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# The monitoring of a substrate strengthened with concrete columns

## Monitorowanie podłoża wzmocnionego kolumnami betonowymi

**Abstract**

The process of interaction between the ground and screw displacement columns (SDC) in transferring loads has not yet been sufficiently investigated. This paper presents the results of pioneering tests in this field, carried out with the application of a long-term structural health monitoring system.

**Keywords:** SDC columns, force distribution, structural health monitoring systems

**Streszczenie**

Proces współpracy pomiędzy gruntem i kolumnami przemieszczeniowymi (SDC) w przenoszeniu obciążeń nie został dotychczas wystarczająco zbadany. W artykule przedstawiono wyniki pilotażowych badań w tym zakresie, przeprowadzonych z wykorzystaniem długoterminowego systemu monitorowania.

**Słowa kluczowe:** kolumny SDC, dystrybucja siły, systemy monitorowania konstrukcji

## 1. Introduction

In situations with unfavourable ground conditions, screw displacements columns (SDC) are increasingly used to strengthen the ground and to safely construct foundations. During the construction of foundations, soil is not extracted, but compressed laterally [1]. This has a positive effect on the state of soil compaction and improves the axial stiffness and load-bearing capacity of columns.

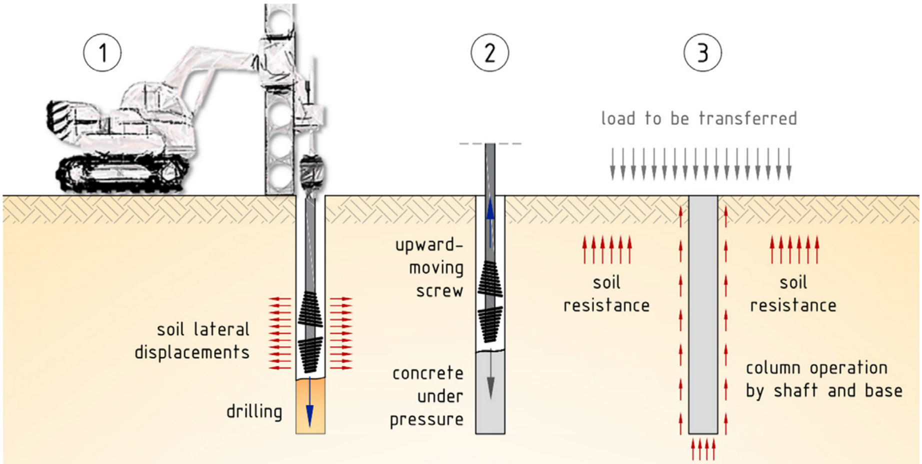


Fig. 1. Construction scheme of screw displacement columns

Other advantages of this technology include the fact that it is a process that does not produce shocks, it produces low noise levels, it has the possibility of being implemented alongside existing facilities without the risk of soil loosening, and it is fast and efficiently executed [2]. However, despite its theoretically simple technology, the design process of displacement columns still causes a lot of problems [3]. The phenomenon of force distribution between the column shaft and the base is insufficiently identified as well as its interaction with the surrounding soil. In [4, 5, 11, 12] some design solutions for displacement columns have been proposed; however, there has been an insufficient number of systematic pieces of in situ research, especially in Poland. In many countries, the standard procedure is to use measuring apparatus during load tests performed with static methods, which enable the measurement of force distribution along the pile or column shaft [6]. Such pieces of research have been conducted more and more frequently in Poland over recent years [7, 8].

This article presents an analysis of the operation of displacement columns on the basis of an automatic structural health monitoring system. The continuous measurement strategy provides the possibility to analyse the interaction between the concrete column and the surrounding soil in the context of load distribution transferred by the foundation slab through the transmission layer to the ground and columns over a long period of time.

## 2. Description of measuring problem

The analysed multi-family building is located within an area where the use of conventional, direct foundation by a shallow foundation slab was not an option due to the geological conditions. Under the building were layers of multigrain sands with thicknesses from 3.5 to 6.0 m and compaction degrees from ID = 0.25 to 0.75; below, there is a layer of sandy silt and humous clay. The thickness of the organic soil layer ranged from 1.5 to 4.0 m. Unfavourably within the foundations there is the water table – as presented in Fig. 2.

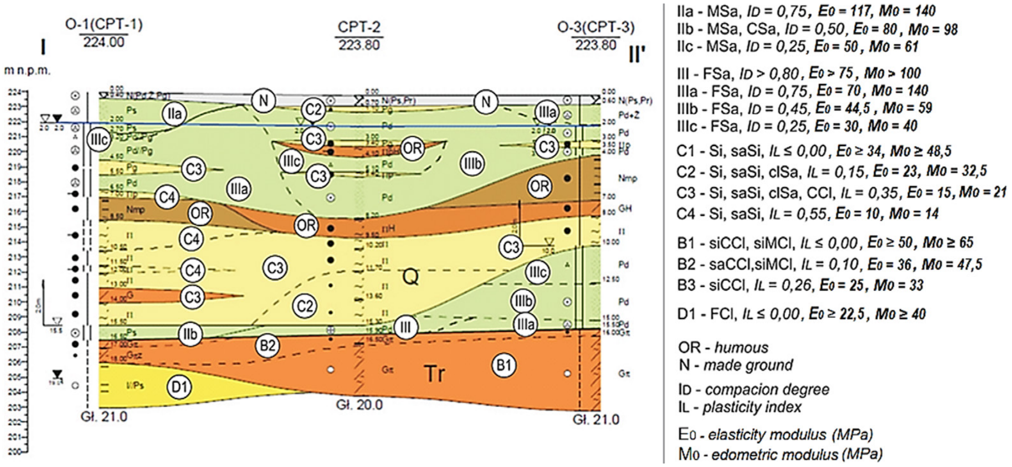


Fig. 2. Geotechnical cross section (author: Ł. Pietrusa, 2011)

Therefore, it was decided to strengthen the ground through the use of concrete columns made in SDC technology. The diameter of the column was 400 mm, the length was approximately 13 m, the spacing was approximately 1.6 × 1.6 m. The columns have been set in a layer of medium and thick sands with a compaction degree of ID = 0.50. At about 4.5 m below the contractual building level of ± 0.00 m, in a layer of clay and fine sand, a so-called transmission layer of 0.5m was constructed from aggregate. Its compaction index IS (ratio of current bulk density to its maximum value) was equal to 0.98 and the secondary elasticity modulus was $E_2$ = 100 MPa. Above transmission layer a 0.1 m thick layer of lean concrete was placed, a foundation slab with a thickness of 0.9 m was then concreted. The analysed building is a near elongated rectangle with dimensions of approximately 62.0 × 15.5 m – Fig. 3, the building height above ground level is around 35 m (11 storeys).

Foundations located on ground strengthened by columns assumes interaction between the ground and the columns with regard to carrying loads transferred by the foundation slab. The uniform transfer of load to the ground and columns is provided by a transmission layer. The aim of measurements taken with the structural health monitoring system was to determine: the value of force captured by one selected column; the stress (pressure) in the subsoil lying beneath the transmission layer. Automation of measurements allowed for the observation of this interaction over a long period of time.

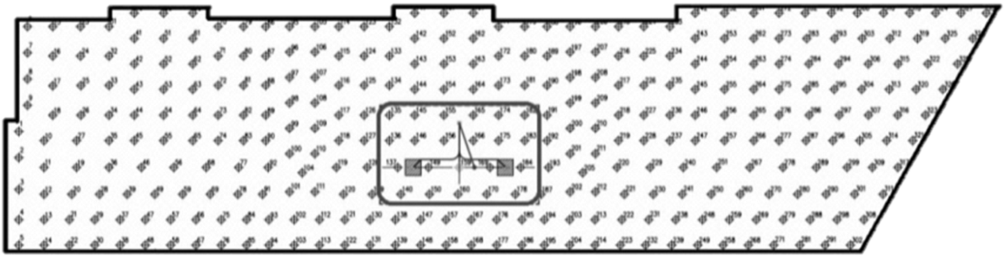

Fig. 3. Location of the analysed area on the plan showing the location of the columns (own elaboration)

## 3. Structural health monitoring system construction

To build a structural health monitoring system, sensors or measuring sets were applied on the basis of a vibrating wire sensing technique [9]. In addition to high measuring accuracy, vibrating wire sensors are characterised by their resistance to external conditions and their decades-long stability of measurements; therefore, they are widely used as elements of automatic, long-term structural health monitoring systems. All vibrating wire sensors include thermistors, which enable temperature measurements to be conducted simultaneously. These measurements are taken into account while correcting the obtained results. They are also used in the analysis of structural response to temperature loading. In the analysed example, the measuring system is equipped with additional temperature sensors (next to the VW-sensors) installed in the transmission layer and the foundation slab. As part of the SHM process, measurements of the following physical quantities are carried out:

- axial force in selected concrete column;
- stress (pressure) in the ground under the transmission layer in a vertical direction next to the analysed column;
- temperature in the ground, the transmission layer, the foundation slab and the air.

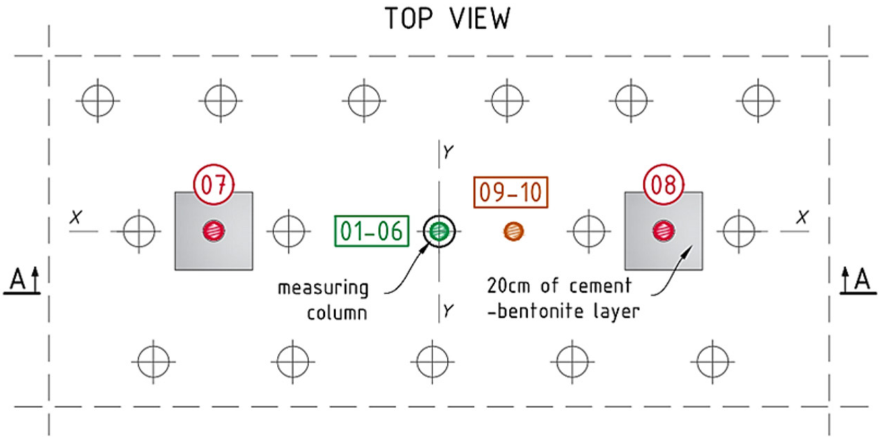


Fig. 4. SHM system scheme with locations of the measuring points: top view (own elaboration)

Measurement of the axial force in the concrete column is performed by a specially created force gauge. This element was made from a steel tube with an outer-diameter of 250 mm, a wall-thickness of 5 mm and a height of 200 mm. On the external surface of the tube, at half its height, six vibrating wire sensors were installed using spot welding. The full range of these sensors is 3,000·10$^{-6}$ (3,000 με) and the measuring base is 50 mm (see Fig. 5 and 7).

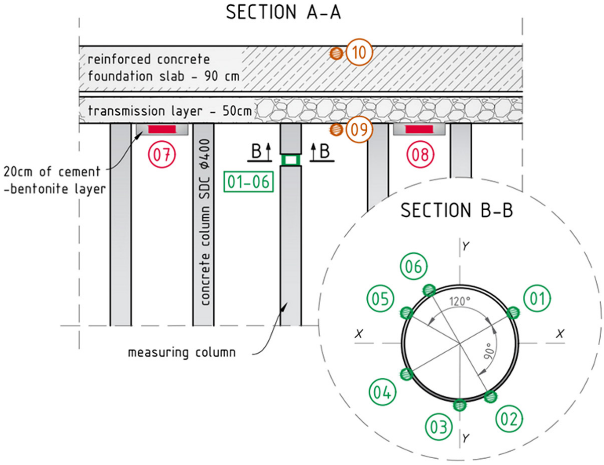


Fig. 5. SHM system scheme: side view and force gauge cross section (own elaboration)

Basic technical specifications of the applied vibrating wire sensors are as follows:

- measuring base – 50 mm;
- range of strains measurements – 3,000 με;
- resolution of strains measurements: 1 με;
- accuracy of strains measurements – ±0.1% of full-scale range;
- range of temperature measurements – –20 do +80°C;
- resolution of temperature measurements – 0.1°C;
- accuracy of temperature measurements – ±0.2°C;
- signing: '+' means strains resulting in compression.

To enable analysis of uniformity force transmission (its eccentricity), strain sensors were arranged around the tube circumference at 120° and at 90° (Fig. 5). On the basis of data obtained from system operation, it was found that loads are transferred to the force gauge in such a way as to cause its uniform (axial) compression (strain increases measured by each VW sensor create parallel lines – Fig. 6).

Calibration of the force gauge was performed on a testing machine with a measuring range of 1500 kN in a laboratory of the Institute of Building Materials and Structures at Cracow University of Technology. Force control was performed manually by visual reading on the manometer. During the entire test, all sensors were read at time intervals of 10 secs; the temperature was also recorded for all sensors. During the entire calibration process, it changed by no more than 0.3°C – this is less than thermistors accuracy. It has been concluded that the temperature effect on strain sensor readings was negligible and it has not been included in calculations.

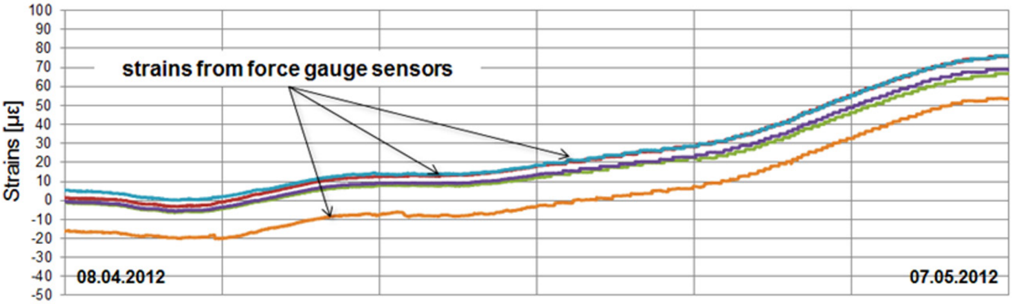

Fig. 6. Strains from vibrating wire sensors installed on force gauge

Strain value indicated by sensors is calculated with following equation:

$$\varepsilon=\left(R_1-R_0\right)\cdot G\cdot B \tag{1}$$

where:

- ε – strain increment with respect to the initial value, [–];
- $G$, $B$ – sensor calibration coefficients;
- $R_0$ – initial reading of string frequency, [$Hz^2$/1000];
- $R_1$ – actual reading of string frequency, [$Hz^2$/1000].

After calculating the average strains and minimising the error with the least squares method, the parameters of linear function were determined:

$$\varepsilon=a\cdot P+b \tag{2}$$

After converting the expression (2), we obtain the formula describing force value $P$ as a function of measured strain:

$$P=\left(\varepsilon-b\right)\div a \tag{3}$$

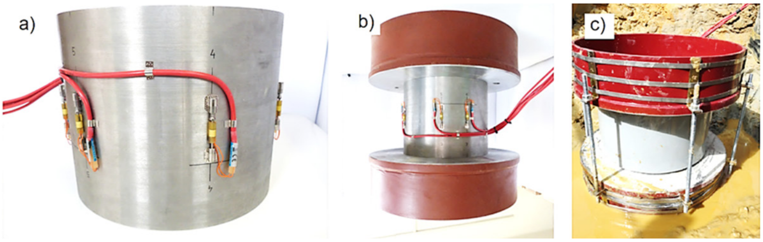

Fig. 7. Force gauge: a) during calibration test; b) with mounting heads; c) after installation in the lower part of the column (photo by Łukasz Bednarski)

After calibration, the force gauge was prepared for installation. Steel heads were specially designed for this purpose, the aim of which was to close interrupted parts of the concrete column in such a way that the geometrical axis of the column aligns with the gauge axis. The device was protected from the outside by a cover made from a section of PVC piping, the gap between the steel tube and the plastic pipe was filled with a permanently-elastic material.

Subsoil stress measurement is performed with two pressure sensors with a measuring range of 350 kPa located directly beneath the transmission layer near the analysed column. These sensors take measurements of vertical stress changes in the ground by measuring the change of hydraulic fluid pressure between two steel plates in the shape of a circle, joined at the periphery by welding. The fluid presses against the membrane which is connected to the vibrating wire. The sensors were factory-calibrated.

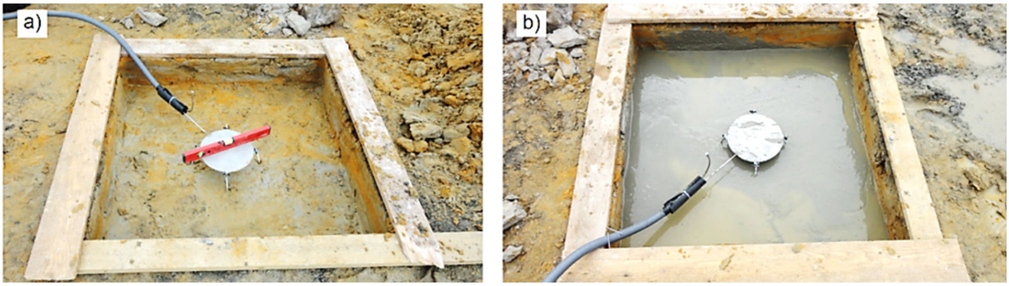


Fig. 8. Stress (pressure) sensor in the ground: a) before pouring with the cement-bentonite mixture; b) during pouring (photo by Łukasz Bednarski)

Basic technical specification of applied stress sensors are as follows:

- diameter – 230 mm;
- range of pressure (stress) measurements – 350 kPa;
- resolution of pressure measurements – 0.025% of full-scale range;
- accuracy of pressure measurements – ±0.1% of full-scale range (linear calibration);
- range of temperature measurements – –20 to +80°C;
- resolution of temperature measurements – 0.1°C;
- accuracy of temperature measurements – ±0.2°C;
- signing: '+' means increase in pressure (compressing stress) in the ground.

In order to eliminate local pressure on the sensor plate and to ensure the best compliance of ground medium operation within the direct vicinity of the sensor with the medium located outside sensor impact area, it was placed in a cube made of a mixture of bentonite and cement with dimensions of 1.0 × 1.0 × 0.2 m. The sensors were equipped with sealed steel tubes, connected hydraulically with the sensor chamber in the interior. These tubes were permanently mechanically clamped after cement and bentonite mixture bonding. This clamp increases the pressure in the measuring chamber and the alignment of the sensor plates with the surrounding medium.

Additional temperature sensors were installed within the transmission layer and the foundation slab – these were located at a depth of approximately 0.05m below the top surface of the transmission layer and approximately 0.10 m below the top surface of the concrete slab. The applied temperature sensors (thermistors) have the following properties:

- measuring range – –20 to +80°C;
- resolution of measurements – 0.1°C;
- accuracy of measurements – ±0.2°C.

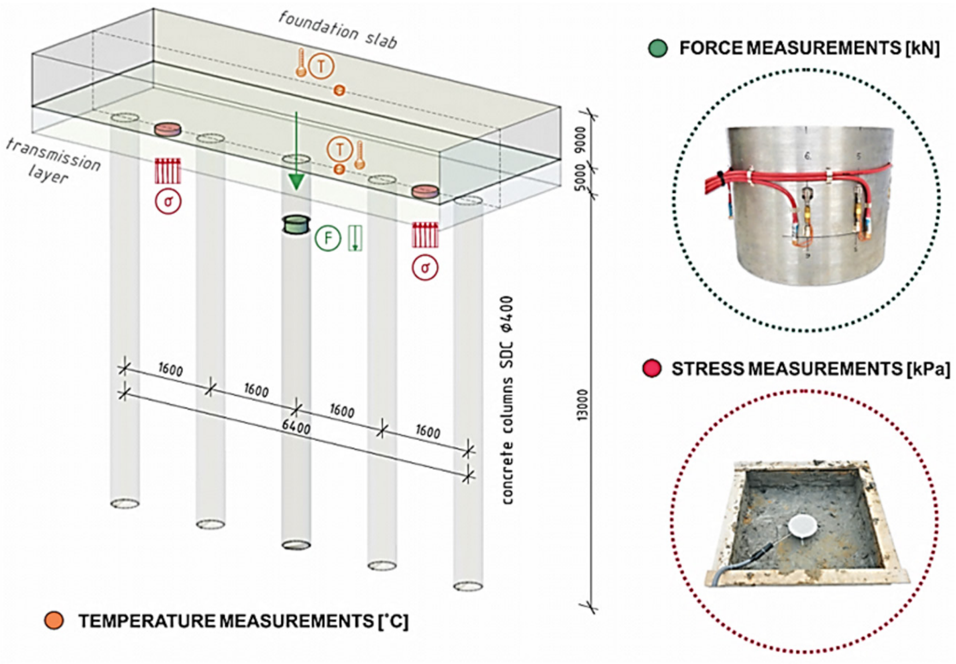


Fig. 9. Spatial visualisation of the structural health monitoring system (own elaboration)

## 4. Measuring data presentation

The measuring system was launched on 8th April 2012; the initial reading values were defined then and these are the reference for all the other measurements. Therefore, values of selected physical quantities presented in this article (except for temperature) should be treated as relative values (increments). During system operation, measurements were carried out with different time intervals from 10 minutes to 2 hours.

If a high level of accuracy of ground stress measurements is required, it is necessary to take into account the impact of atmospheric pressure fluctuations on the obtained results. Up until October 2012, the SHM system was equipped with a barometer; thus, stress results from the initial operation period were corrected for atmospheric pressure variations. In subsequent years, we have benefited from data provided by the Krakow Fiołkowa weather station, which is located a few hundred meters from the analysed building. Data analysis revealed, among other things, that in 2014, the maximum fluctuation of atmospheric pressure was around 4kPa with a standard deviation of 0.6 kPa.

Because the system covers only one concrete column, analysis and inference presented within this article is primarily qualitative rather than quantitative in nature; therefore, the omission of slight atmospheric pressure changes in the calculation does not affect the correctness of inference. The following plot presents the changes in atmospheric pressure in 2014 (for the initial reading, the first measurement carried out this year was defined).

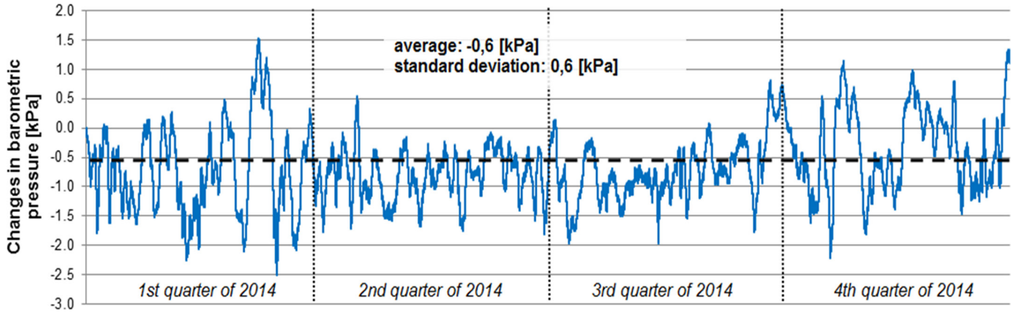


Fig. 10. Changes in atmospheric pressure in 2014 on the basis of measurements obtained from the Kraków Fiołkowa weather station

For the analysed plots, data is presented for three time periods: from 08.04.2012 to 04.12.2012; from 17.05.2013 to 20.08.2013; from 28.02.2015 to 27.05.2015. There are a few distinctive points in time (points 1-3 are marked on the plots):

1. 11.05.2012 – foundation slab concreting;
2. 19.06.2012 – concreting of slab above ground floor;
3. 31.07.2012 – concreting of slab above second floor;
4. 05.02.2013 – (building) shell;
5. the end of October 2013 – finished state.

Below, the increments of force in the concrete column and increments of ground stress registered by the pressure sensors are presented.

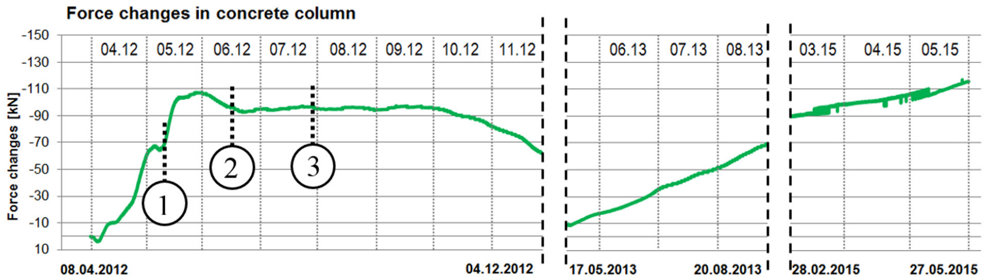


Fig. 11. Increments of force in concrete column over the considered periods of time

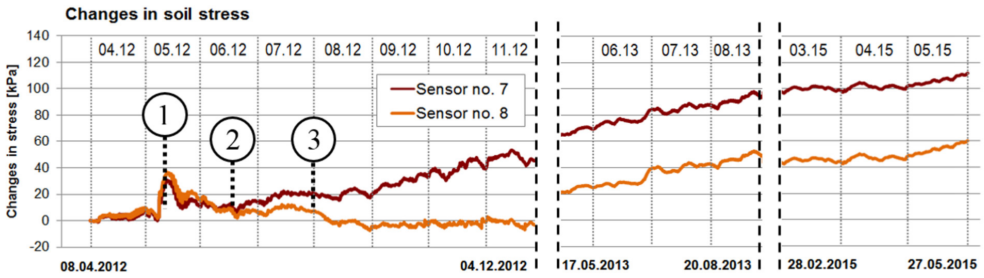


Fig. 12. Increments of stress in pressure sensors located on both sides of concrete column

To better illustrate load distribution between concrete column and the ground, these two charts can be presented within one, converting the stress values from pressure sensors (7 and 8) to the value of force. For this calculations reference area of ground around considered column as shown in Fig. 13 was assumed. In the analysis, the value of stress in the ground was assumed as an average value from data registered by sensors 7 and 8.

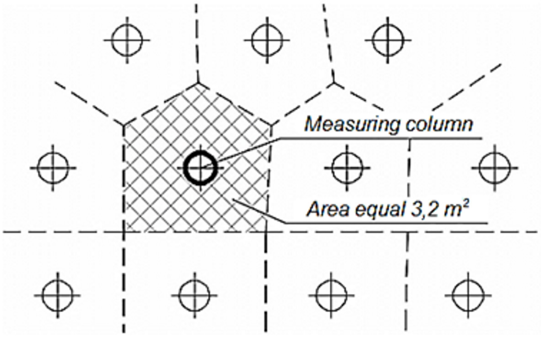


Fig. 13. Reference area for calculation of stress in the ground surrounding considered column

The following plot shows the percentage of force in the concrete column with regard to the total value of the load transferred to the strengthened substrate. In the initial period, the concrete column has taken about 70–80% of the total load; however, since September 2012, a gradual redistribution of stresses has been observed, this has resulted in a decrease in force carried by the column. After three years of operation of the structure, this value has been identified as approximately 30% of the load transferring to the analysed area – this corresponds to a value of force in concrete column of approximately 100 kN.

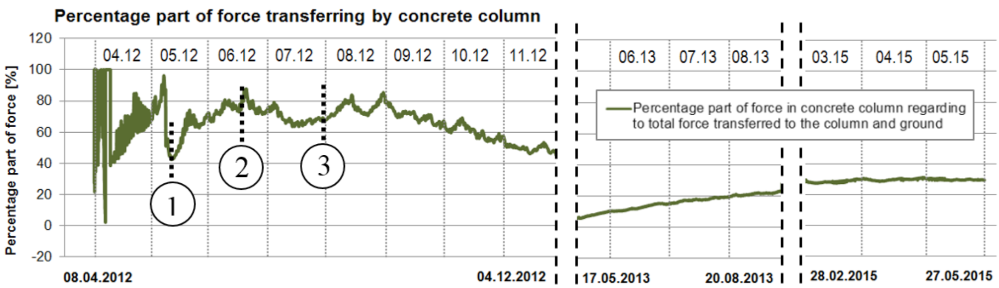


Fig. 14. Reference area for the calculation of stress in the ground surrounding the considered column

## 5. Temperature distribution

Within the structural health monitoring system, the values of temperature are recorded by strain sensors installed in the force gauge, stress sensors in the ground, in the transmission layer of the aggregate and in the concrete of the foundation slab. The plot below shows the distribution of measured temperatures during the considered periods of time and more detailed close-ups in three selected periods.

Regardless of the temperature of the season, amplitudes in the concrete foundation slab are larger than in the other measuring points; sensors located below the slab indicate similar values of temperature.

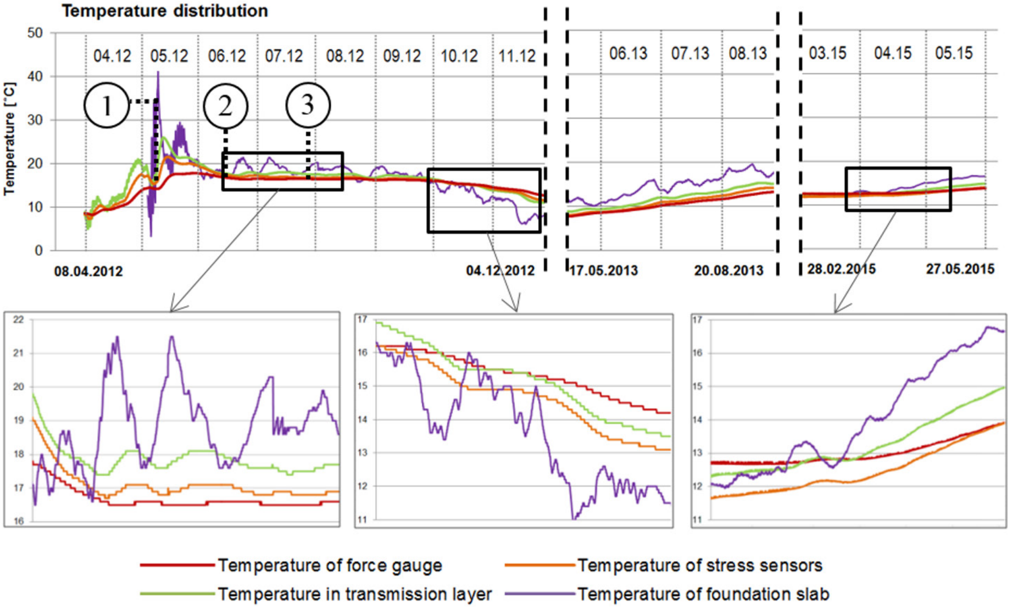


Fig. 15. Temperature distribution in each of the measuring points

## 6. Interpretation of results and conclusions

Described research was one of the first of its kind to be conducted in Poland. The aim was to identify the possibilities of determining the manner of load distribution transferred to a strengthened substrate through a foundation slab placed on a transmission layer. In the considered case, the reduction in the compressive force in the concrete column and the simultaneous increase in stress in the ground located between columns was observed after a few months of operation. Identification of the definite reasons for this phenomenon is not possible on such a small test field; however, measurements have shown that transferring loads through substrate-concrete columns system may be associated with the redistribution of stresses between the columns and the ground. Reaching the static equilibrium is a long-term process depending upon many factors associated with both the substrate and its strengthening.

It should also be noted that the measurements did not include the foundation slab itself, which, as a result of mechanical actions (external loads, the impact of columns and ground) and non-mechanical actions (temperature, concrete shrinkage), is deformed and causes changes in ground stress and forces in the concrete columns.

Analysis of the pressure measurements in the ground provides interesting findings. Extreme values in the vertical stress function correspond to the time of concreting, when the foundation slab does not yet have any bending stiffness. Then, the whole load resulting from the dead weight of the transmission layer and the slab is transferred evenly on the ground – the measured value corresponds to the calculated theoretical value. After concrete hardening, stiffening of the slab occurs – this causes the load value to be transferred to the selected area of the substrate and is dependent upon overall stiffness. This property of substrate strengthened by concrete columns means that over a certain period of time, we can observe ground relief. Longer observation indicates the redistribution of stress between the columns and the ground – this results in an increase in ground stress. Load captured by the ground is associated with pressing columns into the ground. The influence of a concrete creep effect is also possible. Increase in the load-bearing capacity of a substrate strengthened by the columns could also be justified by the partial restriction of ground horizontal displacements, what is caused by resistance of the columns.

Drawing general conclusions based on a small number of sensors installed in one building is impossible. In the future, similar studies should be planned in such a manner that includes the measurements of a minimum of three concrete columns and the surrounding ground. It would be advantageous to monitor at least two groups of columns (min. three columns in each of the group) located in different substrate conditions. The described test may be supplemented by: measurements of columns strains over their length; measurements of deformations (strains) of foundation slab; vertical ground displacements along the column length; pore water pressure in the ground under the slab. It would also be beneficial to measure changes in the vertical 'stress' in concrete columns to determine changes in the elastic modulus and creep of concrete over time. Of course, the research range should be determined in each case depending on local conditions and possibility of measurement result interpretations [10]. The aim of such a research is to provide structural health monitoring system data which enables the building of a correct model of interaction between the foundation and the substrate strengthened by screw displacement columns. Conducting such kind of research is also necessary in the context of developing Polish guidelines for designing and constructing concrete columns. This work will probably be modelled on the French guidelines [11, 12]. It would be advisable to include considerations derived from Polish experience covering the very broad issue of strengthening the ground through the use of concrete columns.

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