THE ROLE OF GEOTECHNICAL MONITORING AT DESIGN OF FOUNDATION STRUCTURES AND THEIR VERIFICATION – PART 2

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Abstract

The main aim of the article is demonstrating successful design of spread foundations of a commercial centre building, where geotechnical monitoring allows us to check design efficiency and calculate reliability in comparison with real vertical deformation of building. Introduction to the case study area and building structure and foundations was done in previously published first part of the article in which engineering geological conditions were described. There was also presented a comparison of calculated vertical settlement of selected footings with the real geodetic measurement provided during construction time till the period of two years' operation time after completion of civil works. Geotechnical engineers do not have many opportunities to evaluate their designs, especially when everything passes successfully. Our presented case study is one of the examples, which could be evaluated from the point of view of reliability index of design adjusted with real geodetic measurement. Index of reliability of selected foundations was calculated by deterministic probability methods. In order to evaluate thousands of statistical data combinations, programming tool in Python language was developed for batch processing calculation of vertical displacement of foundation in Plaxis software. Discussion part of the article contains the actual state of reliability theory in structural standards in Europe.

Keywords:

Geotechnical monitoring;
 Reliability index;
 Batch processing;
 3D FEM model;
 Probability of failure.

1 Introduction

This paper presents calculated theoretical vertical displacement (settlement) of the building of one commercial center and it is compared with the real vertical movement obtained by geodetic survey method that used very precise levelling (VPL). The multi-store building of the shopping centre in the city of Žilina (Slovakia) was designed with spread foundations – rectangular footings. This was allowed by favourable foundation conditions at the construction site, where the active subsoil was formed by sediments of gravel terrace. However, a local geological abnormality was discovered, and gravel terrace on the north side of the building had less thickness and gravels in foundation level were mostly with clayey fillings (clayey gravel GC). The calculations of the settlement by using analytical methods do not confirm the assumption of designers that serviceability limit state is less sensitive to input parameters. This error leads to an underestimation of the importance of the elasticity modulus, which sometimes happens especially in cases of soil formed by non-cohesive soils. The result is then usually unequal settlement, large settlement, and deformation of foundation structure [1]. Thanks to importance of building structure and local geological abnormality, geotechnical monitoring during construction process was realized. Firstly, deformation parameters of foundation soil were tested by static plate load tests before foundation footings were concreted. When deformation modulus did not meet the criterion of design, replacement of foundation soil was realized and measurements were

repeated [2, 3]. Building was successfully constructed and geotechnical monitoring confirmed vertical movements in desirable limits. In these cases of successfully done works no more investigation is necessary. From our point of interest, the construction of shopping centre building confirmed good designer's decision to save costs and design square footings foundation instead of pile foundation. Second reason is learning from this positive case and using data collection to analyse design by reliability theory.

2 Probabilistic approaches

2.1 Reliability theory in structural design

Reliability is defined as the ability of a system (structure and all its elements) to meet all requirements throughout its life. The system fails if the structure fails to meet all the requirements for its operation, i.e. the foundations are damaged and the bearing capacity of the foundation soil is exceeded [4, 5]. The design must be substantiated by proving its sufficient reliability in terms of fulfilling the required function. Experiences in geotechnical design are an important support in evaluating results, especially when more and more numerical computational models and more sophisticated computational tools are used [6, 7]. It is very easy to make a mistake and therefore parallel calculations, or independent calculations are needed for very important constructions.

There are three types of approaches to designing foundations:

- deterministic,
- semi probabilistic,
- and fully probabilistic.

2.2 Reliability index of spread foundation

The reliability index β plays a major role in the probabilistic approach to structural safety assessment. It sets the target safety (reliability levels) for the structure, which takes into account the consequences of its failure and the cost of safety measures. For the purposes of this study, the reliability index β_c is defined by the following equation, C. A. Cornell [8].

$$\beta_c = \frac{E\{g(\mathbf{X})\}}{\sqrt{\text{Var}\{g(\mathbf{X})\}}}, \quad (1)$$

where:

$\text{Var}\{g(\mathbf{X})\}$ is a symbol of variance operator,

$E\{g(\mathbf{X})\}$ is expected value (EV) of random variable $g(\mathbf{X})$,

$g(\mathbf{X})$ is function of limit state.

The resistance (bearing capacity) of the foundation soil R and the load effect E acting on the foundation structure are dependent random variables. Each of them has its own probability distribution $f_R(R)$ resp. $f_E(E)$. Normal probability distributions are assumed, which then combine to form a continuous probability density function. The reliability index can then be rewritten in the form [8]:

$$\beta_c = \frac{\mu_R - \mu_E}{\sqrt{\sigma_R^2 + \sigma_E^2 - 2\rho_{R,E} \sigma_R \sigma_E}}, \quad (2)$$

where:

σ_R, σ_E are standard deviations (SD) of resistance and load effect distribution,

μ_R, μ_E are expected values (EV) of variables R and E ,

$\rho_{R,E}$ is coefficient of correlation between variables R and E .

The expected value and standard deviation are calculated from the following formulas:

$$\mu_R = \sum_j^{2^k} P_j R_j, \quad \mu_E = \sum_j^{2^k} P_j E_j, \quad (3)$$

$$\sigma_R^2 = \sum_j^{2^k} P_j (R_j^2 - \mu_R^2), \quad \sigma_E^2 = \sum_j^{2^k} P_j (E_j^2 - \mu_E^2), \quad (4)$$

where:

$P_j = 1/2^k$ is the probability for the number of random data combinations 2^k ,

k is the number of combinations of random variables.

2.3 Deterministic vs. fully probabilistic approach

The deterministic approach is used in assessing the serviceability limit state (SLS) where calculated settlement $s \leq s_{lim}$ is compared with the limit values of the settlement (s_{lim}). Limit values of the settlement are determined based on many years of experience in designing foundations and also according to type of building or bearable upper structure. In this case, the characteristic values of geotechnical properties of foundation soils and long-term values of operating load are used in the calculations.

The fully probabilistic approach uses statistical analysis to take into account the distribution of random variables (geotechnical parameters along with load), leading to a limit state function that separates the safe area from the faulty area. The aim of the probabilistic analysis is to determine the reliability index β and the probability of failure P_f [9-13].

3 Parametric variations of input data

The construction site for the considered building has a geological origin in Paleogene, where sedimentary rocks are represented by the alternation of sandstones and predominant claystones, completely weathered to clay at the top part. The Paleogene bedrock is covered by a massive accumulation of gravel terrace sediments of the Váh River, which have been verified to a depth of 20 - 21 m. The terrace is formed by gravel with fine soil (G-F), covered by Quaternary sandy clays (CS) or low or medium plasticity clays (CL, CI) [2, 3].

The simple cross section of selected rectangular footing E12 together with 3D finite element model (FEM) parametric model are shown in Fig. 1. For definition of soil layers' parameters, Mohr-Coulomb constitutive model was selected with respect to the available input parameters. The input parameters of the constitutive model are presented in Table 1.

Fig. 1: Cross section of footing with geological profile and foundation soil replacement layer thickness of 1 m (left), FEM parametric model of footing E12 dimensions 3.6 x 1.8 m (right).

Table 1: Input parameters of the constitutive Mohr-Coulomb model.

Soil layer type	γ [kN/m ³]	E_{ref} [MPa]	ν [-]	ϕ [°]	c [kPa]	R_{inter} [-]
Antropogenous soils	19.0	6.2	0.35	19.0	7.0	-
Sandy clay F4/CS	18.0	5.5	0.35	25	1.0	-
Gravel G3/G-F	19.0	80.0	0.25	32.5	0.0	0.9
Soil replacement G3	19.0	80.0	0.25	32.5	0.0	0.9

There have been defined construction stages in Plaxis software, according to realized civil works on the foundation of the building and five individual phases of construction are summarized in Table 2.

Table 2: Construction stages.

Construction stage	Description	Type of calculation
1.	Initial phase	Plastic
2.	Excavations	Plastic
3.	Soil replacement	Plastic
4.	Foot activation and R-interface	Plastic
5.	Activation of load	Plastic

Reliability analysis was performed by variations of important parameters for settlement calculation of selected footing (E12). For the calculation of settlement of designed spread footing, the most influenced parameters (instead of others) are deformation properties of foundation soil and value of load on top of foundation. Depending on the model of settlement calculation (compression of soil layers in active zone), various deformation parameters are used in geotechnical engineering [14-17]:

- oedometric (one-dimensional) modulus E_{oed} ;
- deformation modulus E_{def} ;
- volumetric deformation modulus $m_v = 1/E_{oed}$;
- compression index C_c ;
- recompression index C_r ;
- coefficient of secondary compression C_{α} ;
- reference deformation modulus E_{ref} .

In our practical case, characteristic values of soil deformation properties (gravely sediments) were estimated through dynamic penetration tests and directly measured on the foundation level by static plate load tests [2].

There are many influences on final values of vertical settlement - e.g. value of effective original stress, preconsolidation stress, and stiffness of foundation compared with the stiffness of foundation soil, groundwater level, and very important is the time factor.

Time is important for evaluation of:

- unsprung values of deformation of foundation soil after excavation and,
- consideration of velocity of deformation changes of soil at stress change.

It is a well-known fact that soil skeleton reacts to new stress very slowly in the case of plastic fine low permeable soils (silts, clays) or rapidly when coarse granular permeable soils (sands or gravels) are present. This process is affected also by hydraulic conditions and the properties of soils [17, 18]. In our case of replacement of foundation soil before concreting footing and no influence of groundwater, the values of final settlements taken place in a few days.

For the purpose of this study, analytical calculation would be easier, but authors used precise 3D FEM model in batch processing calculation mode, where input parameters were generated randomly by Monte Carlo simulation within the defined interval, see Table 3.

Table 3: Input parameters of Monte Carlo simulation.

Soil	E_{ref} [MPa]	$E_{ref,min}$ [MPa]	$E_{ref,max}$ [MPa]	Distribution
1. G3/G-F	80.0	50.0	150.0	Normal
2. Soil replacement layer	80.0	60.0	110.0	Normal
Load	F [kN]	F_{min} [kN]	F_{max} [kN]	Distribution
Serviceability load	4 738.56	3 553.92	5 923.00	Normal

The random parameters of calculation were reference modulus of gravel with fines E_1 , reference modulus of soil replacement layer E_2 , and serviceability load combination value q .

The preformation of parametric study using FEM code of Plaxis, the automation Python-based interface wrapper was used. The variation of the material characteristic is automated using the Python API, which is just a wrapper over internal Plaxis commands that can be used as an alternative to interactive (mouse and menus) communication with the Plaxis application. The main Plaxis application

instance runs in either windowed or window-less mode with a simple webserver to the internal Plaxis commands. Any Python-based development environment can use the Python-Plaxis wrapper library to connect to this server (or better Plaxis application), execute any internal Plaxis command, and gain control over the loaded project or create a new one. This wrapper library allows the extension of Plaxis commands with programming constructs such as loops and conditional statements and access to the other data sources (e.g. external files or databases) and specialized data structures. The parametric study was performed by looping the prepared project with the variation of soil layers' Young modulus and storing the value of maximal settlement under the foundation.

4 Results of calculations of probability index

The normal distribution of 10,000 generated values of reference modulus of deformation E_1 of soil layer G3 is displayed on Fig. 2. Statistical normal distribution of variable parameter E_2 which is reference modulus of deformation of soil replacement layer below footing is displayed on Fig. 3.

Fig. 2: Histogram and distribution for E_1 modulus.

Fig. 3: Histogram and distribution for E_2 modulus.

The normal distribution of randomly generated values of load q for evaluation of settlement is depicted in Fig. 4. Load values are in the interval of minimal and maximal values and oscillated regularly around mean value, which is serviceability load intensity. Determining of range of variable parameters (from min. to max.) has an influence on the results of the reliability index and is easier when more tests of soil properties are done. In the case of small amount of in-situ or laboratory tests, it is requiring experienced geotechnical estimation [18].

The lognormal distribution of calculated 10,000 trials via batch processing in 3D FEM program is shown in Fig. 5 with mean value of settlement being 27 mm. The following Table 4 contains the sensitivity of variable in parametric calculation (load is the most influenced parameter) and reliability index and probability of failure of spread foundation E12, selected for this study.

Fig. 4: Histogram and distribution for load of foundation.

Fig. 5: Histogram and lognormal distribution for calculated settlement – 10,000 calculations.

Table 4: The sensitivity of variable in parametric calculation and reliability index and cumulative probability of failure of spread foundation.

Variable	Sensitivity
E_1 modulus	23.45
E_2 modulus	9.87
q - load	397.45
β - index of reliability	2.9290
P_f - probability of failure	0.0017

According to Table 5 expected performance reliability level is close to above average ($P_f = 1.7 \cdot 10^{-3}$ and $\beta = 2.929$), which indicates that spread foundation was designed with adequate safety. Required reliability index according to Eurocode [19] for the evaluation of Serviceability Limit States (SLS – settlement) for the reliability class RC2 is recommended to be higher than 1.5, which means that design meets reliability level.

It means that a very good decision was done by the structural engineers during the foundation stage. They provided foundation soil replacement in the case of measured low deformation moduli by static plate load tests, where locally gravel sediments contain more clayey fillings (G5/GC) of soft consistency. Foundation soil replacement was done by compaction of layers of gravel G3 for the total thickness of 1 m, there was used gravel from a different side of the excavation. Reliability calculation considers these local anomalies, because in large construction zone there is no time to test and prove every place of spread footings.

The reliability index β is associated with the probability of failure P_F and can be expressed by several dependencies according to the implemented statistical method and referenced period [20-22]. In the case of using the Gaussian cumulative probability function, their dependence is expressed by equation (2). The tabular values of the probability of failure and the probability index are given in the Table 5.

Table 5: The range of geotechnical reliability index β [19, 20].

Reliability index β	Probability of failure P_F	Expected performance reliability level
1.0	0.16	Hazardous
1.5	0.07	Unsatisfactory
2.0	0.023	Poor
2.5	0.006	Below average
3.0	0.001	Above average
4.0	0.00003	Good
5.0	0.0000003	High

5 Discussions and conclusions

Using the example of calculating the reliability index of a spread foundation, the procedure for evaluating the reliability level of the design was demonstrated. The degree of safety itself depends on the reliability of the input parameters, which in the case of the calculation of vertical deformations (settlement) means the most accurate determination of the deformation parameters of the foundation soil and the most probable estimation of the load intensity. In the case of favourable geological conditions on the construction site, the risk is low; otherwise it is in the case of local geological anomalies, where the risk of unequal foundation movements (settlement) is high. It is proved by practice that a lot of problems in civil engineering are caused by poor quality during the realization and experienced suppliers can predict a serious problem by operational project modifications.

In the article, the authors demonstrate an innovative approach where the use of 3D FEM calculations may not be a problem due to the programmed batch calculation.

Geotechnical engineers are eagerly awaiting the forthcoming changes and improvements in Eurocode 7 and its parts, which should include more articles addressing safety and usability requirements, so that it does not contain only a description of the principles of design and verification of limit states. It should be emphasized that reliability indices can only be assessed using probabilistic tools [21-24].

When assessing important structures of significant construction types, attention should be paid to the determination of the reliability index through an appropriate method of the statistical probability of failure. It is worth noting that this design principle has already been implemented in the USA and is called Load and Resistance Factor Design (LRFD), which allows a more accurate reliability assessment than the currently valid principles in EC7 [20, 25, 26]. Reliability based methods are subject of current development in geotechnics, concerning previously described spread foundations, foundations on improved soil [27], and deep foundations [28-31], but also slopes [32], and soil retaining structures [33-35].

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