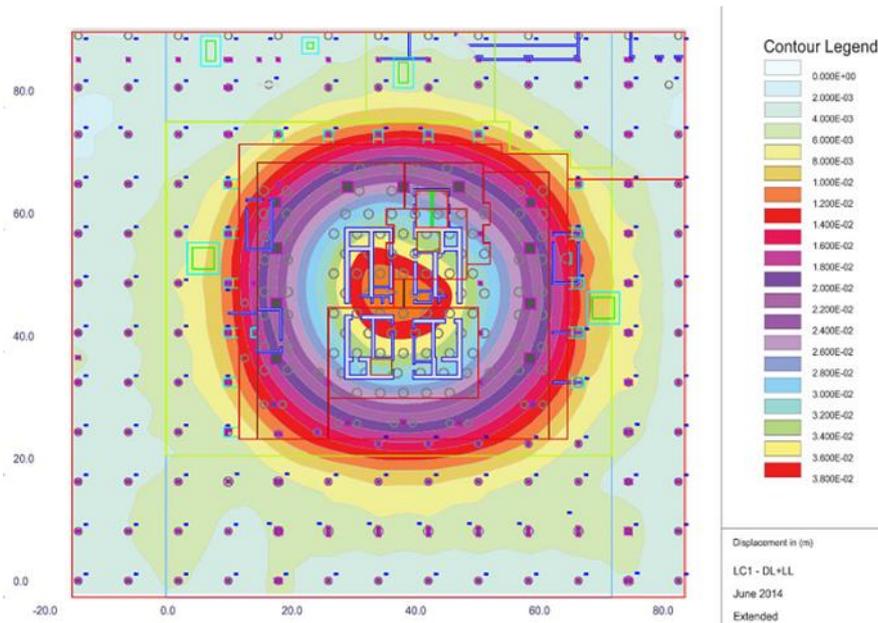
The analysis of the deformations of the base is dependent on the load of its own weight for a single design in the horizontal plane of the vertical deformation, as shown in the figure 3 [5].

The horizontal grid plan is a form deformation reference and used to estimate column settlement in various places. The settlement for each stage of construction is calculated using the ratio of the vertical reaction at each stage to the vertical reaction at the full design load.

Block R and the basement tile of the general basement are modelled by taking into account the changes in thickness. Figure 3 and table 2 show the settlement contour of the site using FEM. Adjustments to the vertical displacement of the tower columns and core walls will be made to allow for the raft deformation. The raft deformation analysis based on full design gravity load produces a vertical deformation contour plan as shown in figure 3 below. Displacement units are in meters. The contour plan represents the reference deformation shape and is used for estimating the settlement at the various core and column locations. The settlement at each construction stage is calculated using the ratio of the vertical reaction at each stage to the vertical reaction at full design load. The stiffness parameters are established using software.

**Table 2.** Pile Raft Foundation Settlements data of Block R.

Location	Model
Core	39.6 mm
Column RC1	13.4 mm
Differential Settlement	26.2 mm



**Figure 3.** Basement (Raft Foundation) Deformation Contours.

During and after construction of the permanent structures unacceptable cracking occurred in the external walls and base slab of the basement. Groundwater has been leaking through the cracks, compromising the serviceability and durability of the basement and rendering it unusable.

ACCL has since engaged Golder to review the design of the basement to establish the likely cause of the cracking and to propose methods for rectification. The chosen method comprised an internal drainage system maintaining a dry interior whilst collecting and draining water leaking through the walls and floor. Golder developed the system into a conceptual design consisting of a voided slab covering the floor and a façade for the walls.

Subsequent to the conceptual design Golder was made aware of the need for detecting and monitoring potential expansion arising from delayed ettringite formation (DEF) and alkali-aggregate reaction (AAR) in particular areas of the base slab. The possibility for DEF and AAR was highlighted by accelerated expansion tests and concrete chemical tests.

The voided slab obstructs visual observation of the slab and access for monitoring. Golder therefore developed a conceptual design for a slab monitoring system enabling the detection and monitoring of DEF- and AAR related expansion and cracking during operation of the basement. The primary element of the slab monitoring system comprises a distributed fibre optic strain sensing (DFOSS) system employing fibre optic cable to monitor strains developing on the slab surface. This paper presents the detailed design of the DFOSS system.

### 3. Design of distributed fibre optic strain sensing system (DFOSS)

DFOSS has been employed for measuring the strain in civil engineering structures for over a decade. It is now harnessed worldwide for monitoring a wide range of structures, including tunnels, bridges, piles, dams, embankments and diaphragm walls.

DFOSS relies upon backscattering when light is transmitted along an optical fibre. One particular component of the backscattered light is produced by Brillouin scattering. At any point along a fibre, the frequency of Brillouin backscattered light depends upon the strain and temperature at that point. Making allowance for the effect of temperature therefore, the strain anywhere along a fibre can be deduced by transmitting pulses of light down the fibre and analysing the frequency of backscattered light.

Compared to the use of isolated strain gauges, DFOSS offers a new paradigm for strain measurement in that [6-13]:

- DFOSS returns the continuous strain profile along a structural element. Strain gauges can provide only discrete pointwise readings and can miss vital strain variations between gauges.
- The backscattering from optical fibres is unaffected by electromagnetic interference.
- The core of optical fibres is made from pure silica which is very stable and inert. The fibres therefore resist corrosion, do not contaminate the local environment and have a design life measured in terms of decades.
- Optical fibres can operate over a much wider range of temperatures than most electronic devices.
- Optical fibres are small and unobtrusive, and hence are easy to integrate into both new and existing structures.
- The complete strain profile can be recovered for a fibre stretching several kilometres, potentially replacing tens of thousands of discrete sensors. The single-cable approach greatly simplifies installation.
- As a result of the ongoing development of DFOSS read-out units, a DFOSS system installed now can benefit from potential enhanced measurement capabilities in the future.

Most analysers require the installation of an additional optical fibre to measure temperature alongside the strainsensing fibre so that the effect of temperature can be eliminated from the Brillouin frequency shift.

The proposed DFOSS system comprises a grid of fibre optic cable bonded to the B4 slab linked to an analyser located in a temperature- and humidity-controlled room at B1 level (see Figure 4 for “General plan of cable routing on B4 slab”).

### 3.1. Gauge length

Fracture of the fibre must be prevented since installing the fibre below the voided slab renders any remediation of the fracture practically unfixable. Fracture at a localised crack in the slab is prevented by fixing the fibre only at discrete points rather than bonding the fibre to the slab continuously along its routing. An unbonded length between two adjacent points of fixture is called a gauge length. Prevention of overstraining relies upon the fibre undergoing the average surface strain of the slab along a gauge length instead of experiencing the maximum localised strain adjacent to a crack.

An alternative to discrete fixing is to bond the fibre continuously along its length but to allow the adhesive bond to yield beyond a predetermined shear stress. However, achieving consistent yielding of the adhesive under site conditions is difficult in practice and risks either inaccurate representation of strain in the case of premature yield or fibre fracture if yield is retarded.

### 3.2. Strain resolution

The degree to which an analyser can resolve the strain in a fibre is limited by noise and so resolution decreases with measurement distance. Strain resolution may be augmented by improving the signal-to-noise ratio with a more powerful analyser or by successively taking a large number of measurements and averaging.

The averaging of strain along a gauge length places a more stringent requirement on the strain resolution compared with the case of a continuously bonded fibre. Furthermore, the spacing of the fibre optic grid determines the distance of fibres from an expansion event and influences the required strain resolution.

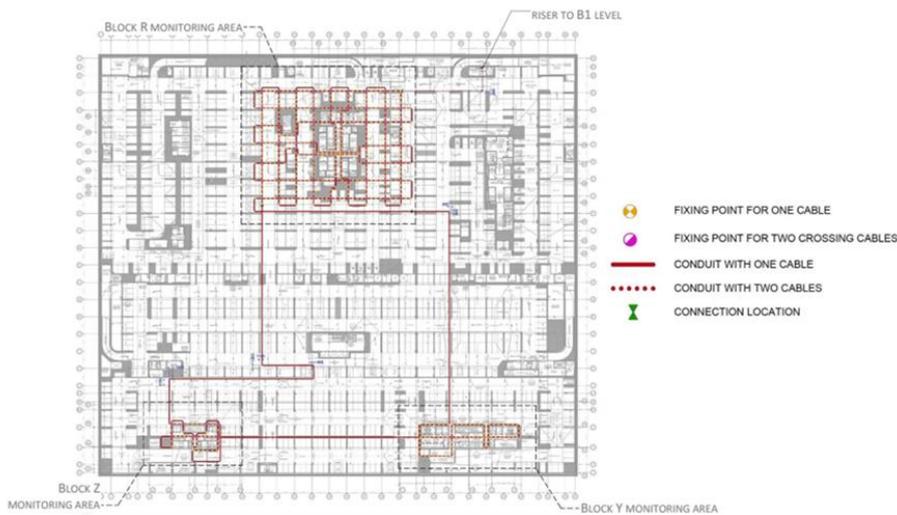
The lowest strain in a gauge length that would be induced by any conceivable expansion event was determined to be  $22 \mu\epsilon$  through assuming:

A requirement to detect surface strains as low as 0.06%, equivalent to the strain of 0.6 mm m<sup>-1</sup> explains the determination of the lowest induced strain which is summarised as follows:

1) For each expansion event, interpolate the relationship of applied volumetric expansive strain and maximum induced surface strain obtained by numerical analysis to determine the critical value of expansive strain required to induce the lowest detectable strain of 0.06%

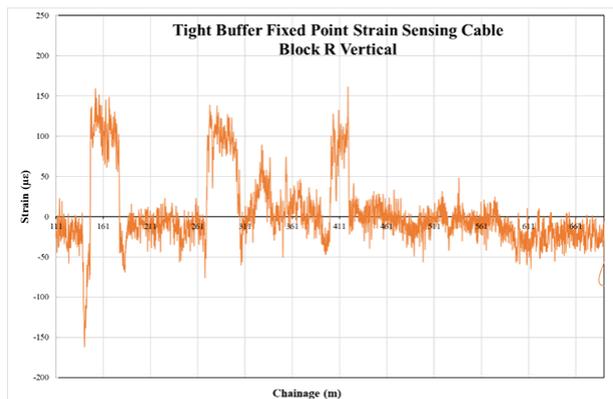
2) For each expansion event and for a range of gauge lengths and grid spacings evaluate the maximum strain induced across a gauge length by the critical value of expansive strain.

When considering expansion events across the entire conceivable range of events the lowest induced strain is  $22 \mu\epsilon$ . Although specifications for most analysers state a strain resolution in the order of 2 to 5  $\mu\epsilon$  this refers to the condition of uniform strain along the entire fibre. Under nonuniform strain conditions the resolution of typical analysers increases to around 20 to 30  $\mu\epsilon$  which is adequate to detect practically all expansion events considered. Strain resolution is therefore not a governing factor in the DFOSS design.

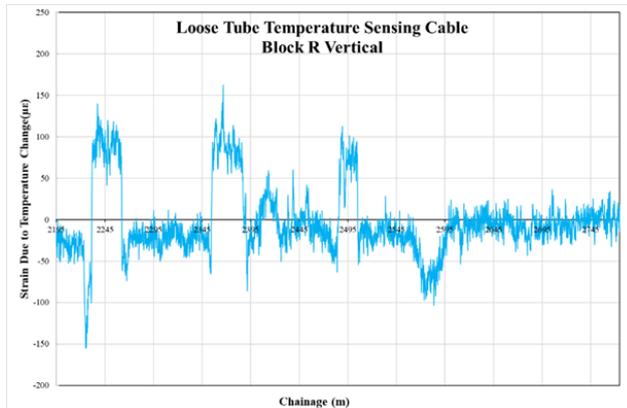


**Figure 4.** General plan of cable routing on B4 slab.

The commission test results were able to capture temperature changes caused by curing of concrete during the testing as shown in figure 5 and Figure 6. The temperature changes were significant at certain locations at Block R where slab casting process were ongoing during the measurement time. Similar measurement trends between both temperature and strain sensing cables indicates that the strain changes were caused by change in temperature rather than structural movement [6-13].

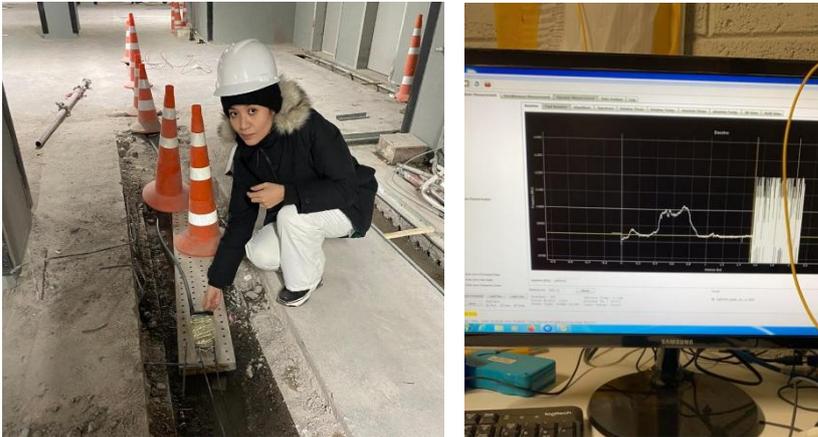


**Figure 5.** Strain measured at Block R vertical on 18/2/2020 16:45 (result of geotechnical monitoring).



**Figure 6.** Strain due to temperature effect measured at Block R vertical on 18/2/2020 16:45 (result of geotechnical monitoring).

As slab casting and repair works were ongoing during the test, the temperature changes affected the recorded strain measurements which increased the standard deviation of both fibre optic cable at certain locations along the monitoring route (see Figure 7).



**Figure 7.** Installation fibre optic cable (Gauge length) and geomonitring in construction site ADP.

By comparing the standard deviation of the first and second test, the results has shown that both tests have very similar magnitude of standard deviation except for those areas where there were significant changes in temperature. Therefore, for the current analyser used, the thermal shift in electronic components does not affect the precision error when the analyser is powered off.

Up to date, the slab casting and repair works at the monitoring area (Level B4) are still ongoing. Long term monitoring work will start after the completion of the slab casting and repair work at the monitoring area [12-13].

#### 4. Conclusion

Over the last decade, infrastructure monitoring has proven to be a demanding application of distributed fibre optic sensors (DFOS) in terms of strain and temperature measurements. The technology is continuously developing. For instance, advances in the systems have reduced the minimum spatial resolution of an advanced system to the centimetre scale. However, interpretation of the distributed strain/temperature data obtained in the field is sometimes not easy because of unavoidable measurement errors.

Distributed Fibre Optic Cable has received increasing demands in civil engineering applications especially in structural health monitoring application. The performance of fibre optic cable is of engineers and researchers' interest in recent years. This paper describes the field test on the Distributed Inner-Fixed-Point Fibre Optic Strain Cable to determine the performance in concrete cracks detection. The Distributed Inner-Fixed-Point Fibre Optic Cable was installed in Reinforced Concrete raft foundations shown in figure 4.

Results of geotechnical monitoring on the Distributed Inner-Fixed-Point Fibre Optic Strain Cable to determine the performance in concrete cracks detection on figures 5 and 6 for Project of Abu-Dhabi Plaza in Nur-Sultan city.

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