VARIOUS ASPECTS OF PARAMETERS IN GEOTECHNICS

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Abstract

Each geotechnical design includes subsoil stratification and estimation of "geotechnical" parameter values for every individual soil layer. The term "parameters" covers many different quantities: physical values referring to the soil's properties, like porosity or cohesion, coefficients describing subsoil loading history (OCR) or initial state of stress (K_0), dimensionless designate constants of linear approximation of material response or other non-linear regression coefficients. In this thicket of meanings there is no clear classification, which could suggest which of these quantities are important for the specific analysed problem. It is rarely emphasized that a design consists in a forecast of soil behaviour under loading and this forecast boils down to the use of a theoretical constitutive model. Hence, estimation of geotechnical parameters in laboratory or *in situ* tests should amount to evaluation of the chosen model's coefficients.

This paper suggests three definitions (groups) of parameters: "geotechnical" – all quantities referring to soil and used in geotechnical design, "mechanical" – describing strength and deformability and "soil constitutive model parameters" – identifying the "stress – strain" relations in the numerical model equations. The most important problems related to wrong understanding of the parameters and to the errors resulting from their incorrect evaluation are elucidated.

Streszczenie

Integralnym elementem każdego projektu geotechnicznego jest określenie profilu podłoża i oszacowanie wartości parametrów poszczególnych warstw gruntów. Parametry te w skrócie nazywa się geotechnicznymi. Pod tym pojęciem może kryć się wiele znaczeń. Mogą to być wielkości fizyczne dotyczące samego gruntu, takie jak np. porowatość czy spójność, współczynniki dotyczące historii obciążenia podłoża (OCR), stanu naprężeń początkowych (K_0), bezwymiarowe współczynniki kierunkowe prostych aproksymujących pewne odcinki odpowiedzi materiału lub też inne współczynniki regresji krzywoliniowych. W tym gąszczu pojęć brakuje jasnej systematyki, która podpowiadałaby, które z tych wielkości są istotne dla analizowanego zagadnienia. Rzadko uwypukla się fakt, że projektowanie polega na predykcji zachowania się gruntu pod obciążeniem, a predykcja ta sprowadza się do zastosowania teoretycznego modelu konstytutywnego. Szacowanie parametrów geotechnicznych w badaniach laboratoryjnych i polowych powinno się więc koncentrować na szukaniu wartości parametrów, będących współczynnikami wybranego modelu.

W niniejszym artykule wyodrębniono trzy grupy parametrów: „geotechniczne" – obejmujące wszelkie wielkości wykorzystywane w projektowaniu a dotyczące gruntu, „mechaniczne" – opisujące wytrzymałość i odkształcalność, oraz „parametry modeli konstytutywnych gruntu" – identyfikujące związki „naprężenie – odkształcenie", wynikające wprost z równań modelu teoretycznego. Naszkicowano najważniejsze problemy związane z nieprawidłowym rozumieniem tych pojęć i błędami wynikającymi z ich niewłaściwego wyznaczania.

Keywords: **Geotechnical parameters; Constitutive modelling of soil; Mechanical parameters; Model calibration; Loading Path Method.**

1. INTRODUCTION

There is no precise definition of the term "parameter" in geotechnics. It may refer to any numerical value used in design referring to soil-related problems, beginning from properties describing behaviour of a laboratory soil sample or *in situ* tested deposit to some truly abstract factors with no physical meaning. Based on this very general description, very often the estimated parameter values are wrongly understood or used. Some simple classification is missing, based on the context and adequacy of a specific parameter's application, which would put all the different meanings in order.

This paper will try to satisfy this demand by grouping the parameters into three categories, representing consecutive levels of the definition:

a) geotechnical parameters,

b) mechanical soil parameters,

c) soil constitutive model parameters.

2. GEOTECHNICAL PARAMETERS

The term "geotechnical parameter" is the broadest and the most universal one. According to the Polish Standard PN-B-02481:1998 [1] it denotes a value used in design calculations and control tests, describing properties of soil or rock in a quantitative way. It may refer to all sorts of geotechnical problems: stability, deformation, settlement, permeability, contaminants transport, etc. The definition encloses not only the easily recognisable parameters like: cohesion c, internal angle of friction ϕ, Young modulus E or Poisson's ratio ν but also: state/consistency measures I_L, I_D, I_p, I_C, I_s or several other coefficients like void ratio e, coefficient of permeability k, coefficient of uniformity C_U, overconsolidation ratio OCR, etc.

There is often no temptation to consider the geotechnical parameter's physical nature, if such exists, or evaluate its precision and limitations, even though wrong estimation of soil parameters may lead to tragic consequences. *Młynarek* [1] noticed after Brandl [3] that 80-85% of all building catastrophes in Europe were connected with subsoil and, after *Chapman* and *Marcelteau*, that there were serious discrepancies between the geotechnical documentation and the real subsoil conditions in 46-50% of analysed geotechnical projects. *Van Staveren* [5] noticed that 80% of all the described building catastrophes in the Netherlands were caused by incorrect evaluation of parameter values or lack of professional knowledge. Hence, proper identification of soil profile and its parameters is a matter of utmost importance.

Unfortunately the easiest solution for a Polish engineer is simply to pick a needed value from a table available in a standard or a handbook, based only on the vague information about the type of the soil encountered in the geotechnical profile and its state – both evaluated as a result of a macroscopic analysis in field or in laboratory. Therefore, one can rely the judgment of the soil strength and deformation characteristics on not transparent correlations between the "physical" or "strength" parameters (c, ϕ, E, ν – by default) and state measures I_D or I_L, which become "other", equally important, soil parameters in the light of (still) valid Polish Standard PN-81/B-03020 [6]. What is even more terrifying is the possibility, sanctioned as the method C by the same standard, to assess the values of the geotechnical parameters based on experiments conducted for different "similar" ground conditions – without even performing any tests! It is of course obvious that experiments in laboratory or with the use of advanced *in situ* testing equipment do not always provide a remedy for all the problems related to the wrong estimation of parameter values, unless appropriate tests are conducted. "Appropriate" means adequate to the parameter that is to be evaluated and to the loading conditions exerted on the considered subsoil. Recklessly chosen simple tests, e.g. UU triaxial test to estimate parameters of soil subjected to slow loading and in fully drained conditions, may give the same amount of error as using the previously mentioned correlations between state measures and mechanical parameters.

3. MECHANICAL SOIL PARAMETERS

"Mechanical soil parameters" is a narrower term and refers only to these characteristics, which directly describe the strength and deformation of soil or its filtration. They are treated as physical values and their estimations can usually be found in every geotechnical documentation. The most common representatives of this group are the "default" parameters: c, ϕ, E, ν, sometimes complemented by the values of oedometric moduli: M, M_0, m_v or oedometric coefficients: C_c, C_s. The mechanical parameters are evaluated in properly planned laboratory or in situ tests.

The high quality penetration tests, such as SCPTu [7] and DMT [8], have this advantage over laboratory experiments that thanks to their high testing rate they enable obtaining continuous profiles of stratification and mechanical parameter value changes with depth in a short time. Employment of statistical procedures adds another benefit – possibility of spatial characterization of the subsoil [9]. However, in the author's opinion, the most important feature of in situ testing is the investigation not influenced by sampling and structure disturbance problems. Apart from the information about 'undisturbed' parameter values it allows to obtain reliable data on the initial state of stress and the loading history (K_0, OCR) [10]. It should be mentioned though that the vast majority of the mechanical parameter values estimations in case of penetration methods relies on the quality of the, much more expensive and slower, advanced laboratory calibration tests. That is why the both approaches are correct and complement.

The weakness of this parameter definition is its detachment from the constitutive modelling. The mechanical "default" parameters mentioned above are usually considered universal and the only, even though they specify just two simple linearly elastic – perfectly plastic models: with the failure condition associated with the Coulomb – Mohr's (CM) or Drucker – Prager's (DP) equation. As a rule, the standard geotechnical documentation does not include estimation of other mechanical parameters, such as)Ψ (dilatation angle), s (sensitivity), M (critical state line inclination to hydrostatic axis), λ and κ (inclination of isotropic normal consolidation and swelling line on the semi-logarithmic $p' - e$ graph, respectively, where p' is the mean pressure), etc., although they are equally important when other constitutive models are to be applied in design.

If soil behaved linearly elastic or linearly elastic – perfectly plastic, there would be no need to estimate these other non-standard parameters. Unfortunately soil, being a very complicated material, requires much more than the four 'default' mechanical parameters for the realistic simulation of its behaviour under loading. That is why all the time newer and newer constitutive models are being developed with such a tendency, that the more advanced the model is – the more parameters it employs. Consequently, some of the new parameters do not have any physical meaning and hence become simply numerical coefficients, impossible to evaluate in standard laboratory or field tests.

4. SOIL CONSTITUTIVE MODEL PARAMETERS

The term "soil constitutive model parameters" stands at the third, narrowest and most advanced level of definition. Parameters named in this way are understood as numerical values quantitatively identifying the relation "stress – strain" and closely connected with the constitutive model used in an analysis. Within this notion there does not have to be any physical meaning applied to the parameters. They are rather coefficients of, mostly nonlinear, regression.

One of the most striking examples is the interpretation of the parameter c (cohesion) in CM model. Its physical explanation clearly dictates that cohesive soils, e.g. high plasticity clays, due to their microstructure, consisting of (often tightly) bonded plate – shaped particles, should have cohesion understood as interparticle attraction, adhesion. From the same point of view, non-cohesive soils should be characterized by zero value of cohesion, corresponding to parameter's value: $c = 0$. Then there is no surprise, that laboratory test results: $c > 0$ in case of gravels or $c = 0$ for clays, even if the correctness of the test procedures was proved, can elicit indignation or at least incomprehension, even amongst scientists [11]. Only if the c is treated as one of linear regression coefficients, precisely – a designate constant of the Coulomb-Mohr line or interpolated shear resistance value at zero normal stress, the physical definition can be neglected and these results become undoubtedly correct. Sometimes the term "apparent cohesion" is used as a substitution. For non-cohesive soils it may be explained with interlocking of particles.

It is commonly assumed that the parameters of a constitutive model within one selected homogenous layer of subsoil are constant, depend only on soil type and state and do not vary with loading. From the theoretical point of view, in case of continuum mechanics, such an assumption is correct, but frequently it does not reflect the results of experiments. The term "calibration of soil constitutive model" should be understood as estimation of appropriate values for parameters so that the simulated stress-strain relationship of soil is possibly consistent with the behaviour observed in field or in laboratory tests. Only an ideal model could guarantee such a perfect coincidence of the theoretical response to any kind of loading and boundary conditions with the natural soil response, when equipped only in one set of constant optimum parameter values. There is still a long way to go before such a model is developed. And even if it was elaborated one day, probably the number of its parameters would have to be infinite. So far, with the already existing constitutive models, the only method to achieve the consistency is to assume that parameters vary with the loading history (= the entire course of the stress or strain path – its length, shape and timing). Hence, the parameter values should depend not only on physical features of the material but also on soil formation processes (geological and anthropological) influencing the initial *in situ* conditions and soil structure, on magnitude and geometry of surface load, its application rate, boundary conditions and location in the ground. Such a complete identification becomes possible with the advancement, computerization and automatization of the field and lab-

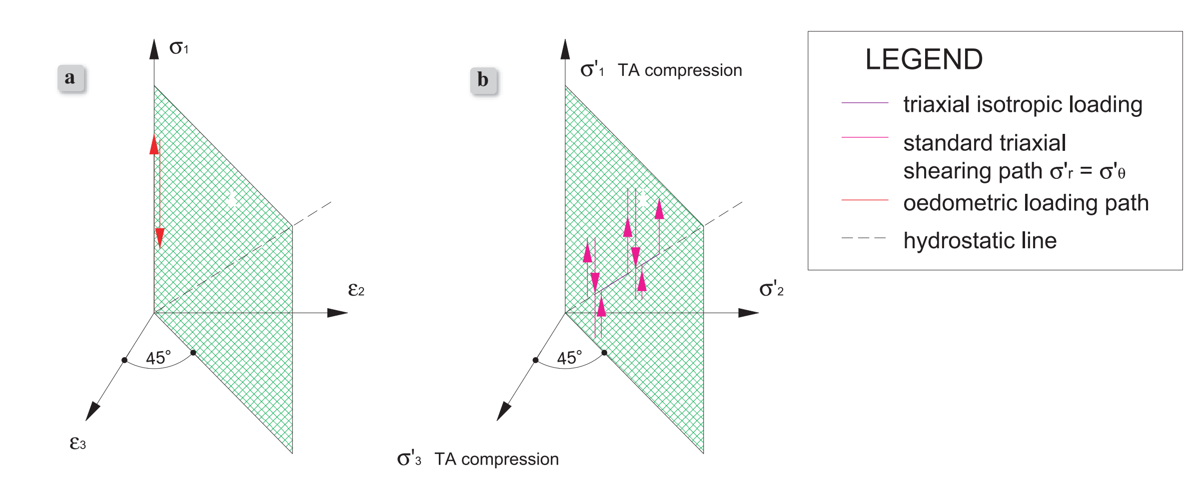

Figure 1.
Loading paths feasible in standard tests in: a) a conventional triaxial apparatus, b) an oedometer

oratory instrumentation (e.g. automatic stress path control systems, true triaxial apparatuses, hollow cylinder apparatuses etc.), which enable to control and observe soil behaviour under complicated 3D loading states with changes in the magnitude and even direction of the principal stress, rate of loading, incomplete saturation etc.

The most common type of model calibrations is a local calibration [12] based on definition of each particular parameter. Laboratory experiment is then directed towards value estimation of the chosen parameter/parameters provided that it has/they have a physical sense. Simple stress paths are usually applied to the tested specimen and the evaluation often amounts to solving a linear regression problem. Good examples are the parameters of CM model – the "default" parameters: c, ϕ, E, ν or parameters of Modified Cam Clay model (MCC): M, λ, κ, Γ, ν. Let's look at the latter. Each of the five MCC parameters can be estimated on the basis of a separate test conducted in a conventional triaxial apparatus. The M, similarly to ϕ in CM model, is defined as the inclination of a critical state line (CSL) to the hydrostatic axis in the p' – q stress invariants space, where q is the deviatoric stress. The CSL is positioned based on at least three standard shearing tests with constant cell pressure. The λ and κ also represent an inclination – this time – inclination of a normal isotropic consolidation and swelling line, respectively, on a ln(p') – e graph. The Γ-1 defines the ordinate of the CSL for p' = 0 on the same graph. So, all of them may be easily defined as the best fit line coefficients. The Poisson's ratio ν can be evaluated as a negative ratio of horizontal strain to axial strain of a specimen loaded uniaxially in a triaxial apparatus without cell pressure.

Such a local calibration, based on the definition of a parameter and the simplest stress paths available in laboratory apparatuses, does not take any information about the loading history into account. The simple stress paths used for parameter evaluation do not represent any realistic cases. They are simply the only technically feasible loading paths: isotropic and simple shearing stress paths in conventional triaxial apparatus or uniaxial strain paths in oedometer (Figure 1). Even if the triaxial apparatus is equipped in an automatic stress path control system the stress path cannot leave the plane defined by the condition: $\sigma'_2 = \sigma'_3$ in case of triaxial compression and $\sigma'_2 = \sigma'_1$ in case of triaxial extension. Additionally, if a parameter of a soil constitutive model doesn't have a physical meaning (like e.g. C and μ in NAHOS by *Gryczmański* et al. [13] or μ in S-Clay by *Wheeler* et al. [14]), then it is impossible to estimate its value in this kind of tests.

Sometimes, especially in research regarding influence of the stress path direction and its abrupt changes on soil stiffness or while looking for a shape of the state boundary surface, a series of simple stress paths in the permissible stress space (e.g. a bunch of radial stress paths with the same starting point) is applied on laboratory specimens [15] [16]. It was mainly thanks to this method that the strong dependency of strain magnitude and the loading history on stiffness moduli: E (Young's m.), K (compressibili-

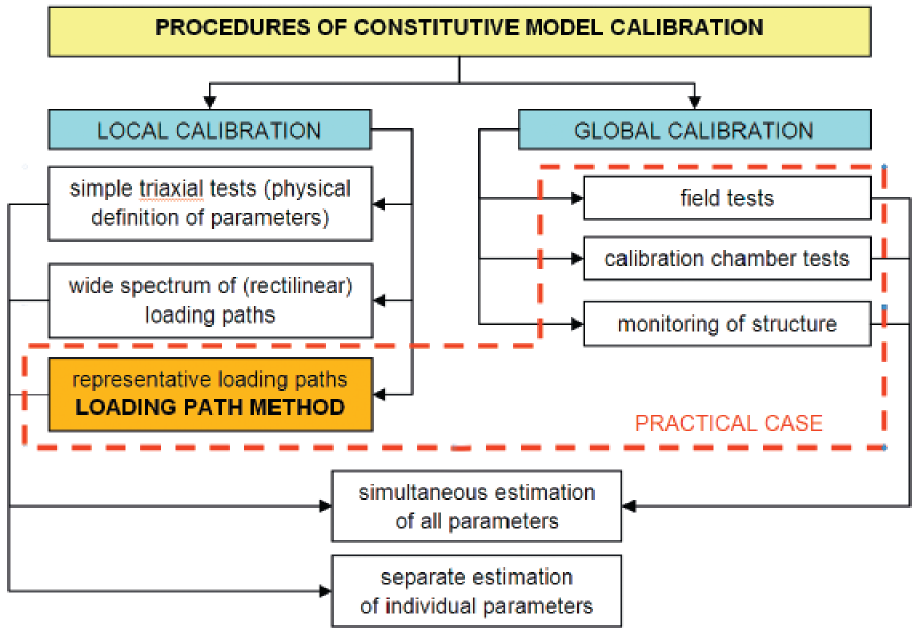

Figure 2.
Constitutive model calibration procedures [18]

ty m.) and *G* (shearing m.) was discovered. Despite of these merits, the rectilinear stress paths still do not represent any real subsoil loading course so the direct results should be very cautiously used in practice.

As far as local calibration is concerned, only the stress paths representative for the analysed real case could guarantee reliable estimation of parameters and may result in a good simulation of soil response in natural conditions. This kind of research on the one hand stays very close to global calibration method [12], based on in situ subsoil monitoring. However, on the other hand, it makes use of all the advantages of local laboratory calibration: controlled and homogenous state of stress and strain, transparent correlations etc. In the author's opinion the strongest representative of this approach is the Loading Path Method, announced for the first time in 2005 [17] and described in detail in the author's dissertation [18]. It's position within the classification of the calibration methods is presented in Figure 2.

5. CONCLUSION

Many errors committed in the process of geotechnical design have their sources in wrong interpretation of parameters. There should be awareness awaked amongst engineers that the popular "mechanical parameters" form only a narrow cluster out of the general group called 'geotechnical parameters' and should be often treated rather as numerical coefficients of a particular constitutive model – not as universal parameters with physical sense. In this light, their values may change and depend on the loading history, boundary conditions etc. Such an approach results in better fitting of the theoretical predictions to the soil behaviour observed in field. When describing these parameters the form "soil constitutive model parameters" seems much more adequate. Their estimation may be conducted on the basis of local calibration methods with the use of representative stress paths (e.g. Loading Path Method).

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