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Research paper

Identification of ground anchors reliability based on acceptance tests and the polynomial chaos expansion method

Marek Wyjadłowski[1], Michał Špitalniak[2], Zofia Zięba[3], Łukasz Gajowniczek[4]

Abstract: The paper presents a reliability analysis of ground anchors based on acceptance tests and the polynomial chaos expansion method. First of all, it was estimated the probability of meeting the requirements of acceptance tests based on anchor tests realised within the S10 expressway near Bydgoszcz (Poland). The testing of grouted anchors is a mandatory requirement. The Test Method 3 TM3 was used in the given case, according to the EN ISO 22477-5:2018 standard. Based on the direct statistics of anchor displacement over a cycle of two measurements of 3 minutes and 15 minutes, creep velocity values were generated using the polynomial chaos expansion *PCE* and Monte Carlo *MC* methods. The polynomial chaos expansion is one of the available approaches to describe probability densities function *PDF*. The *PCE* method is an extension of techniques using the Fourier series or Taylor series. *PCE* is dedicated to density functions and is based on specific polynomial functions. The *PoCET* package, which is a set of computational tools in the *Matlab* environment, was used to carry out the calculations. Creep speeds calculated using the *PCE* method take into account possible inaccuracies in the time reading of the two measurements of 3 and 15 minutes. Based on the generated creep velocities, the Cornell reliability index β_c was estimated to meet the requirements of acceptance testing of ground anchors. The obtained values of the β_c meet the requirements for the *RC3* reliability class for structures with a service life of 50 years.

Keywords: acceptance test, ground anchor, polynomial chaos expansion, reliability

[1]PhD., Eng., Wrocław University of Science and Technology, Faculty of Civil Engineering, Grunwaldzki Sq. 11, 50-377 Wroclaw, Poland, e-mail: marek.wyjadlowski@pwr.edu.pl, ORCID: 0000-0003-0411-952X
[2]PhD., Eng., Wrocław University of Environmental and Life Sciences, Institute of Environmental Engineering, Grunwaldzki Sq. 24, 50-363 Wroclaw, Poland, e-mail: michal.spitalniak@upwr.edu.pl, ORCID: 0000-0002-9801-9388
[3]PhD., Eng., Wrocław University of Environmental and Life Sciences, Department of Civil Engineering, Grunwaldzki Sq. 24, 50-363 Wroclaw, Poland, e-mail: zofia.zieba@upwr.edu.pl, ORCID: 0000-0002-0106-3527
[4]MSc., Eng., Gollwitzer Polska Sp. z o.o., Cesarzowice 21A, 55-080 Katy Wroclawskie, Poland, e-mail: gajowniczek@gollwitzer.pl, ORCID: 0009-0003-9254-6421

1. Introduction

The paper presents an application of statistical methods for the determination of the force-displacement curves of prestressed grouted anchors installed in boulder clay and the calculation of the anchor's reliability in meeting the requirements acceptance test. Designing ground anchors requires knowledge and experience in engineering practice. Construction elements of this type have been used willingly for many years, which proves that they fulfil their tasks. Injection anchors as part of the system constituting the retaining structure are an element responsible for the safety of the entire structure.

The bearing capacity of the anchors is predicted and designed as a deterministic value based on an empirical expression; however, due to the random nature of the substrate, the final verification is conducted using creep tests after a static pull-out load test [1,2].

The external load-bearing capacity of the anchor is the limiting force, when exceeded, creep occurs, leading to the removal of the fixed length from a substrate. The value of the force is equal to the limiting resistance of the side of the grout body at contact with the soil medium. The geotechnical load-bearing capacity of the anchor depends on the surface of the side and the geotechnical parameters of the soil (density index I_D, liquidity index I_L, internal friction angle φ, cohesion c, filtration coefficient k, soil porosity n) which determine the strength of the soil medium and the injection range. In loose soils, the load-bearing capacity depends mainly on the density index and grain size of the soil and the injection pressure, and in cohesive soils on the liquidity index of the substrate and the number of secondary injections [3,4].

Calculations based on geotechnical data should only be used for suitability determination of the geometric parameters of the anchor. Standard EN 1997-1-2004 [5] specifies that anchors may be used only after preliminary tests or by analogy to already constructed structures in similar ground conditions.

Following the EN 1997-1-2004 [5] and EN 1537:2013 standards [6] each anchor should be subjected to acceptance testing. Such a test takes place during the stressing of the anchor tendon and involves the anchor deformations as a function of the load increase. This is an essential step in the construction of the anchor, allowing for a qualitative assessment of its paper in the ground and confirmation of achieving the design load-bearing capacity.

This work analysed tests of ground anchors carried out in October and November 2020 as part of the construction of the S10 expressway near Bydgoszcz. The design solution assumed the construction of a retaining wall made of steel sheet piles between the access road and the expressway. On a section of 474.00 m, the planned expressway route was located near the existing buildings, so it was not possible to design a slope. The project assumed securing the excavation using the technology of vibrated sheet piles, which at a later stage, after providing support with permanent ground anchors and a reinforced concrete cap, constituted the final retaining structure.

The anchor capacity was predicted and designed as a deterministic value based on empirical formulation. The final verification of anchorages was subsequently performed using creep tests after prestressing of anchors by a static pull-out load test The results of the acceptance tests were used to calculate the reliability of the anchors in meeting the requirements of this test.

2. Geotechnical site investigation

The geotechnical conditions in the subsoil and the quality of the material become important in the construction and use of massive structures, in particular embankments and the protection of deep excavations. Physiographically, the studied area is located within the Toruń Valley mesoregion, which is part of the macroregion Toruń-Eberswald ice-marginal valley [7]. In the axis of the Toruń Valley, the Vistula flows in the ice-marginal valley, which takes an active part in shaping the relief of the land. The ice sheet was also a geomorphological factor. As a result of glaciation, a moraine plateau was created.

The area under consideration is dominated by fluvial-glacial sands formed at the end of the Pomeranian phase, as a result of mixing material transported by glacial waters flowing from the north and river waters. In the Pleistocene, during the middle stage of the Vistula glaciation, boulder clays with a thickness ranging from several to 25 m were also formed [8]. In the vicinity of the investment, they may occur in the form of lenses or thin layers.

Hydrographically, the area is located in the catchment area of the Bydgoszcz Canal, which is part of the Vistula catchment area. The mentioned Bydgoszcz Canal is located in the close vicinity, approximately 1.5 km north of the investment being implemented.

To design ground anchors, a homogeneous geotechnical layer *IXd* presented in Fig. 1 was assumed with the following geotechnical parameters:

– shear strength for undrained conditions c_u = 103 kPa,
– moisture content of the soil w = 18.5%,

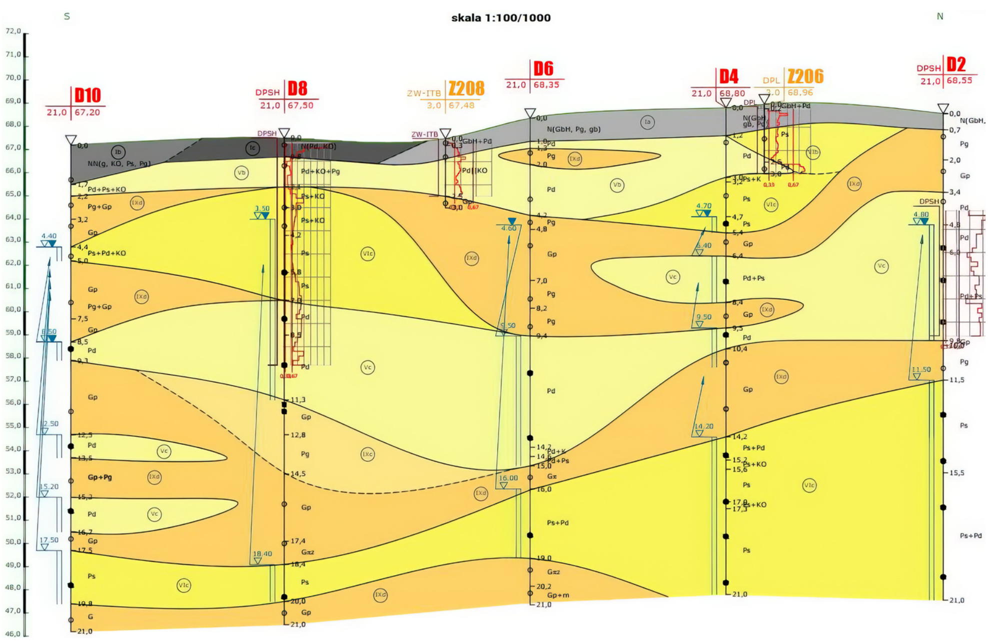

Fig. 1. Geotechnical cross-section along the retaining wall

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– plasticity limit $w_p = 12\%$,
– liquidity limit $w_L = 24.4\%$,
– liquidity index $I_L = 0.20$,
– effective internal friction angle $\varphi' = 47.20°$,
– effective cohesion $c' = 27.30$ kPa.

Soil parameters were determined on the basis of technical tests with a Cone Penetration Test and additional laboratory tests.

As shown in Fig. 1, the boundaries of layer *IXd* are variable and it is possible to make the designed anchor head in the adjacent layer of non-cohesive soil *Vc* or *VIc*.

Complex and random conditions in the substrate justify further reliability calculations for fixed length.

The project assumes the construction of 339 ground anchors with various load-bearing capacity and geometric parameters. Figure 2 shows the retaining wall after the installation of ground anchors and a reinforced concrete capping beam.

(a) (b)

Fig. 2. View of the retaining wall: (a) visible anchor heads; (b) during construction works, front view

After comparing the geological cross-section with the course of excavation wall and the designed fixed length, the one selected segment was further analysed. This segment meets the assumptions of this work because, given various geotechnical conditions, their designed heads are located entirely in cohesive soils. Due to the length of the section where the works were carried out, there was a possible variability of ground conditions.

3. Anchor test description

3.1. The principles of design and testing

The general definition of the considered retaining wall element of the structure is given in the standard EN 1997-1-2004 [5]. The part of the anchor that transfers the force to the surrounding soil is called the "fixed length". Based on it, an anchor is a structure capable of transferring tensile loads through the free length of the tendon to the fixed length to the

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load-bearing layer. However, in the case of an injection anchor, it was determined that an anchor solidified by injection of resin, cement paste or other material transfers the tensile force to the ground. The standard EN 1537:2013 [6] applies to temporary or permanent ground anchors that are injection grouted, prestressed-and tested by the strictest safety measures described. The main document referenced for the testing procedure in this study is the standard EN ISO 22477-5:2018 [9]. It concerns only the design and testing of anchors with free length. However, at present, there is no effective automated or maintenance-free method for measuring the force and the displacement during the test. The three coordinated standards [5, 6, 9] assessing the design, execution and testing of grouted anchors, respectively, in the European Union, establish three types of tests: investigation tests, suitability tests and acceptance tests. The standard EN ISO 22477-5:2018 [9] includes 3 test methods: Test Method 1 *TM1*, Test Method 2 *TM2* and Test Method 3 *TM3*. All of these tests are designed to evaluate the global performance of the anchors by taking external measurements (e.g., applied force, relaxation and creep). In particular, the investigation test is a load test aimed at evaluating the ultimate geotechnical resistance of the anchor and its behaviour at working loads. This article discusses an acceptance test according to the *TM3* model. The performed field test of the anchor head is shown in Fig. 3. The measuring set consists of a dial indicator sensor and an actuator (conventional hollow-piston cylinder) with an independent reference system.

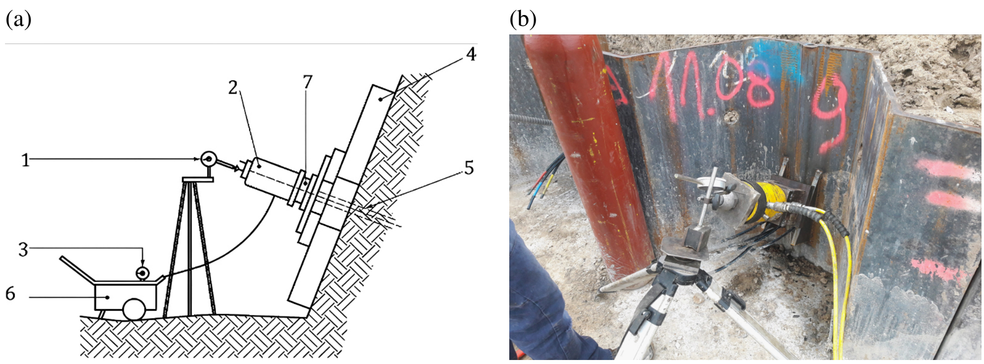

Fig. 3. Field measuring station: (a) scheme with basic elements of the measuring station: 1 – dial indicator sensor for measuring the displacement of the tendon end, 2 – hydraulic jack, 3 – pressure gauge, shows pressure inside jack chamber, 4 – retaining wall being anchored, 5 – anchor tendon, 6 – hydraulic power pack, 7 – load cell (sensor) [9]; (b) measuring station at the construction site

Currently, the field tests are being performed using instrumentation with manual reading, registration and data processing in offline mode. To accomplish the test requirements a set of variables should be monitored, namely the force applied to the anchor, the displacement of the jack rod, pressure in the jack chamber, and the displacement of the anchor tendon and retaining wall [10]. The displacements of the anchor tendon should be referred to as a fixed point, placed away from the wall to avoid disturbance. An acceptance test is performed for each anchor, therefore it is possible to obtain a data set useful for applying reliability methods to estimate the safety of anchors.

During construction, it was possible to look closer at the substrate and uncover some mechanical dependencies thanks to the observation of the excavated material from the boreholes [11,12]. In particular, the material obtained during drilling was compared with the soil in the geotechnical documentation, where the boundaries of the layers are determined by drilling at distances much greater than the spacing of the anchors. Based on this, it was determined, for example, that there were differences in cohesion in the layers considered homogeneous.

Therefore, due to the natural randomness of the soil medium and technological inaccuracies, it is justified to calculate the reliability for the considered set of anchors.

During the test, the change in head displacement became visible. At the initial stage of the experiment, for small deformations, the soil connection with the anchor behaved as an elastic material. As the head load approached the P_p load, an increase in displacements velocity occurred. At this stage, they have developed clear rheological effects [13, 14]. Moreover, in cohesive soils that may be subject to creep, the long-term behaviour of which is poorly understood, which justifies testing of each anchor according to the *TM3* model. Load capacity assessment requires checking possible failure modes: rupture of the steel tendon, grout tendon bond failure, rock-grout bond failure; and conical failure to surface in the soil or rock mass [15, 16].

Cohesive soils that are likely to creep are ones with a plasticity index I_p greater than, or equal to 20, and notably: clays, silts, marly clays and some marls (which have a $CaCO_3$ content lower than 30%).

The set of test results for anchors designed in the separated geotechnical layer will be the basis for reliability calculations.

3.2. Acceptance testing methodology

The purpose of the test is to demonstrate that the anchor carries the test tension and to confirm the apparent free length of the tendon. In the case under consideration, the *TM3* was used. An acceptance test according to this method is a test in which an axial load is applied by step to a ground anchor up to proof load P_p to confirm that a particular anchor meets the design requirements, particularly creep ratio value. It only concerns the design and testing of anchors with free length. The design load capacity of the anchors is 280 kN, there is the proof load P_p, the total length of the anchor will be 14 m, it was made at an angle of 30 degrees.

Each load is maintained constant only during the necessary time to perform the measurement (extension of tendon, load). At the proof load the measurement of the extension of the tendon head versus time during a specific time is recorded.

Standard 2247 [9] considers 15-minute stages, the values of t_a and t_b used to assess creep ratio α are respectively 3 and 15 minutes. The loading sequence is shown in Fig. 4.

Creep ratio α at constant is derived from the linear end of a logarithm of elapsed time vs displacement plot. The creep rate α is defined by the following formula:

$$\alpha = \frac{(s_b - s_a)}{(\log(t_b) - \log(t_a))} = \frac{(s_b - s_a)}{\log(t_b/t_a)} \tag{3.1}$$

where: s_a – displacement of the anchor at the time t_a, s_b – displacement of the anchor at the time t_b, t_a – start of the respective time interval, t_b – end of the respective time interval.

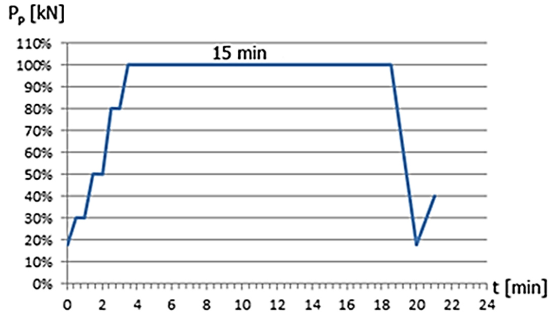

Fig. 4. Loading sequence for acceptance test *TM3*

The anchor is loaded in incremental steps from a datum load to a maximum load P_p. The incremental steps were: 10%, 30%, 50%, 80%, and 100% of proof load P_p which is equal to design capacity R_d. The displacement of the anchorage points was measured under maintained load at each loading step. Creep measurements were recorded between 3 and 15 minutes of maintained maximum load.

The acceptance criteria according to EN 1997-1-2004 [5] for investigation, sustainability and acceptance tests for persistent and transient design assumptions at the ultimate and serviceability states have been summarized collectively in [17]. The acceptance criterion is deemed as satisfied for the serviceability limit state if the value of creep ratio α is lower than 1.5 mm for the permanent anchor and 1.8 mm for a temporary anchor. The displacement Δs_{3-15} of the marker between the times of +3 minutes and +15 minutes is also checked. The test is deemed as being satisfying if $\Delta s_{3-15} < 1.5$ mm.

4. Polynomial chaos expansion *PCE* method

One available approach to defining and describing probability density is the polynomial chaos expansion *PCE* developed by Norbert Wiener in 1938 [18]. In essence, *PCE* is an extension of methods using the Fourier series or Taylor series. The *PCE* is dedicated to density functions and is based on specific polynomial functions. Thanks to the method, any system with time-invariant uncertainty (e.g. in initial conditions or parameters) can be transformed into a set of deterministic equations.

The transformed system allows for very fast simulation times compared to sampling methods, but the transformation itself is burdensome because it requires solving a large number of integrals.

Due to the increase in computational capabilities in recent years, *PCE* is being applied to numerical problems. Its main applications are probability and uncertainty assessment [19], stochastic differential equations [20], and systems with probabilistic uncertainties [18, 21].

The ability to rapidly propagate uncertainty has made *PCE* a widely used tool for optimization problems such as stochastic model predictive control *MPC* [22,23] or experimental design [24, 25].

4.1. Application of the *PoCET* package for creep ratio estimation

To perform the calculations, the *PoCET* package was used, which is a set of computational tools in the *Matlab* environment [26]. The *PoCET* computational package is dedicated to performing calculations using the polynomial chaos expansion method in systems with time-invariant uncertainties. Package automates the processes of selecting and configuring a polynomial basis, calculates the induced integrals and matrices of the extended system, and saves the appropriate *Matlab* function files required for the solution extensive system.

Generally, the (limited) *PCE* method contains basic data: the number of random variables N_ξ and the dimension of the polynomial expansion P, φ_n is a polynomial of degree n from the polynomial base Φ.

Internal variables, their expansions and the vector of their expansions are marked as, respectively, $\hat{x}_i, \hat{x}$, respectively. While μ is the probability density function in space Ω and $\nu^{(m)}$ is a stochastic moment of the m^{th} order. Gaussian variables are denoted as $\xi \sim N(\nu^1, \hat{\nu}^2)$, the variables of the normalized distribution are denoted as $\xi \sim U(a, b)$, the variables of the beta distribution as $\xi \sim B(\alpha, \beta)$ and for $\xi \sim B_4(\alpha, \beta, l, u)$ the standard four-parameter beta distribution.

The general *PCE* method for N_ξ random variables and P dimension expansion of random variables x is given by the following formula:

$$x \sim N(\mu\sigma) \Rightarrow x \approx \sum_{i=0}^{\hat{P}-1} \hat{x}_i \varphi_i(\hat{\xi}) = \hat{x}^T \Phi(\xi) \tag{4.1}$$

where: x – output variable, $\hat{x}_i$ – expansion factor, $\hat{P} = \dfrac{(N_\xi + P)!}{N_\xi! P!}$, $\hat{x}, \Phi \in \mathbb{R}^{\hat{P}}$, $\hat{\xi} \in \mathbb{R}^{N_\xi}$.

The polynomial basis Φ consists of P orthogonal polynomials φ_n, that meet the conditions shown in the Eq. 4.2.

$$\langle \varphi_i, \varphi_j \rangle = \int\limits_{\Omega} \varphi_i(\xi)\varphi_j(\xi)\rho(\xi)\, d\xi = \lambda_i \delta_{ij} \tag{4.2}$$

where: $\lambda_i \in \mathbb{R}$ and $\delta_{ij} = \{1 \text{ when } i = j, 0 \text{ otherwise}\}$.

The choice of polynomials φ_n depends on the probability density function *PDF* of the variable ξ.

Polynomial bases have been prepared for many probability distributions, for example for the Gaussian, Hermite, Legendr and beta distributions.

In the given example, it was assumed that the values of the anchor head displacements at the 3$^{\text{rd}}$ and 15$^{\text{th}}$ minute are described by a normal distribution. However, the reading of displacement values is subject to a reading time error that differs from the standard values of 3 and 15 minutes.

In particular, the reading error was assumed that the values of tendon extension to be within ±10 seconds. This means that the displacement readings were taken in the range of (170–190) seconds for reading time t_3 and (890–910) seconds for reading time t_{15}. Therefore, a random variable $x = (1/\log(t_{15}/t_3))$ was introduced to take into account the time inaccuracy of the displacement reading.

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The minimum value of the function $\log(890/190) = 0.67$ and the maximum value of the function $\log(910/170) = 0.73$. The value of the random variable $x = (1/\log(t_{15}/t_3))$ is within the range of values (1.39; 1.50). A uniform distribution was assumed for x random variable in the range (1.39–1.50).

Displacement readings were assumed as normally distributed parameters:

– parameter a – displacement for reading time t_3: mean value $\mu = 8.21$ mm, standard deviation $\sigma = 0.77$ mm,
– parameter b – displacement for reading time t_{15}: mean value $\mu = 8.36$ mm, standard deviation $\sigma = 0.78$ mm.

5. Results of *PCE* calculation and ground anchor reliability estimation

Creep velocity values were generated for the reading time interval. The results of creep ratio α calculations are shown in Fig. 5.

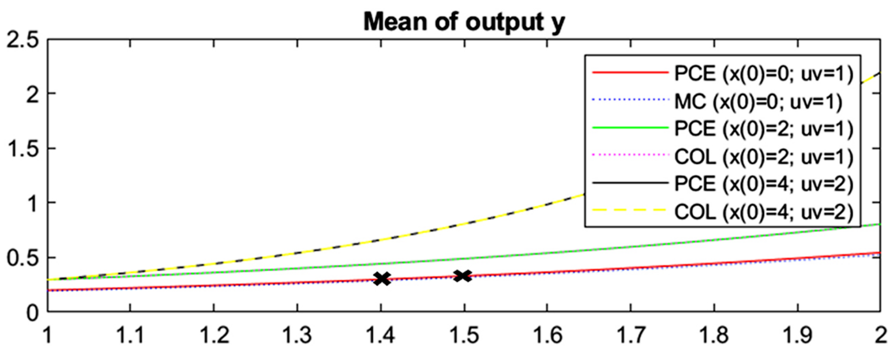

Fig. 5. Results of creep ratio $\alpha(y)$ calculations obtained from the *PoCET* package for $x = 1.50$ and for $x = 1.39$

The red curve shows the values for the method *PCE* and is consistent with the values generated by the Monte Carlo *MC* method. The generated average values of the creep ratio are $\alpha = 0.293$ mm and $\alpha = 0.327$ mm for interval limits values of the random variable $x = 1.39$ and $x = 1.50$, respectively.

For comparison, the average value creep ratio for the segment based on measurement data for each anchor is $\alpha = 0.301$ mm.

Several methods have been developed to determine this indicator depending on the input data, including type and difficulty in determining the limit state function of the structure. The arguments of the limit state function here are random variables x_i. The idea of the method for determining the reliability index is to present all variables affecting the reliability of the structure using expected values (first moment) and covariance (second moment) of the introduced parameters x_i. The calculations of this method are distribution-free, i.e. they do not require hypotheses about the type of probability distribution.

To objectively determine the degree of safety of the structure, a dimensionless reliability index β_c was introduced in Eq. (5.1)

$$\beta_c = \frac{E(R) - E(S)}{\sqrt{\mathrm{Var}(R) + \mathrm{Var}(S)}} \tag{5.1}$$

where: $E(R)$ – expected allowable creep ratio, $E(S)$ – expected creep ratio, $\mathrm{Var}(R)$ – variance of allowable creep ratio, $\mathrm{Var}(S)$ – variance of calculated creep ratio.

The limit state is assumed to be met for the allowable creep value R and the creep value S obtained from measurements. In the equation, the operator denotes the expected values R and S, respectively. An indicator of this form can be introduced if R and S are independent and the safety condition $SM = R - S > 0$.

Three cases were considered due to the inaccuracy of the anchor head displacement readings:

– creep speed based on the displacement of the anchor head assuming accurate readings at 3 and 15 minutes (case 1),
– creep speed based on the displacement of the anchor head for the most favourable condition (above standard time increments of readings – case 2) $x = (1/\log(t_{15}/t_3) = 1.39$,
– creep speed based on the displacement of the anchor head for the least favourable condition (below standard time increments of readings – case 3) $x = (1/\log(t_{15}/t_3) = 1.50$.

The results of the calculated reliability index for the above assumptions are presented in Table 1.

Table 1. Results of reliability index β_c

Reading time	**Case**	***E*(*R*)**	***E*(*S*)**	**Var(*R*)**	**Var(*S*)**	$\boldsymbol{\beta_c}$
Standard	1	1.50	0.21	0	0.050	25.80
Above standard	2	1.50	0.28	0	0.055	22.18
Below standard	3	1.50	0.32	0	0.065	18.15

The issue of reliability of building structures has been taken into account in the system Eurocodes [27]. When starting design, the reliability class *RC1–RC3* and a failure consequence class directly related to its *CC1–CC*3, should be determined. The obtained high values of the reliability index β_c for various assumptions meet the requirements for reliability class *RC3* for buildings with a service life of 50 years.

New proposal for Eurocode 0 (prEN 1990: 202x) emphasizes the issue of judicious use of the concept of reliability and introduces five, not three as in current practice, classes of damage consequences that are associated with defined geotechnical categories. Within the defined geotechnical categories, the scope of detail of geotechnical reconnaissance, design, construction, monitoring and supervision will be defined. Unfortunately, no corresponding reliability parameters have been proposed, which will be taken based on the other standard or left to the designer's choice [28].

6. Conclusions

A grouted anchor is a structural component used to transfer tension forces from the structure to the subgrade. It is typically used as a support for retaining structures of excavations or for slope stabilisation [29, 30]. Ground anchor design shall take into account the results of the geological and geotechnical investigation campaign, as well as observations from field anchor tests taken to failure and the long-term behaviour of prestressed anchors. This design can also rely on ground knowledge, resulting from previous works. The testing of grouted anchors (referred to as anchors in EN 1997-1-2004 and ground anchors in EN 1537:2013) is a mandatory requirement. The principle in all cases is that the anchor is subjected to tensile loading and its load vs extension or load loss vs time behaviour is monitored and assessed against established acceptance criteria. The present research work documents field tests of grouted anchors, that were carried out and their results analysed according to the EN ISO 22477-5:2018 (*TM3*). The use of *TM3* allows for shortening time routine acceptance tests, however the function of measuring the moment of anchor displacement is even more accessible and can be carried out effectively for a large number of anchors.

Physical measurements are inherently corrupted by uncertainties (e.g., measurement noise, sensor accuracy, instrument reading), and understanding the sources of uncertainties is indispensable to the application of a robust control and reliability analysis. Estimation of the creep ratio for the introduced random variable of reading time uncertainty using the *PCE* method significantly affects the calculation of the reliability of anchors due to the serviceability limit state. The obtained reliability index for the considered assumptions meets the requirements for the reliability class for permanent geotechnical structures.

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Identyfikacja niezawodności kotew gruntowych na podstawie badań odbiorczych oraz metody rozszerzenia chaosu wielomianowego

Słowa kluczowe: badania odbiorcze, kotwy gruntowe, niezawodność, rozszerzenie chaosu wielomianowego

Streszczenie:

W artykule przedstawiono analizę niezawodności kotew gruntowych w oparciu o testy odbiorcze i metodę rozszerzenia chaosu wielomianowego. W pierwszej kolejności oszacowano prawdopodobieństwo spełnienia wymagań badań odbiorczych na podstawie testów kotew wykonanych w ciągu drogi ekspresowej S10 w okolicach Bydgoszczy (Polska). W analizowanym przypadku projekt konstrukcji oporowej w technologii ścianki szczelnej jednokrotnie kotwionej zrealizowano w celu zabezpieczenia skarpy. Kotwy gruntowe jako konstrukcje geotechniczne podlegają badaniom wstępnym, przydatności oraz badaniom odbiorczym i muszą spełniać wymagania stanu granicznego nośności i użytkowalności. Przeprowadzone w artykule analizy bazują na wynikach badań odbiorczych, które wymagały zmontowania stanowiska pomiarowego z niezależną bazą odniesienia. Na podstawie normy EN ISO 22477-5:2018 testy przeprowadzono metodą badawczą *TM3*. W metodzie tej kotwa jest obciążana stopniowo od obciążenia bazowego do maksymalnego, a przemieszczenie końca cięgna mierzy się w każdym stopniu obciążenia w celu oszacowania parametru prędkości pełzania i porównania z wartością dopuszczalną. Na podstawie uzyskanych bezpośrednich statystyk przemieszczeń głowicy kotew w cyklu dwóch pomiarów trwających 3 minuty oraz 15 minut wygenerowano wartości prędkości pełzania, stosując metodę rozszerzenia chaosu wielomianowego *PCE* oraz metodę Monte Carlo *MC*. Wprowadzono zmienną losową czasu, która uwzględnia niedokładności czasu pomiaru w odniesieniu do czasów normowych (3 min oraz 15 min). Do wykonania obliczeń wykorzystano pakiet *PoCET*, będący zestawem narzędzi obliczeniowych w środowisku *Matlab*. Prędkości pełzania obliczone metodą *PCE* uwzględniają możliwe odchyłki czasu odczytu przemieszczenia dla momentu 3 i 15 minuty testu. Na podstawie wygenerowanych prędkości pełzania oszacowano wskaźnik niezawodności Cornella β_C dla spełnienia wymagań badań odbiorczych kotew gruntowych. Uzyskane wartości wskaźnika niezawodności spełniają wymagania dla klasy niezawodności *RC3* dla budowli o żywotności 50 lat.

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