

Example of geotechnical monitoring of soil improvement using rigid inclusions under road embankment

Research Article

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Abstract: The article describes an existing and pioneering measurement system, which can be called a geotechnical monitoring system. This system has string sensors measuring strains, stresses and forces and was installed in concrete columns strengthening weak soil subgrades. Concrete columns using full displacement technology strengthen the ground under the embankment of the expressway No. S7 between Gdańsk and Elbląg in Poland. In terms of geological structure, the area where the measuring columns were made is characterized by the presence of low-bearing, large-thickness organic soils, such as peats and soft plastic silts, and a high groundwater level. The described geotechnical monitoring system consists of a total of eight measurement columns in four test areas. This article is a presentation of the measurement system and the first results of measurements carried out during column load-bearing tests.

Keywords: Displacement columns • Soil improvement • Geotechnical monitoring • Deformations and stress sensors • Dynamometer

1. Introduction

A popular method of improvement of the ground under road or railway embankments is concrete columns with displacement technology [1]. The working tool forming a column in the ground is a special auger with a characteristic shape, thickened in central part [2]. There are two phases in this method: drilling a hole in the ground and concreting the column. The drilling stage ends when the expected depth of the column is reached in the bearing soil, and then, when the drill is lifted upwards, the next phase of concreting the column shaft begins. A definite advantage of this method is that the excavated material is not carried outside, as the soil material is moved sideways, thereby compacting the native soil. The phenomenon of soil improvement (especially mineral soils) after column installation is shown in two cone penetration tests (CPT's) test logs (Figure 1). A

characteristic feature of the displacement technology is the variability of the diameter along the length of the column side, depending on the shape of the bit and ground conditions [3]. Therefore, it can also be expected that the value of Young's modulus of concrete is not constant [4]. In order to effectively strengthen the native soil under the designed structure, rigid concrete inclusions are made at regular, most often square, spacing [5]. Typically, the element accompanying this technology is a transmission layer in the form of an aggregate mattress reinforced with geosynthetics, steel meshes or meshes made of composite rods (e.g., fiberglass). Sometimes enlarged reinforced concrete column heads are used to increase the efficiency of the columns or to increase their spacing [6]. The basic design parameters are the diameter, spacing, length and material of the columns [7].

Since the technology of displacement columns began to be used in construction, many scientific publications have been published that attempt to better understand the technology and operation of columns in the ground [8-12].

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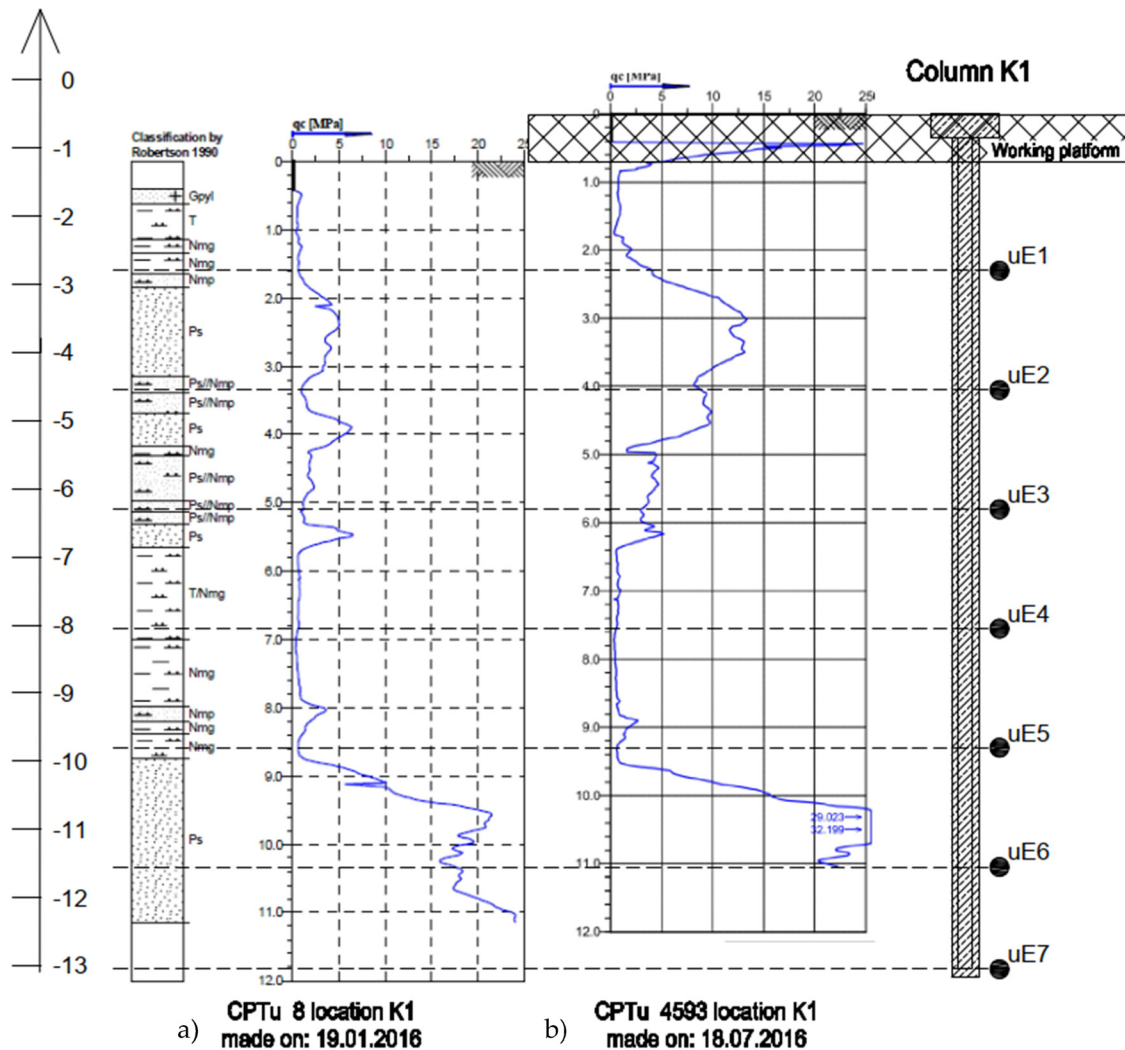


Figure 1. CPT test logs. (a) Before ground improvement and (b) after ground improvement.

Source: "Report on geotechnical studies performed for the investment project - Construction project of the S7 expressway on the Koszwały - Kazimierzowo section, task 2 Nowy Dwór Gdański - Kazimierzowo, section MA-19 km 43+900 - 44+330." "in Polish" (2016). Prepared by: GEOTEKO Projekty i Konsultacje Geotechniczne Sp. z o.o.

However, we still know relatively little about what happens to the reinforcement and the embankment in the long term, during the long-term operation of the structure.

This article presents one of the proposed research methods that allows monitoring phenomena occurring in columns in real time under a constructed and used road embankment. The proposed measurement system was installed in eight columns on four test plots during the construction of the S7 expressway from Nowy Dwór Gdański to Kazimierzowo in 2016/2017. The article describes the idea and characteristics of the measurement system used and presents selected, preliminary measurement results. Detailed monitoring results and their analysis will be presented in the author's doctoral thesis, because the whole issue of the monitoring in question is related to the subject of the doctoral thesis of the main author (A. Jabłonowski) carried

out at the Gdansk University of Technology under the supervision of A. Kosiński, as part of the "Implementation Doctorate" program.

2. Site conditions and test program

2.1 Soil and water conditions occurring on the test plot

The entire section of the S7 road between Gdańsk and Elbląg runs through Żuławy Wiślane. This region is located in the northern part of Poland, exactly in the delta of the

mouth of the Vistula River. The mentioned area is characterized not only by low, and sometimes depressed, ground level in relation to sea level, but also by unfavorable geotechnical conditions. There are large thicknesses of low-bearing organic soils in the form of peats, silts and gytja, often with interlayers of mineral soils, most often in the form of sands. This geological structure (layered) and the high level of groundwater make this area difficult to foundation of any construction or infrastructure facilities.

The following are two CPT test logs taken at the location of the K1 measuring column. The first log is from 19.01.2016, half a year before the ground improvement works in this area (design stage) and the second log is from 18.07.2016, a month after the installation of displacement columns in the ground improvement area and after the load-bearing capacity test of the K1 measuring column.

The CPT graphs therefore show the characteristics of the geological profile before and after the improvement works. A clear improvement in conditions is visible, especially in the mineral interbeddings. The qc value for the upper layer sands increases from 5 to more than 10 MPa (Figure 1).

2.2 Purpose of monitoring

The aim of monitoring is to better understand the issue of soil strengthening using the method of rigid displacement columns and to attempt to describe the cooperation of the embankment–transmission layer–rigid inclusion (concrete column)–subsoil system, taking into account phenomena and changes occurring during many years of operation. Because monitoring is active from the moment it is installed in the column, it also provides a lot of interesting information about the concrete maturation phase and the mutual influence of columns made in the vicinity.

2.3 Description of the measurement system

In the discussed research project, it was decided to measure selected physical quantities only within the columns. Measurement of the transmission layer, its reinforcement and the embankment was omitted. The system used the Geokon

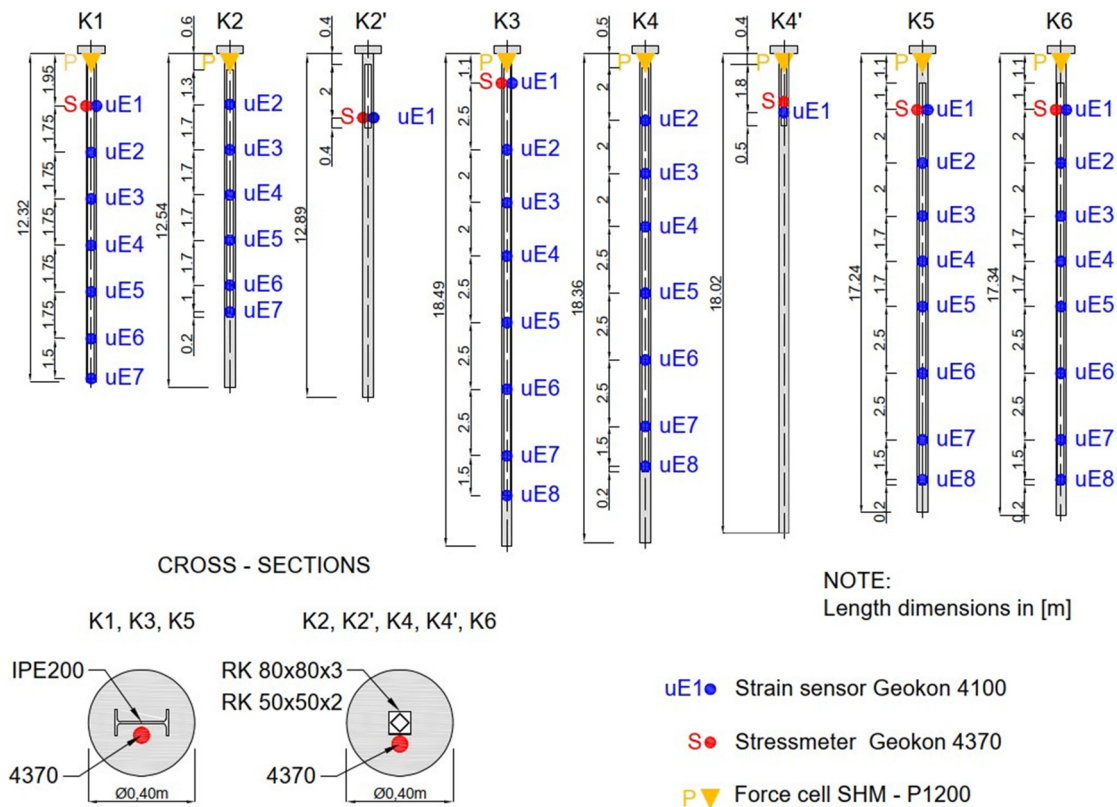


Figure 2. Detailed location of sensors in given columns.

Source: Author's contribution.

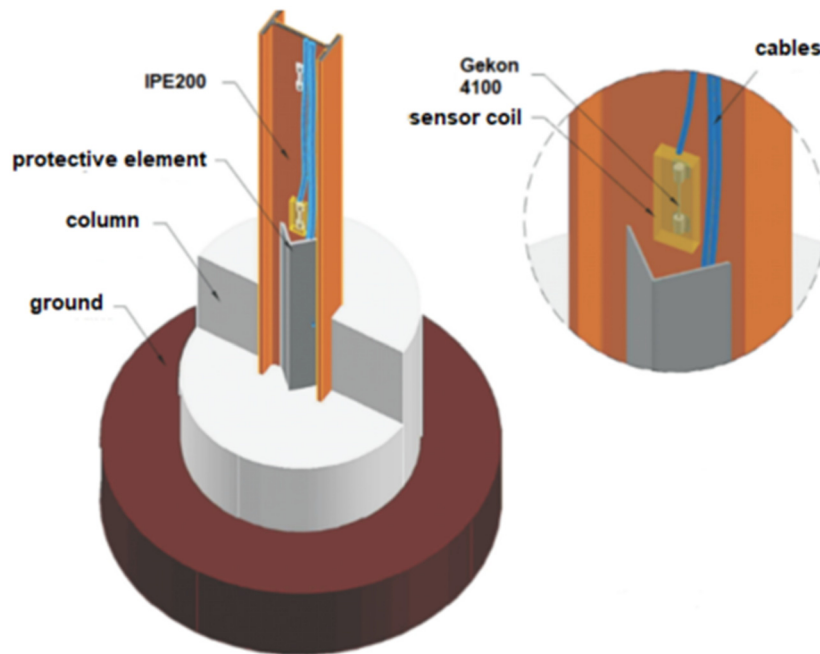


Figure 3. Details of the installation of strain sensors in columns reinforced with IPE 200 profiles.

Source: From ref. [13].

vibrating wire (VW) measurement technique, described in numerous documents [13-16].

The measurement system used consists of a number of sensors installed along the entire length of the tested columns, but most of them are located in the upper parts of the columns (the first 2 m of length). In a given column, a force sensor was installed in a specially widened and built-on column head, followed by a stress sensor and a strain sensor. Subsequent sensors were used to measure strains and were installed along the length of the column at specific intervals ranging from 1.5 to 2.5 m (Figure 2).

Figure 2 shows that in two locations, the sensor system was divided into two additional columns (K2' and K4'). This happened due to technological problems when embedding the measuring system into the freshly concreted column. A total of 64 strain sensors, 6 stress sensors and 7 load gages were installed in 8 columns. The entire system, including cabling, is connected to four dataloggers, where measurement data are continuously recorded.

Additionally, each sensor is equipped with a thermometer to measure temperature.

The sensors were installed in two variants:

- Columns with reinforcement: Reinforcement column made of IPE 200 profile. It was used in odd numbered

columns K1, K3 and K5. C30/37 concrete was used in these columns (Figure 3).

- Columns without reinforcement: No steal profile column made of square hollow profiles RK 80 × 80 × 3 and RK 50 × 50 × 2.

It was used in even numbered columns K2, K2', K4, K4' and K6. C16/20 concrete was used in these columns (Figure 4). The outer part of the 80 mm × 80 mm × 3 mm profile had specially cut holes through which the concrete mixture was to flow. This procedure allowed for a full connection of the steel elements with the concrete. The inner part of the 50 × 50 × 2 profile was to stiffen the steel element so that it could be inserted into a pile several meters deep.

Location of measurement columns:

The sensors were installed in eight displacement columns on four test fields under the road embankment at the following locations (road kilometers):

- cross-section km 44 + 050 – column K1 (sensor installation date: June 15, 2016),
- cross-section km 45 + 575 – column K2 and K2' (sensor installation dates: October 7–11, 2016),
- cross-section km 48 + 150 – columns K3, K4 and K4' (sensor installation dates: August 26–30, 2016),
- cross-section km 48 + 250 – columns K5 and K6 (sensor installation date: October 12, 2016).

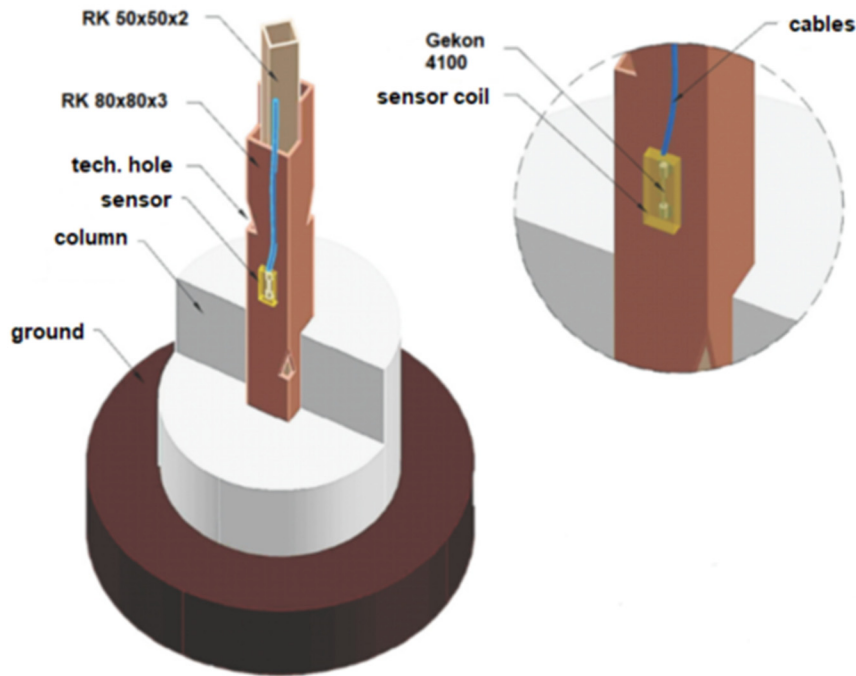


Figure 4. Details of the installation of strain sensors in columns without reinforcement.

Source: From ref. [13].

2.4 Specification of installed sensors

2.4.1 Load cell SHM-P-1200 model for measuring the force transmitted to the column

These sensors were specially designed to measure the force transmitted to the column heads while they were under test loading and during embankment execution. Their design used strain measurement of three steel rods fixed in two steel circular plates (numbers 1–3 in Figure 5). The plates are connected to the head of column using steel rebar. The site conditions caused significant eccentricity of the compressive force to occur very frequently during the load tests, resulting in tension in one

of the force-measuring rods. The force value in the column was calculated as the average of the forces in the individual rods (Figure 5).

2.4.2 Concrete Stressmeter, Geokon 4370 model

The Geokon 4370 sensor is used to measure stresses in concrete in the place where the sensor is installed, i.e., at a distance of approximately 2.0 m from the column head. It is made of a 600 mm long plastic tube with an external/internal diameter of 76/66 mm and steel base. Inside the tube, a vibrating strain sensor with a thermistor is placed. The sensor tube is filled with the same concrete mix from which the column is made (Figure 6).

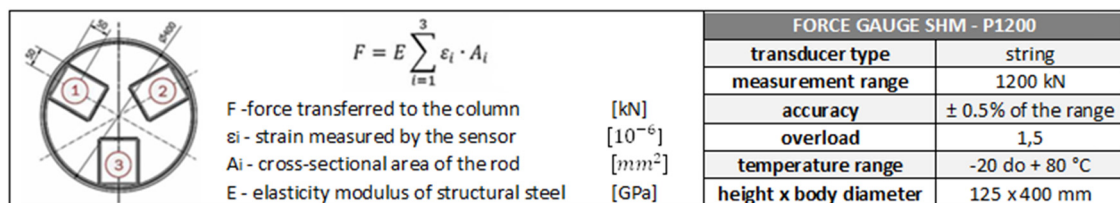


Figure 5. Specification of the SHM-P-1200 load cell.

Source: From ref. [13].

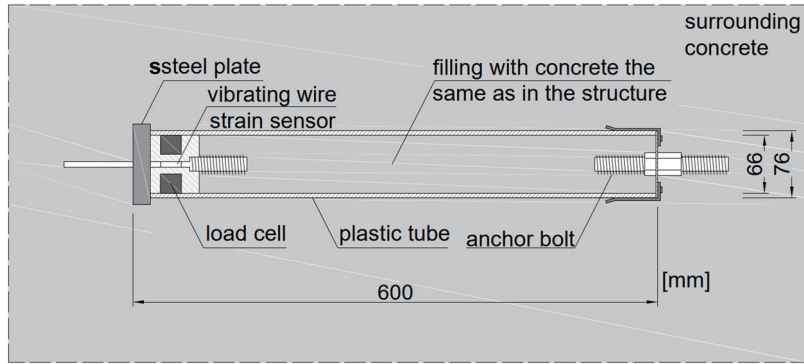


Figure 6. Concrete VW Stressmeter Geokon 4370 model.

Source: Author's contribution.

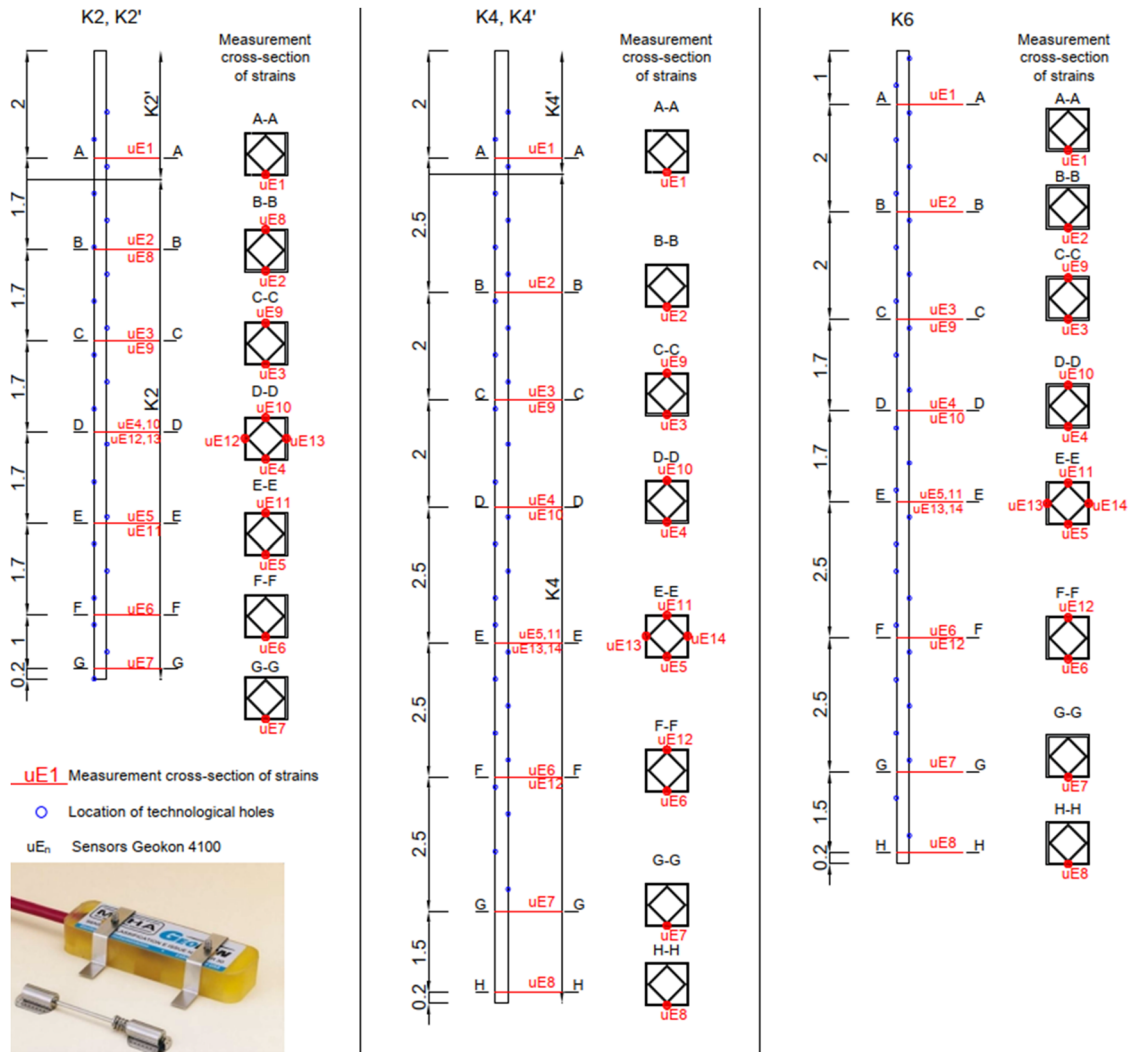


Figure 7. Installation details of strain sensors for an unreinforced column.

Source: Author's contribution.

Design load capacity			761 kN		
Cycle I			Cycle II		
Percentage of charges (%)	Load value	Stabilization	Percentage of charges (%)	Load value	Stabilization
12.5	95	Yes	25.0	190	No
25.0	190	Yes	50.0	381	No
37.5	285	Yes	75.0	571	No
50.0	381	Yes	100.0	761	No
62.5	476	Yes	112.5	856	Yes
75.0	571	Yes	125.0	951	Yes
87.5	666	Yes	137.5	1,046	Yes
100.0	761	Yes	150.0	1,142	Yes
75.0	571	No	75.0	571	No
50.0	381	No	50.0	381	No
25.0	190	No	25.0	190	No
0.0	0	Yes	0.0	0	Yes

Table 1. Load test program for the K1 column.

Source: Test load results of displacement piles T08b, piles no. 8064, 7341, 4632, 4593, 7250 (object 19, area no. 13.1 – 13.3, km 43+900 to 44+440) “in Polish” (2016) Prepared by: Consortium Menard Polska sp. z o.o. i Keller Polska sp. z o.o.

Compacting a concrete mix made of aggregate with a grain size of up to 16 mm in the tube is not an easy task and requires particular accuracy and delicacy. An additional difficulty in installing this sensor is the time pressure,

because the sensor had to be embedded in the concreted pile before the concrete mix hardened. The use of this sensor model completely eliminates the need to know the actual compressive force and the diameter of the

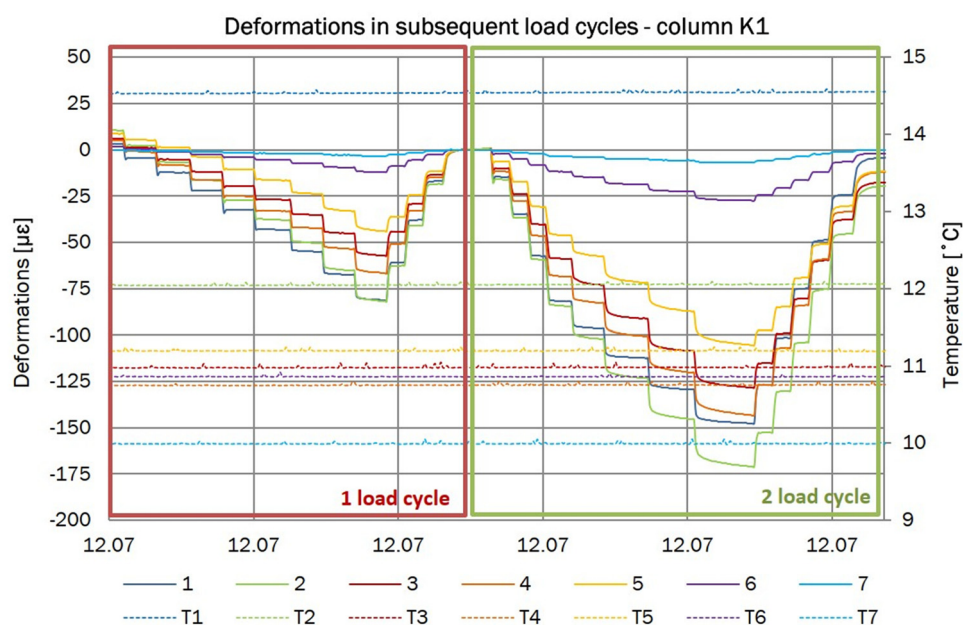


Figure 8. Results of strain measurements in the K1 column shaft during test loading.

Source: Author's contribution.

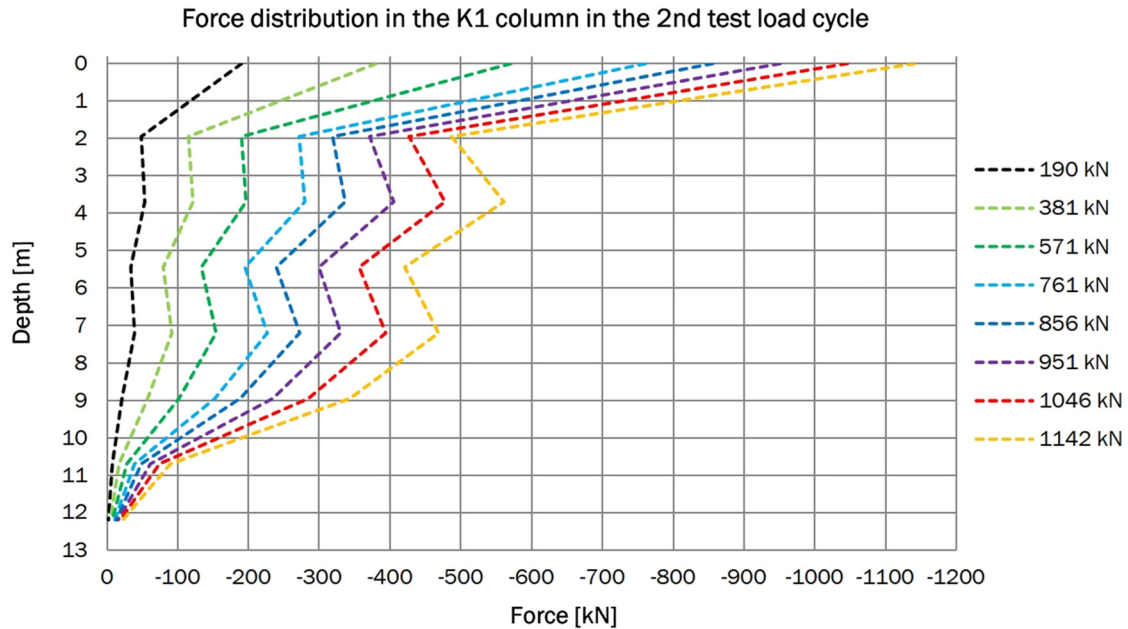


Figure 9. Distribution of force in the K1 column shaft during the second load test cycle.

Source: Author's contribution.

column. The innovation of this measuring system combining a stress sensor and a strain sensor built into the same height of the column shaft causes the equation $E_i = Q/\varepsilon_i \cdot A_{ti}$ to be simplified to the form $E_i = \sigma_i/\varepsilon_i$, where both required data are directly read from the sensors.

There are several publications available about this sensor [17, 18]. Additionally, another publication by the author will appear soon, which will be created as part of the laboratory tests performed using this very strain sensor.

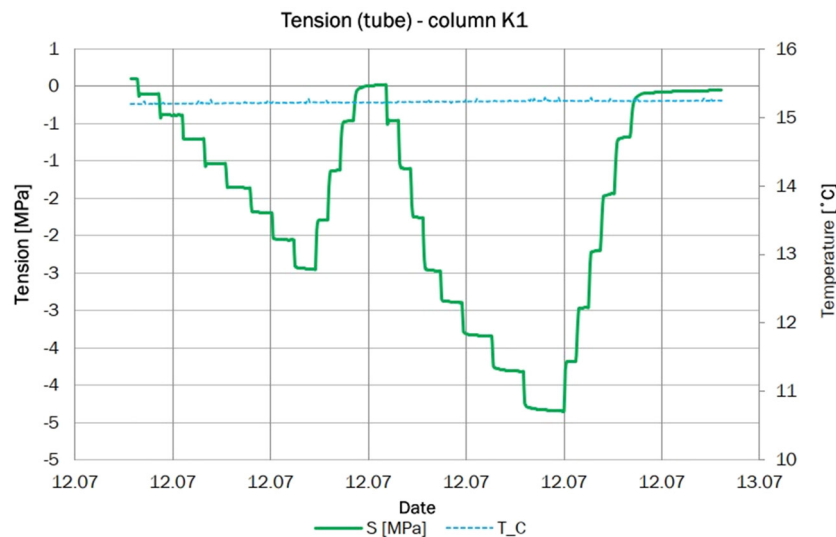


Figure 10. Stress changes for subsequent load levels of the K1 column load-bearing capacity test (negative values indicate compression).

Source: Author's contribution.

Stress distribution and calculation of Young's moduli in the K1 column in the second test load cycle										
Column K1		[1] 25%	[2] 50%	[3] 75%	[4] 100%	[5] 112.5%	[6] 125%	[7] 137.5%	[8] 150%	$E_{average}$ (GPa)
		-190	-381	-571	-761	-856	-951	-1,046	-1,142	
σ (MPa)	1.95 m	-0.46	-1.10	-1.8	-2.5	-2.9	-3.3	-3.8	-4.3	30.2
$\varepsilon''\sigma''$ ($\mu\epsilon$)		-14.55	-34.67	-57.23	-81.70	-96.01	-111.78	-128.48	-146.63	
E (GPa)		31.58	31.75	30.71	30.18	30.04	29.79	29.56	29.49	

Table 2. Change in strains and stresses in the first measurement cross-sections for the K1 column.

Source: Author's contribution.

2.4.3 Strain sensor for measuring vertical strains along the length of the column

For two variants of measuring columns (with and without reinforcement), a different number of strain sensors were installed. The sensors Geokon model 4100 were installed onto the web of the I-section using a spot-welding technique (Figure 3). The challenge was to mechanically protect the sensors with housings that would not modify the strain measurement at the same time. For this purpose, special housings made of thin sheet steel were designed, which underwent controlled deformation during the embedding of the steel elements, but, thanks to their low compressive stiffness, did not interfere with the measurement. In columns reinforced with a I-section, one sensor was used for each measuring cross-section.

Placing the strain sensors in columns without reinforcement required the design of special elements (Figure 4). Geokon model 4100 strain sensors were installed on this element. One to four sensors were used in the measuring cross-sections (Figure 7).

Although the measuring columns were located only in the central part crown of the embankment, in building phases and execution phases, vertical forces are not the only forces acting on the column. Because during the installation of adjacent columns, the strain sensors indicate the occurrence of lateral forces that cause tensile forces of the measuring column. Moreover, the installation of the reinforcement to which the sensors are attached, in construction conditions, is doomed to certain imperfections and the occurrence of unintended eccentricities that can generate additional bending moments in the cross-section of column.

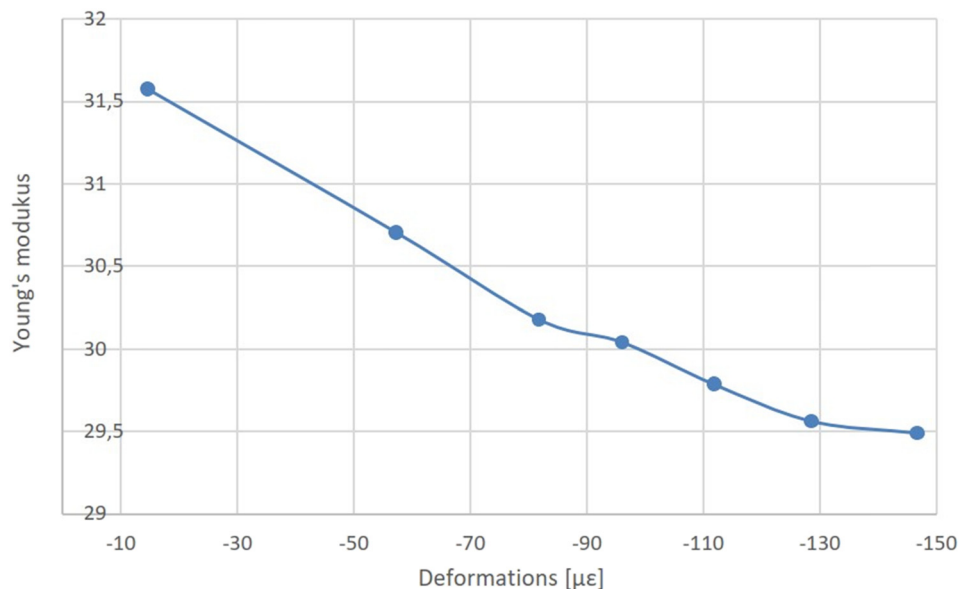


Figure 11. Change in the Young's modulus of concrete in relation to the increase in strains in the load-bearing capacity test.

Source: Author's contribution.

The computational analyses took into account the steel elements' presence by using their equivalent cross-sections, derived to the concrete cross-section by multiplying the area of the pipes by the ratio of the elastic modulus of steel and concrete. This way of measuring spot strains in concrete columns was, to the authors' knowledge, used for the first time in the world.

The measurement recording for a particular column started as soon as the sensors were connected, i.e., usually the same day as the installation of the instrumentation in the columns, and has continued uninterrupted to this day. The first sensors were installed on 15 June 2016, more than 8 years ago. Such long measurements carried out throughout all stages of road construction, i.e., construction of columns, column tests, building of the embankment, construction and operation of the road, are an unprecedented phenomenon not only on a national but also global scale. The measurement results obtained will be a source of much valuable information and analyses published in the doctoral thesis of the author of the article.

3. Results

The aim of this article is to present to the reader only the measurement system installed in displacement columns in the actual operating conditions of a construction structure such as a road embankment in difficult geological conditions. The graphs below show the capabilities of this measurement system at the time of carrying out a load-bearing capacity test on the K1 column. Table 1 contains data regarding the load test of the K1 column.

Figure 8 shows the results of measurements of deformations of the K1 column shaft, recorded during the test load by Geokon 4100 sensors. High sensitivity and accuracy of the measurements can be seen.

Figure 9 shows graphs of the change in shaft strains along the depth of the column for the steps of load applied to the column head. The graphs show the results of the measurements taking into account only the calibration factors of the sensors, the nominal cross-section of the column and the nominal (according to the EN standard) elastic modulus of the concrete E_c .

Figure 10 shows a graph of stress changes for subsequent load steps performed in two cycles of the K1 column load-bearing capacity test.

Based on these measurements and readings from the strain sensor installed in the same measuring section at a depth of 1.95 m, the Young's modulus for the concrete of the K1 column can be calculated (Table 2).

With subsequent load levels for the second load cycle, a simultaneous increase in strains and stresses can be observed, while the values of Young's modulus decrease, which is a natural phenomenon. The only exception to this rule can be observed in the second load stage for the force value of 381 kN, where the calculated modulus value is higher than for the first load cycle. For further analyses, this measurement can be omitted, then the graph of the relationship between the modulus and strains can be written as a parabolic function (Figure 11). The range of Young's modulus values depending on the change in strains ranges from 29.5 to 31.5 GPa, and for further analyses, the value of modulus can be averaged and taken as 30.2 GPa.

4. Summary

The displacement-formed piles have been introduced into widespread use relatively recently. There is a lack of long-term tests of them in the literature, particularly when these columns were used to strengthen the ground under a road embankment.

In this work, the authors describe an advanced monitoring system, using VW technology sensors, that continuously measures (from an engineering point of view) the various physical quantities necessary to evaluate the performance of displacement columns over time. This study is the first to define the elements of the monitoring system and present the initial results.

The main conclusions from the research results are listed as follows:

- (1) The example shows that with three types of sensors it is possible to create a measurement system to reflect the behavior of rigid inclusions.
- (2) Presented part of the results from load tests shows that true Young modulus can be estimated from this kind of measurement. This modulus should be used for back analysis and interpretation of further results.
- (3) Presented distribution of force along the pile showed that the suggested sensor setup can bring valuable information of understanding the pile–soil interaction and behavior.
- (4) Strain sensors installed along the length of the column can successfully show the behavior of the column during the production of neighboring columns, thus showing the phenomena occurring in the column during this process. These results have not been shown in this article, they are a further analysis that will be published on the occasion of the author's doctoral thesis.

Analysis of the performance of new structural elements should be the subject of further research.

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Author contributions

Adam Jabłonowski: drafting the entire article. Piotr Kanty: assistance with paragraphs 4 and References. Adam Krasieński: assistance with paragraphs 3 and 4. Rafał Sieńko: assistance with paragraphs 2. Łukasz Bednarski: assistance with Chapter 2. Karolina Makowska: Preparation of the data necessary to create charts (Figures 8–10).

Conflict of interest statement

Authors state no conflict of interest.

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