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Analysis of rheological phenomena in reinforced concrete cross-section of Rędziński Bridge pylon based on in situ measurements

Łukasz Bednarski[a], Rafał Sieńko[b,]*, Tomasz Howiacki[b]

[a]*AGH University of Science and Technology, Al. Mickiewicza 30, 30-059, Poland*
[b]*Cracow University of Technology, Warszawska 24, 31-155 Kraków, Poland*

Abstract

The creep of concrete is a phenomenon that is often the cause of excessive deformation of the structure in serviceability limit state. In fact, creep strains are generally larger than elastic strains which occur on the application of load. Creep is affected by many factors both internal - related to the properties of specific concrete and external - related to the operating environment. In addition, attention should be paid to the fact that in real structures concrete almost always interacts with the reinforcement. This article examines the rheological phenomena that occur in the reinforced concrete cross-section of the Rędziński Bridge pylon in Wrocław, using in situ measurements from an automated structural health monitoring system.

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Keywords: Creep of concrete; Structural Health Monitoring

1. Introduction

Several hundred years before Christ, Heraclitus's statement: "everything flows" (Greek. panta rhei) became famous. Of philosophical nature originally, many centuries later it became an inspiration for giving the engineering science a name of rheology. In general, this science deals with the flow properties of materials, i.e. progressive strains under acting stress over time, the strains being plastic.

* Corresponding author. Tel.: +48-502-646-975
E-mail address: rsienko@pk.edu.pl

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The most important rheological phenomena occurring in concrete cross-sections, and practically in reinforced or prestressed concrete, include shrinkage and creep of concrete as well as steel relaxation. This article analyzes the changes in stress and strains in the concrete, highly reinforced cross-section of the Rędziński Bridge pylon in Wrocław (Fig. 1).

Relaxation is defined as a decrease of stress in the material with no changes in strains. Relaxation of steel depends significantly on the value of the stress ratio in the analyzed element to the strength of the material from which it is made. The effort of reinforcing steel caused by a long-term loading, in most cases does not exceed 50%, hence the relaxation phenomenon is not so important. Therefore, this paper focuses primarily on the phenomena of shrinkage and creep in concrete.

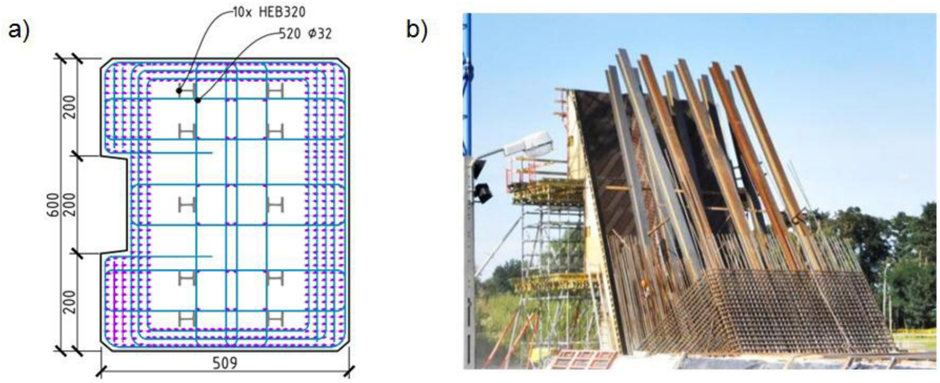

Fig. 1. Rędziński Bridge in Wrocław: (a) cross section; (b) view from a construction stage [10].

The pylon is made of concrete class C50/60 on broken granite aggregate, with a maximum size of 16 [mm]. Portland cement CEM I 42.5 was used as a binder, but in the initial phase of the concreting (for the most massive sections) CEM III 42.5N was applied [2].

2. Concrete shrinkage and creep

The shrinkage of concrete should be understood as a reduction of its volume as a result of the hydration process and the loss of water by drying. This phenomenon is affected by, inter alia, water-cement ratio, type and amount of aggregate, cement type, concrete strength, admixtures used, the operation conditions and the duration and type of concrete curing in the early stages of hardening [12, 13]. This is when concrete is particularly susceptible to shrinkage cracking.

The legs of the Rędziński Bridge pylon are of custom, very large sizes: the section perpendicular to the longitudinal axis just above the upper surface of the foundation slab has dimensions of 6x5 [m]. Therefore, the value of notional size defined in [1] as the ratio of doubled cross section area to perimeter of that part which is exposed to drying is very large and is equal to h_0 = 2580 [mm]. The drying shrinkage in such a massive element will occur over a long period of time. Typically, its value compared with autogenous shrinkage is much greater at an early stage of hardening, but in the considered case, these values are equalized theoretically after about 30 years from the date of concreting of the analyzed segment. The growth of autogenous, drying and total shrinkage strains, calculated according to [1], is shown in the plots below as a function of time. The shrinkage strains values are expressed dimensionless in microstrains: 1 [uD] = 10^{-6}.

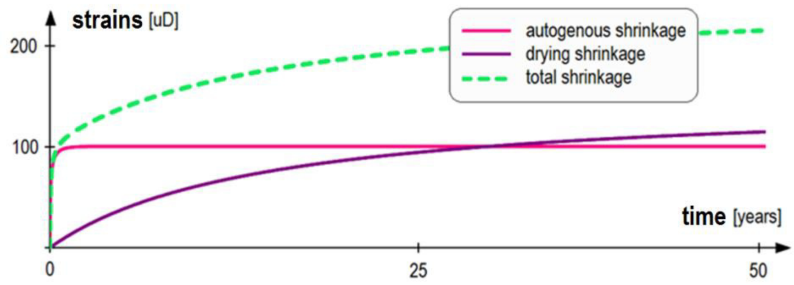

Fig. 2. Autogenous shrinkage, drying and total as a function of time [10].

Looking at the curves it can be noticed that in the analyzed period of time, i.e. after two years from the time of concreting the bottom section, autogenous shrinkage was completed, so further shrinkage strains will result only from strains caused by drying. However, both the values and the speed of increase are relatively small.

The increase in concrete strains under constant, permanent load (stress), called creep, will occur parallel to the shrinkage. In fact, this definition refers to the simple creep. In reality, the section analyzed will working in a more complex way, also because the total constant load has not been applied at a single point in time. The construction of the pylon took many months, working in a variety of static schemes, and finally it was loaded by the weight of the decks transferred by the shrouds. Creep coefficient φ physically represents the ratio of plastic strains caused by the phenomenon of creep, to the elastic, which arose in the element immediately after the load transfer. Graphic interpretation of the coefficient is shown in Fig. 3a.

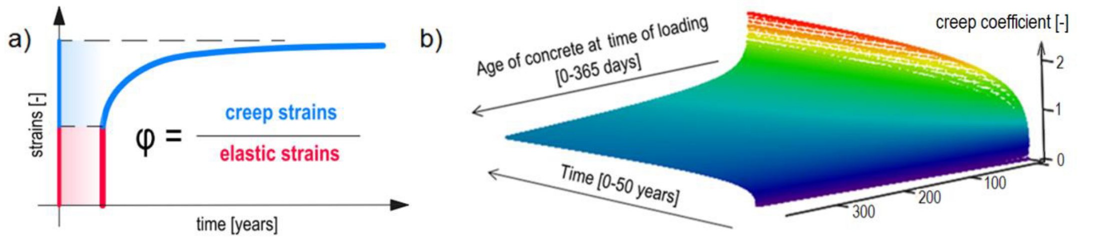

Fig. 3. (a) Idea of simple creep coefficient; (b) variability of creep coefficient depending on time and age of concrete at time of loading.

The value of the creep coefficient is influenced by many factors, the most important ones are: the analyzed moment of time, the age of concrete at time of loading, the value of this load, concrete strength, type of cement and aggregate used, ambient temperature, relative humidity, and also geometry (notional size of the section).

Above (Fig. 3b) a spatial graph of creep coefficient is presented, determined according to [1] for the relative atmospheric humidity of RH = 80[%], depending on the age of concrete at the time of loading and analyzed time. The figure clearly shows that the value of creep coefficient increases with time, and becomes higher with the load applied earlier. However, on the basis of the procedures described in [1], it is not possible to estimate the theoretical value of the coefficient in specific time, due to the lack of a clear definition of loading time. The final creep strains in [1] are calculated from the formula:

$$\varepsilon_{cc}(\infty,t_0)=\varphi(\infty,t_0)\cdot\frac{\delta_c}{E_c} \tag{1}$$

where σ_c is a permanent compressive stress in the cross-section, E_c elasticity modulus of concrete, and t_0 is the age of the concrete at time of loading. During the construction of the Rędziński Bridge pylon due to, among other things, incremental loads and the changing static schemes, tensile stress occurred at selected places in the pylon legs. In this case, the actions were not long-term, so they did not have a significant impact on the course of creep. It should be noted, however, although it was not explicitly stressed in [1], that creep takes place also under the influence of tensile stress and rheological strains may be in such cases even higher than those resulting from compression [4, 5]. It should also be remembered that in the case of cross sections under long-term compression, such as the analyzed example, shrinkage and creep phenomena cause strains of the same sign, and therefore their value should be added. Finally we can write:

$$\varepsilon_{tot}(t,t_0) = \varepsilon_{ca}(t,t_s) + \varepsilon_{cd}(t,t_s) + \varepsilon_{cc}(t,t_0) \quad (2)$$

where ε_{tot} is the total rheological strain, ε_{ca} - autogenous shrinkage strain, ε_{cd} - drying shrinkage strain, ε_{cc} – creep strain, t - considered time moment, t_s - the age of concrete at time when curing was terminated. In the case of tensile stress, creep effects would be reduced by the effects of shrinkage.

There are many mechanical models representing the work of (reinforced) concrete cross sections over a long period of time. Some of the basic visco-plastic models for concrete and reinforced concrete are shown below.

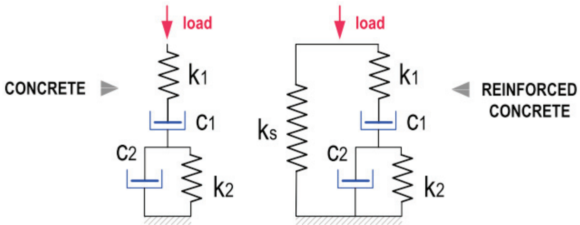

Fig. 4. Visco-plastic models for concrete and reinforced concret in axial stress state [3].

The springs of stiffness k_1 and k_2 represent the elasticity modulus of concrete, $c_{1,2}$ – specified damping values and k_s - steel work. However, it should be noted that even the most advanced mathematical models are not able to represent the full complexity of the real structure work. The best solution is to examine the structure in situ.

3. Structural Health Monitoring System for Rędziński Bridge in Wrocław

Rating of bridges in Poland, estimated on the basis of periodic inspections taking into account such criteria as safety and load-bearing capacity of the structure is increasing in recent years.

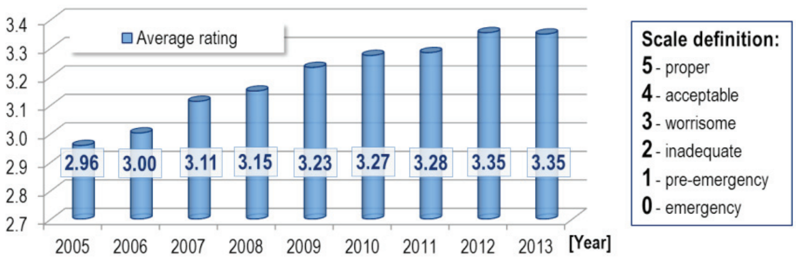

Fig. 5. Average rating of bridge structures in Poland in recent years [GDDKiA].

Independent of periodic inspections, structural health monitoring systems are installed on bridges more and more frequently, which not only improves their safety, but also provide many important information from the scientific point of view about the work of the monitored structures. One of the most modern and biggest of such type of systems in Europe was installed on the reinforced concrete bridge with the largest surface area in the world – the Rędziński Bridge in Wrocław. This bridge is a structure suspended to the A-shaped pylon [6].

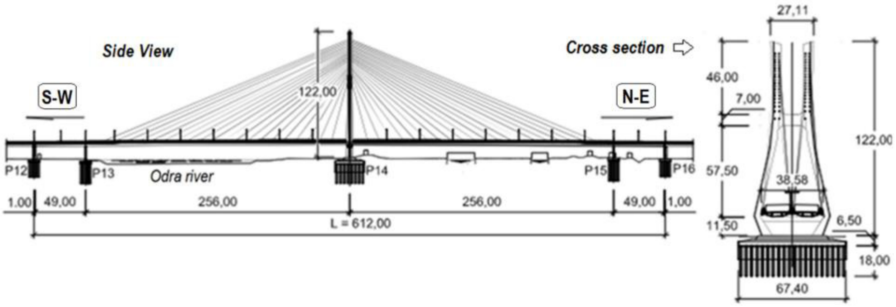

Fig. 6. Bridge side view and cross section through the pylon [6].

What is a particularly interesting element in the whole structure, from the scientific point of view, is the pylon because of its very large dimensions, geometrical form and strong reinforcement. To determine the part of strains (stress) which are transferred only by concrete cross-section and by reinforcing steel, string sensors were installed in every corner of both legs of the pylon to measure concrete and rebars strains as well as "stress" in concrete. These sensors are based on the relationship between the changes of natural frequency of the built-in strings depending on the length changes [7]. The measurements are carried out continuously from the engineering point of view (every 15 minutes), which enables a comprehensive evaluation and analysis of the steel – concrete interaction in the reinforced concrete cross-section over a long period of time (i.e. taking into account the impact of rheological phenomena).

Stress is a fictional quantity which cannot be measured directly. However, the “stress" sensor design allows comparing the force resulting from the strains of steel string to the cross-sectional area formed by concrete cylinder inside the porous pipe, connected in series with the string. To fill the tube, the same concrete as in the analyzed part of the pylon was used. The use of the "stress" sensor with three strain sensors (with 150mm base) arranged around, allows the estimation of the changes in the effective elastic modulus of concrete over the time [11].

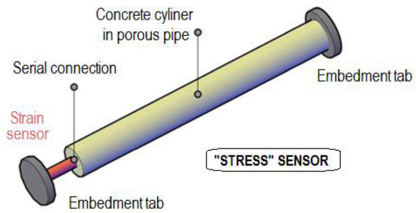

Fig. 7. Design scheme of string “stress” sensor in concrete [9].

To measure the strains of rebars two sensors with measuring base of 50mm were attached to the steel sheet by spot welding of their tabs. The sheet was welded directly and in parallel to the examined bars. The location of measurement points in the cross section of the pylon legs just above the upper surface of the foundation slab and the sensor layout in each of the measuring points is illustrated below.

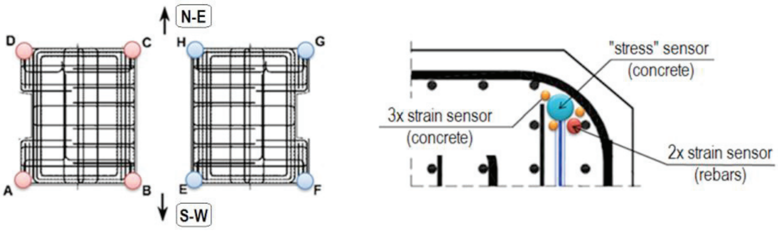

Fig. 8. Cross section of the pylon legs just above the upper surface of the foundation slab with the sensor layout in each of the corners [6].

4. Interpretation of results

The Rędziński Bridge was put into operation in early August 2011. This paper presents data from the measuring system which were obtained after that date, although earlier measurements were also carried out. However, during the construction, due to the increasing load, changing static scheme and other factors, the interpretation of these data would be very difficult. Structural health monitoring system in this case is primarily designed to analyze the structure's response during its operation time. The plot in Fig 9 shows the changes in the value of stress in the concrete and reinforcement bars (it was assumed that steel works in the elastic range with Young's modulus of 205 [GPa]) in the period from 08.08.2011 to 28.12.2011, that is in the first months of the bridge operation. The beginning of this period corresponds to the age of concrete in the analyzed section equal to about two years.

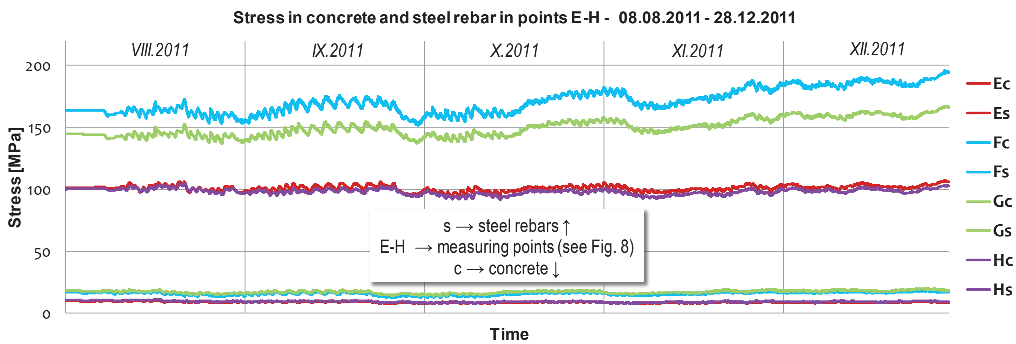

Fig. 9. Stress in concrete and steel rebars in analyzed cross-section in measuring points E-H.

The outer edges of the cross section of the pylon, due to its geometric configuration, will be characterized by a larger compressive stress than the inner edges - Fig. 10. In this areas we will expect higher stress increases in reinforcing rods over a time.

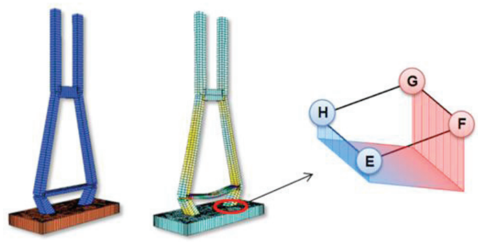

Fig. 10. Numerical model [SOFiSTiK] of the pylon with the scheme of stress distribution at the base caused by its dead weight.

Stress in each of the materials were compared to the total value of stress, which are applied to the section, to better illustrate the steel and concrete cooperation. The following formulas are proposed for this purpose:

$$\delta_{s\%} = \frac{\delta_s \cdot A_s}{\delta_s \cdot A_s + \delta_c \cdot A_c} \cdot 100\% \tag{3}$$

$$\delta_{c\%} = \frac{\delta_c \cdot A_c}{\delta_s \cdot A_s + \delta_c \cdot A_c} \cdot 100\% = 100\% - \delta_{s\%} \tag{4}$$

where $\sigma_{s\%}$ and $\sigma_{c\%}$ mean percentage of stress transferred in section, respectively by the steel and concrete. σ_s and σ_c are the stress in steel and concrete, determined directly from the measurements, and A_s and A_c are areas of both this materials. Results of the analysis are shown below. The linear trend lines are bolded for each of the points.

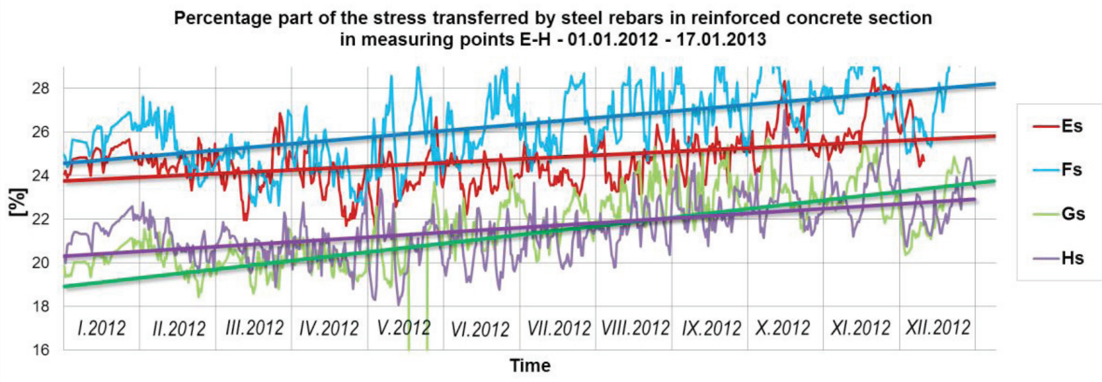

Fig. 11. Percentage part of the stress transferred by steel rebars in reinforced concrete section in measuring points E-H in the period from 01.01.2012 to 17.01.2013.

Looking at the plot above we can notice that the stress transfer in steel rebars occurs faster in points F and G, where there are greater compressive stress (compare Fig. 10). A similar situation takes place in the second leg of the pylon, i.e. in the measuring points A-D. This behavior confirms the rightness of the formula (1), in which creep strains depend directly on the value of compressive stress.

It would be very interesting to analyse the impact of weather conditions on the behavior of the bridge pylon. To make this analysis possible and valuable, the sensors for humidity of air as well as concrete, should be installed. Then, the influence of relative humidity and temperature on mechanical work of the structure would be estimated. Also it should be noticed, that inference about the influence of the ambient would be reasonable only after interpretation data from more than one year of the bridge operation.

The data from the measuring system can be compared with calculations made in accordance with [1]. Rheological strain in the considered period of time will consist of drying and creep strains of concrete, wherein the values obtained after two years should be subtracted from values calculated after three years. Assuming the age of the concrete at time of loading equal to 1.5 years and the stress in the concrete at 15 [MPa], the theoretical strain rheology is: ε_{reo} = 47 [uD], which corresponds to a change in rebar strain at 9.7 [MPa]. Assuming initial average stress in steel rebars at 130 [MPa], during one year it should be increased by approximately 7 [%]. Looking at the plot above it can be stated that the annual increase in stress which are transferred by rebars in reinforced concret cross section was equal approx. 15 [%]. However it should be noted that in [1] there is no accurate method for determining the age of the concrete at loading time. When we assume this age equal to two years, the theoretical value of the percentage growth of steel stress exceeds 20 [%]. The analysis of measurement data from consecutive years of operation will be extremely valuable in the context of further comparisons of the real response of the structure with theoretical calculations.

5. Summary

The massive concrete structures are usually calculated using numerical models, in which a simple model of creep is used. However this model does not include the actual conditions of erecting process and structure operation, as well as differences in the case of compression or tension [5]. In reinforced concrete cross section the rheological phenomena are become stronger over a time, and they are associated primarily with the creep of concrete, but also with its shrinkage and steel relaxation. As a result of rheological strains in concrete we should expect that in the long term it will be "relaxing", transferring some stress on the rebars. This phenomenon is confirmed by data from the structural health monitoring system installed in the lower segments of Rędziński Bridge pylon in Wroclaw. The percentage of the stress transferred by the steel in the first year of operation of the bridge has increased by approx. 15 [%]. This results fit in the strain values estimated in accordance with [1].

In the past many attempts were undertaken to examine the phenomenon of creep by laboratory tests or computer simulations, but the advantage of using structural health monitoring systems is that the actual structure is examined under its operation conditions. Measurements on Rędziński Bridge will be carried out over next several decades. Thus, great database, extremely valuable from a scientific point of view, will be created. In the future, data analysis and interpretation will help us to better understand the way of work of strongly reinforced, massive concrete elements. The long term behavior of the concrete (especially high strength) have not been comprehensively investigated [8]. Thus, it seems reasonable to install monitoring systems in structures made particularly of this material.

References

[1] PN-EN 1992-1-1 Eurocode 2, Design of concrete structures, Part 1-1: General rules and rules for buildings.
[2] Seruga A, Kańka S, Lisowicz T. Granite concrete modulus of elasticity in view of experimental investigations, *Technical Transactions* 2012;4-B:103-17.
[3] Castro J. Time-dependent Residual Stresses in Reinforced Concrete Columns, Proceedings of the XIth International Congress and Exposition, Orlando; June 2008.
[4] Atrushi DS. Tensile and Compressive Creep of Early Age Concrete: Testing and Modelling, Doctoral Thesis, Norway; March 2003.
[5] Hilaire A. Modeling basic creep in concrete at early-age under compressive and tensile loading. Nuclear Engineering and Design, NED 7392; 2013.
[6] Barcik W, Sieńko R, Biliszczuk J. System monitorowania konstrukcji mostu Rędzińskiego we Wrocławiu. Wrocławskie Dni Mostowe, Aktualne realizacje mostowe, Wroclaw; November 2011.
[7] Bednarski Ł, Sieńko ., Pomiary odkształceń konstrukcji czujnikami strunowymi. *Inżynieria i Budownictwo* 2013;November:615-19.
[8] Al-Omaishi N, Tadros MK, Seguirant SJ. Elasticity modulus, shrinkage, and creep of high-strength concrete as adopted by AASHTO. *PCI J* 2009;Summer.
[9] www.geokon.com.
[10] www.obwodnica-wroclawia.pl.
[11] Bednarski Ł, Sieńko R, Howiacki T. Estimation of the value and the variability of elastic modulus of concrete in existing structure on the basis of continuous in situ measurements. *Cem-Lime-Concr* 2014;6:396-404.
[12] Seruga A, Zych M. Research on Thermal Cracking of a Rectangular RC Tank Wall under Construction. I: Case Study. *J Performance Constructed Facilities*, December 2014.
[13] Zych M. Research on Thermal Cracking of a Rectangular RC Tank Wall under Construction. II: Comparison with Numerical Model Journal of Performance of Constructed Facilities, December 2014.