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Monitoring System of the Road Embankment

Mikołaj Miśkiewicz[1], Błażej Meronk[2],Tadeusz Brzozowski[3], Krzysztof Wilde[4]

[1,2,4] Department of Mechanics of Materials and Structures, Faculty of Civil and Environmental Engineering, Gdansk University of Technology, Gdansk, Poland
[3] Keller Polska Sp. z o.o., Gdynia, Poland
E-mails: [1]mikolaj.miskiewicz@wilis.pg.gda.pl (corresponding author); [2]blazej.meronk@wilis.pg.gda.pl; [3]tbrzozowski@keller.com.pl; [4]krzysztof.wilde@wilis.pg.gda.pl;

Abstract. The paper presents the monitoring system of the embankment supported on concrete columns and overlaid by a load transfer platform (LTP) with the embedded steel grid. This field investigation was to study the complex interaction between the columns, the LTP layer, and steel reinforcement via full-scale in situ measurements during erection of the embankment. The study was focused on the behaviour of steel reinforcement and the behaviour of the outer rows of columns since there are limited reference data available for this problem. The system was designed to provide information to engineers about the condition of the embankment at every stage of construction and during standard exploitation of road. The measurements provided information about the changes of strains of steel grid and concrete columns and settlement of the structure.

Keywords: Embankment, monitoring, SHM, reliability.

Conference topic: Roads and railways.

Introduction

In most civil engineering structures structural health monitoring systems (SHM) are not necessary since civil structures must be systematically checked by an experienced engineer to ensure their technical condition. However, in the case of non-standard structural solutions or objects which technical condition that suggests a special treatment, the use of SHM systems might be the way to obtain a complete knowledge of the current structure state. Therefore, the new structural solution of the road embankment has been equipped with dedicated measurement in situ system. The monitoring system was designed to provide to engineers information about the condition of the embankment in every stage of construction and during standard exploitation of road. The customer assumption for the SHM system was the requirement of supplying as many data from in-situ measurements at the lowest possible price. As in the systems described in Chróścielewski *et al.* (2016), Kaminski *et al.* (2015), Mariak *et al.* (2016), Miśkiewicz *et al.* (2016), Rucka *et al.* (2013), Wilde *et al.* (2013), Rucka *et al.* (2013), the design team was required to provide a product that meets the established conditions. The minimum required scope of the system was to make measurements that provided information about the changes of strains of steel grid and reinforced concrete columns and settlement of the structure. The assigned task was performed even better than expected. The allocated budget allowed for the implementation of the system in such a way that the most important measurements were confirmed by additional, independent sensors and devices of a different type. Unfortunately, the realities of the site and lack of caution of the worker during the construction caused that part of the sensors at the beginning of their work were damaged.

Embankment and monitoring system

The monitored embankment is located next to the bridge (Fig. 1a). It is supported on Controlled Stiffness Columns (CSC), constructed by Keller Polska, and overlaid by a Load Transfer Platform (LTP) with embedded steel grid (Fig. 2). The subsoil condition near the bridge is very unfavorable: over 15 meters of mud, peat and gyttja over moraine clay and fine sand. The structure of the embankment is the foundation on CSC columns diameter 360 mm with spacing changing from 1.4×1.9 m to 1.6×2.2 m. The design was based on ASIRI 2012.

The aim of this field investigation was to study the intricate (complex) interaction between the CSC columns, the LTP layer, and steel reinforcement via full-scale in situ measurements during erection of the embankment. The study was focused on the behaviour of the steel reinforcement and the behaviour of the outer rows of columns since this component is crucial for proper operation of the embankment. Appropriate design of the LTP layer with steel grid should reduce the significant horizontal forces acting on the outer CSC columns reducing their bending. The obtained measurement data will be used for subsequent back analyses and FE calculations, with the aim to develop and verify own design procedures and enabling better handling of the risk involved in similar ground strengthening projects.

It was assumed that the key parameters of the embankment monitored during the progress of the construction were measured by independent sensors working with different technology. For example, the elongation of the steel grid was measured by a long base extensometers and small base extensometers based on vibrating wire sensors technology.

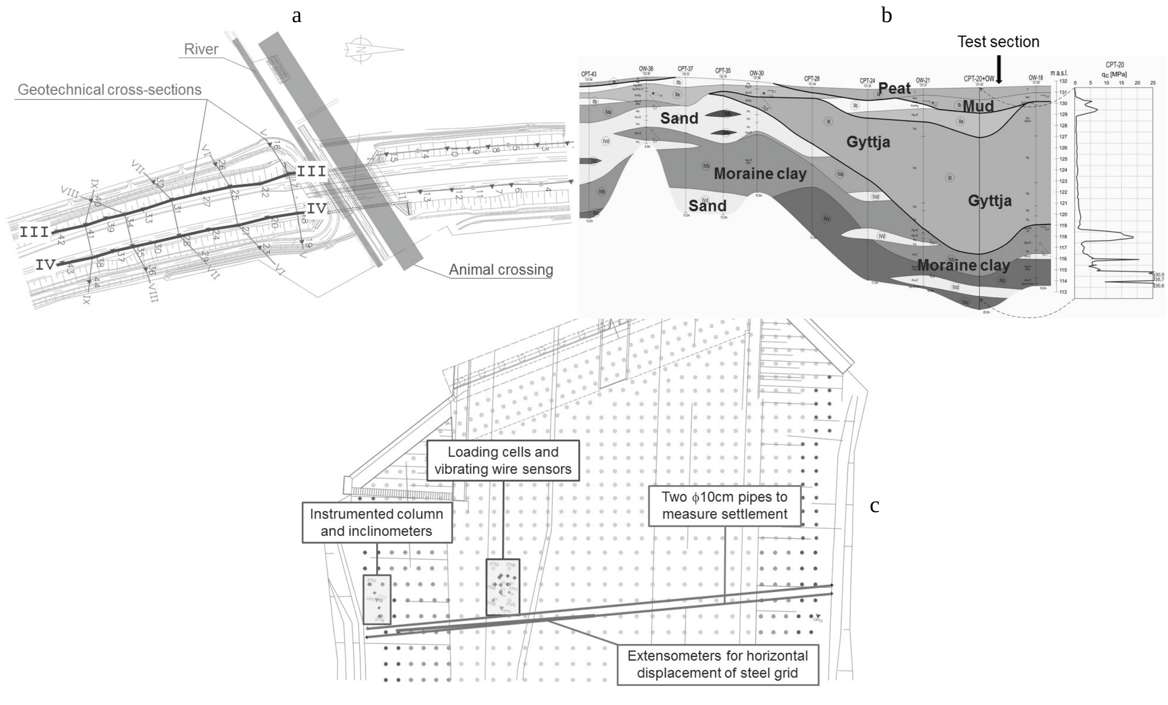


Fig. 1. a. Top view of the monitored embankment; b. Soil cross-section; c. Location of instruments in the selected cross-section of the embankment

The monitoring program included the following measurement components (Fig. 1b, 2, 3a, 3b):

– forces in outer CSC column − 12 strain gages welded to steel beam IPE160 (4 sensors at three levels);
– distribution of vertical stresses on the columns and subsoil − load cell sensors mounted on the columns heads (2 sensors) and the subsoil (4 sensors);
– forces in the steel grid and horizontal displacements of steel grid − 14 strain gauges and four long base extensometers mounted to the steel grid;
– settlement of the embankment − measurements in one cross-section of the embankment, in two PVC pipes using “hydrostatic leveller”;
– horizontal displacements of the outer columns − measurements carried out using an inclinometer. Two steel square inclinometer tube, length about 12 m, were installed alongside steel reinforcement in two outer columns;
– horizontal displacements of the subsoil between outer the columns − task carried out using an inclinometer. Two inclinometer PVC pipes, diameter 70 mm and about 16 m long, were installed between outer columns.

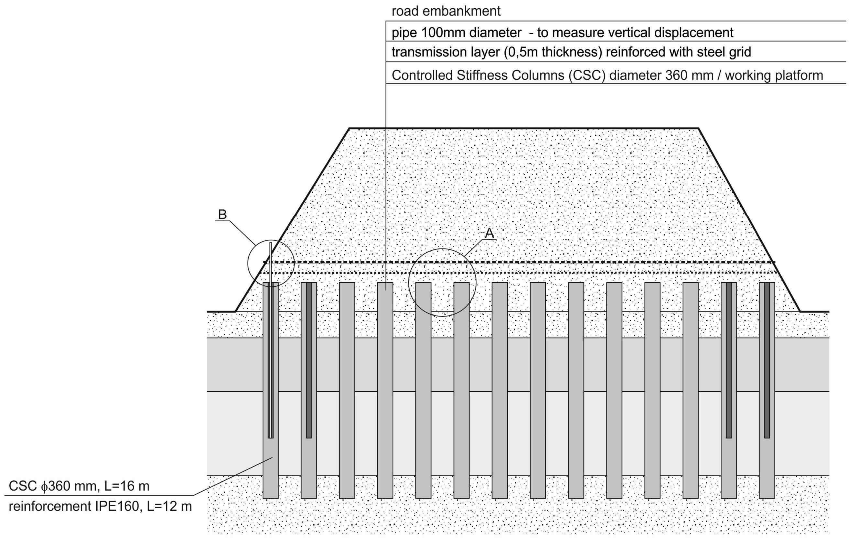


Fig. 2. Measurement scheme on cross-section of the embankment

The monitoring system designers sought to create a system that will not require electrical supply. What was also important they were looking for solutions mostly based on the compatible sensors allowing to simplify the data acquisition process? Finally, vibrating wire sensors were used for monitoring strains in the steel grid and column reinforcement as well as the pressure acting on columns heads and subsoil.

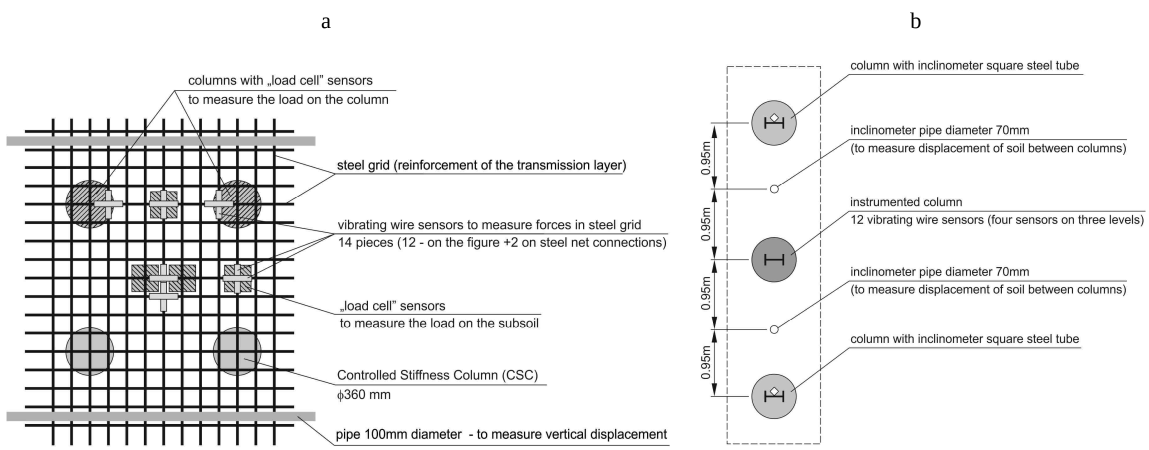


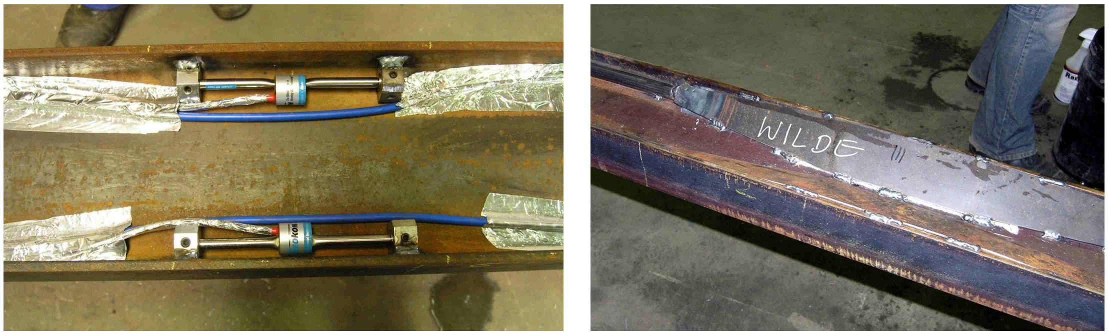
Fig. 3. a. Location of measurement points of forces in steel grid and pressure on columns heads and subsoil; b. Location of measurement points on CSC columns

Measurements

Location of various components of the monitoring system is shown in Figure 1b.

Forces in CSC outer column

Force identification in CSC columns was possible on the base of strain measurements. The vibrating wire sensors with the base 150 mm were used (Fig. 4a). Its range is 3000με, resolution 1με, accuracy ±0.5% F.S. and nonlinearity <0.5% F.S. These sensors can work in the temperature range from -20°C to +80°C. The sensors consisted of a length of steel wire tensioned between two mounting blocks that were arc welded to the steel surface. The sensors had excelent stability over an extended period. The essential task was to protect the vibrating wire sensors and cables against possible damage during installation in the CSC column. That was why preliminary tests and calibration procedures were done in workshop few weeks before installation on a construction site. After sensors installation, they were protected by steel plates (Fig. 4b).



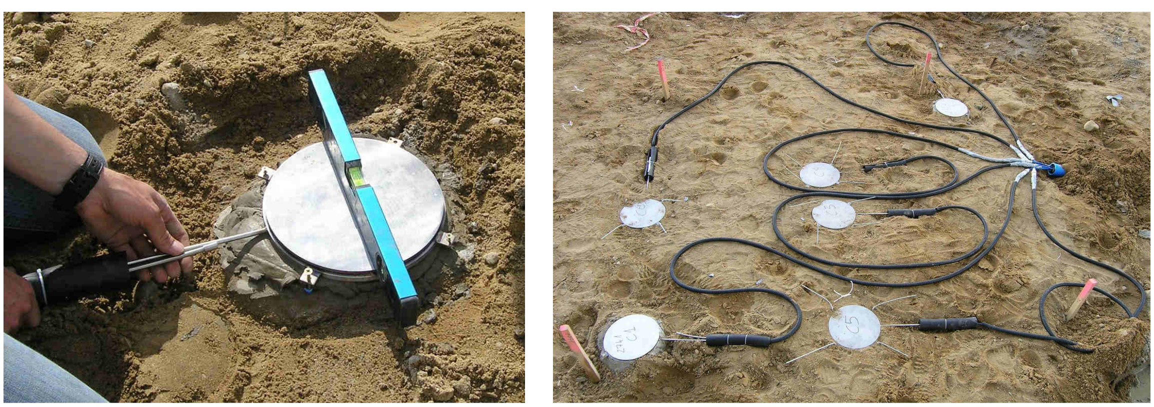
a b

Fig. 4. a. Strain gages installed on IPE160 profile CSC − column reinforcement; b. Steel plate protecting measuring points

Control measurements taken after installation of the instrumented profile in the chosen column indicated that all 12-sensors were fully operational and that the readings were in the desired range. It confirmed that the protection and installation procedures were appropriate.

Pressure on CSC columns and subsoil

Vertical stresses acting on the columns heads and the subsoil were measured using vibrating wire earth pressure cells with diameter 230 mm (Fig. 5b). These cells with ranges 5MPa (on columns heads) and 70kPa (on subsoil) had a resolution of 0.025% F.S., and accuracy ±0.1% F.S. These can work in the temperature range from -20°C to +80°C. Used cells (Fig. 5a) consisted of two circular stainless steel plates welded together around their periphery and spaced apart by a narrow cavity filled with de-aired oil. Changing earth pressure squeezed the two plates together causing a corresponding increase in fluid pressure inside the cell. A vibrating wire pressure transducer converted this pressure into an electrical signal which is transmitted to the readout location. The site of the used cells is presented in Fig. 5b. Stresses acting on the ground were measured at the centre between four adjacent CSC columns and between "side" CSC columns. Cells placed on the columns were levelled and screwed (Fig. 5a). Pressure cells on the ground were placed directly on a compacted soil between the columns, fixed in positions with pins and backfilled.



a b

Fig. 5. a. Pressure cells assembly; b. Pressure cells before backfilling

Forces in steel grid

Two independent systems made force identification in a steel grid. First of them based on strain measurements with the use of the same type of sensors that were used in columns, i.e., strain gages. The second system was based on long base multiple point extensometers.

Short base vibrating wire sensors were attached to the steel grid by welding (Fig. 6a). The works were conducted after backfilling of the first part of the LTP layer (Fig. 6b). The instrumented steel grid was laid down on the compacted fill. Afterward, the vibrating wire sensors were covered with waterproof boxes to protect them from external influences. The sensor shields were constructed using plastic boxes, sealed with micro-rubber and silicone sealant. The control measurements after installation of all sensors showed that each of them was operational and the readings were within the desired range.

a b

Fig. 6. a. Strain gages on the steel grid; b. Location of the protected sensors before backfilling

Unfortunately, during fill compaction by the GC using the smallest vibrator equipment available on site, 7 of 14 strain sensors experienced excessive deformations. The vibro-compaction caused seven sensors to reach the readings above the allowable range. It was assumed that some of the sensors have been damaged and have changed their measurement parameters. Most likely they were damaged due to excessive bending occurring during compaction and localized plastic deformations of the transmission layer and the soil underneath. Consequently, the possible readings of the remaining and still "operating" grid sensors had to be interpreted with caution and cross-checked with other measurements.

Long base extensometers measured "elongation" of steel grid sheets laid down on the ground with an overlapping. The device consisted of four steel wires with different lengths (from 14.465 m to 23.743 m) connected to steel grid sheets in selected locations, and the measuring "box" with four extensometers screwed to the steel grid at the centre of the embankment (Fig. 7). All wires were covered with PVC protection tubes. Extensometers were installed across two or three separate steel grid sheets.

Fig. 7. Long base extensometers for measuring elongation of the steel grid

Embankment settlement

The last elements of the monitoring system, installed after backfilling previous sensors, was the embankment settlement system along the entire cross-section of the embankment. The system was based on the assembly of tubes in which precise differential pressure transducer was moved. The method is called hydrostatic levelling (Boerez *et al.* 2012).

Two horizontal tubes were installed (Fig. 8a, 8b). Initially, it was planned to install one tube beneath the transmission layer and the second one above this layer. However, because the monitoring system was a prototype, it was decided to double the measurements conducted at the top of the transmission layer. Both tubes of 10 cm diameter were made of PVC, corrugated outside and smooth inside. At both ends of each tube steel H-beams of 1 m length were attached (Fig. 8a). The steel beams allowed to stabilize the tubes and were also used for installation of the reference pins needed for geodetic measurements.

a b c

Fig. 8. a, b. Installation of tubes; c. First measurement after tubes backfilling

The settlement at the LPT level was measured using a very precise differential pressure transducer (Fig. 8c). The device consists of a probe, inserted into the tube and pulled the tube using a rope. Inside the probe, there is a sensor with a membrane recording small pressure changes for determining the relative height of the probe. The relative height readings were converted to absolute level data based on geodetic measurements taken at the reference pins located on both sides of each tube.

The initial tests have confirmed that the accuracy of settlement measurements with the described system was less than 1 mm. It is noted that this device has a measurement precision on other geodetic systems like for example terrestrial laser scanners (Bernat *et al.* 2014; Janowski *et al.* 2015; Laskowski *et al.* 2014; Szulwic *et al.* 2016). The hydrostatic levelling device, designed and produced by this monitoring system, made control of vertical displacements of the entire cross-section of the embankment possible. The measurements could be conducted within the transmission layer providing reliable information about its response.

Results

The data obtains from the monitoring system are in the process of interpretation and verification. Due to the failure of some sensors during embankment construction, at this stage, the settlement results may be used for direct presentation. The obtained results indicate that settlement process finished around 12 months after completion of the embankment construction (Fig. 9).

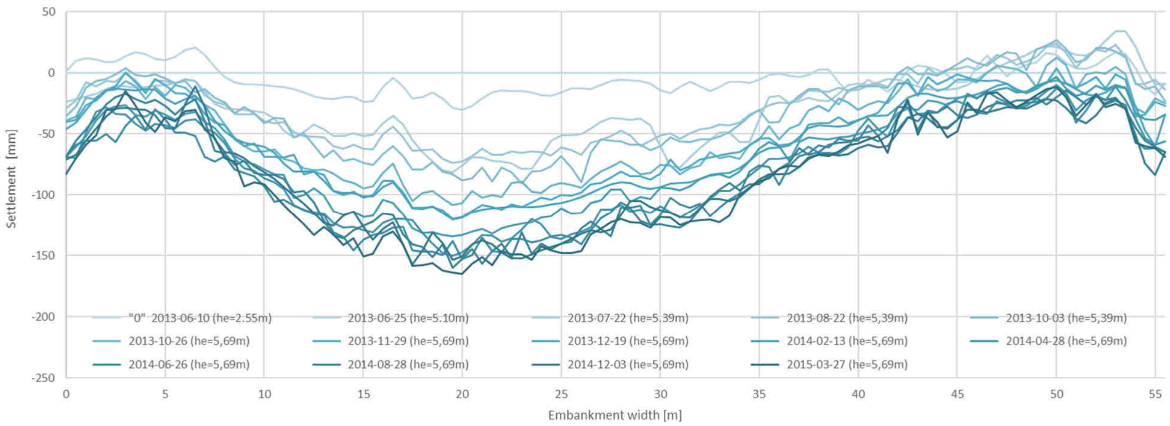


Fig. 9. Embankment settlement during construction (he – height of embankment)

It can be stated that the real behavior of the embankment was in line with designer expectations (Sondermann *et al.* 2014). However, the interpretation of other measurement data is relatively complex. It requires extensive numerical simulations to find the solution to the inverse problem.

Conclusions

The Load Transfer Platform with steel grid reinforcement is an innovative structure. For this reason, the scientists from Gdansk University of Technology have been invited to cooperation by Keller Polska to apply the technical system monitoring of that solution. The system installed under the embankment, allowed to perform detailed measurements of the foundation behavior for several years. It consisted of several measurement methods. Two of them were the prototype ones: hydrostatic levelling of the embankment and long base multiple point extensometer measurements of the steel grid. Both systems have proven themselves in the presented *in-situ* application. They gave a reasonable results and allowed caring out long-term structure observation. Much worse experience were gathered by authors from measurements of strains on CSC columns and steel grid with the use of short base vibrating wire strain gages. The test column was impacted by installation of the adjacent columns. This process resulted in temporary increase of stress to very high values, that consequently disturbed the interpretation of further measurements. The similar problem concerned the strain measurements in the steel grid. Some of the vibrating wire sensors were destroyed during backfilling and compaction of the transmission layer. This happened despite the use of a thicker transmission layer and switching off roller vibrations.

Nevertheless, the collected results enabled the insight into the embankment condition. They allowed for assessment of the effectiveness of the adopted solutions with the use of steel grid in transmission layer of the embankment. In addition, the prototype technical monitoring system gave the opportunity to draw conclusions regarding the installation of similar systems in the future.

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