Studia Geotechnica et Mechanica, Vol. XXXIII, No. 2, 2011

THE INFLUENCE OF THE CHOICE OF STRAIN MODULUS VALUE ON FOUNDATION SETTLEMENT

MAŁGORZATA JASTRZĘBSKA, MARIAN ŁUPIEŻOWIEC

Silesian University of Technology, Gliwice, Poland.
E-mail: malgorzata.jastrzebska@polsl.pl, marian.lupiezowiec@polsl.pl

Abstract: The paper aims at presenting the influence of strain moduli chosen at the stage of designing on the values of foundation settlement. The settlement forecasting prevailing now is still based on the readings of the primary and secondary values of soil deformation moduli from standard PN-81/B-0320 as the values dependent on soil state and the type or origin. Such an approach is contradictory to the discovery of a strong nonlinearity of strain characteristics in the range of small strains (10^{-5}–10^{-3}) and does not take into consideration an increase in the modulus with the depth (with increasing mean effective stress). Therefore, for the needs of this paper, Young's modulus E has been determined for silt, based on precise triaxial tests with a local measurement of strains, and also a numerical FEM analysis has been carried out using the Z_Soil v. 2007. The analysis carried out for small foundations (2.0 m × 2.0 m footing, 400 kPa load, and 0.5 m × 0.5 m footing, 600 kPa load) and for a large foundation (40.0 m × 40.0 m raft, 200 kPa load) has shown a clear reduction of settlement, even threefold, assuming a variable value of the modulus E. This reduction is especially visible for large foundations.

NOMENCLATURE

E – Young's modulus of elasticity, MPa,
OCR – overconsolidation ratio,
s – settlement under the center of foundation, cm,
ε_1 – axial strain, %,
ε_s – shear strain, %.

1. INTRODUCTION

KRIEGEL and WEISNER (figure 1, [5]), and primarily BURLAND (figure 2, [1]) find that the subsoil deformations under operational loads (of the order of 150–200 kPa) fall entirely into the range of small strains (from 10^{-5} to 10^{-3}) referred to at the beginning. The smaller the average unit pressure transferred by the foundation, the higher the strain modulus. However, standard triaxial, oedometric or pressiometric tests of soils performed to evaluate the safety of use are now carried out in the range of moderate strains, of the order of $5\cdot10^{-3}$–$5\cdot10^{-2}$. In this area, the values of the deformation moduli are subject to relatively small changes and at the same time are even a dozen or so times smaller than those obtained at very small strains ($<10^{-5}$). So the settlements predicted without taking the above phenomenon into consideration can be drastically overestimated.

It is necessary to notice that even these not very precise strain measurements resulting in underestimation, sometimes significant, are extremely seldom performed in the country in order to analyse a geotechnical design. The settlement forecasting still prevails based on the readings of primary and secondary values of soil deformation moduli from standard PN-81/B-03020, as these values depend on the state and the type or origin of soil. Only the determination of state does not raise significant objections. In the case of non-cohesive soil, it is represented by the degree of compaction, while in the case of cohesive soil – by the liquidity index. Non-cohesive soils identification based on the results of sieve analysis is reliable in a similar way. Instead, an attempt to consider the influence of geological history by means of correlation between genetic classes A, B, C, D and the values of strain modulus suggested by Polish standard PN-91/B-03020 raises serious doubts with regard to cohesive soils. These correlations are not documented, they are rather a source of noncommittal evaluation of deformation parameters in the aforementioned standard.

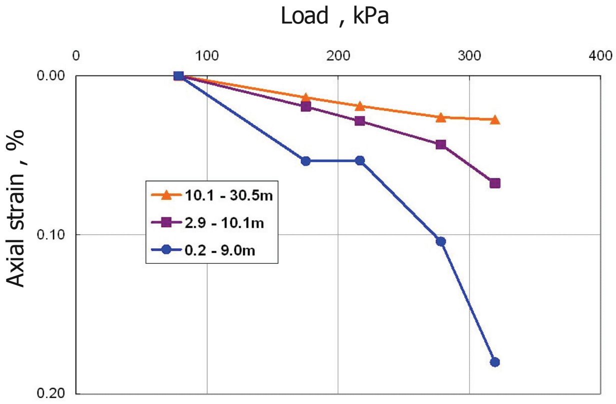

Fig. 1. Deformations under a high-rise residential building founded on a boulder clay (KRIEGEL and WEISNER [5])

Taking into account the observations mentioned, the paper is aimed at presenting the problem, showing the scale and directions of discrepancies, using the results of our own experimental work and numerical analyses. The objective will be implemented through a comparative analysis of the settlements of foundations varying in projection – raft and footing with the use of:

1. Deformation modulus estimated on the basis of precise triaxial tests, assumed in the area of small strains (10^{-5}–10^{-3}) or in the area of moderate strains, determined in a laboratory in a standard way.

2. Deformation parameters chosen according to standard PN-81/B-03020 based on the assumed liquidity index $I_L = 0.10$.

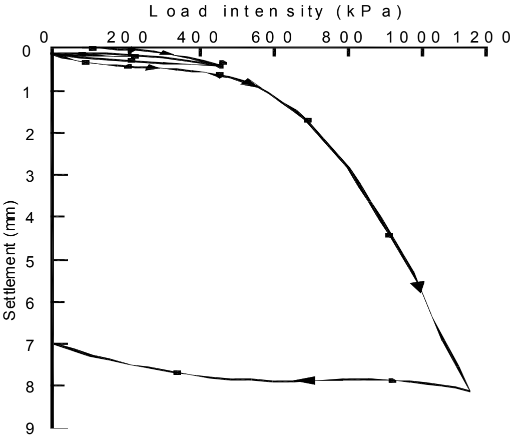

Fig. 2. An example of the steep drop of stiffness resulting in the highly progressive increase in settlement (after BURLAND [1])

In addition, the influence of depth on the values of Young's modulus *E* assumed for calculations and experimentally determined was considered in a comparative analysis. The analysis of the behaviour of the foundations under load was carried out using the finite elements method (Z_Soil v. 2007).

2. SMALL STRAINS' PROBLEMS

A dynamic development, which occurred in the mid-eighties of the twentieth century and has been continuing up to date, not only improved the quality of the tests carried out, but also contributed to discovering very strong physical nonlinearity of the soil environment in the area of small strains (10^{-5}–10^{-3}). The nonlinearity discussed manifests itself as a decrease (a dozen or so times) of Young's modulus *E* (and also the moduli of shear deformation *G* and of compressibility *K*, figure 3) in the range considered. Figure 3 presents, in a comprehensive way, the approximate application ranges of various, both laboratory and field, measurement techniques and, in addition, the deformation ranges corresponding to the operation of individual structures (MAIR [8]) as well as a visual characteristic of soil stiffness. While analysing figure 3, it is possible to think that the range of equipment possibilities of determining Young's modulus *E* variability in the full deformation range is pretty extensive. However, the practice shows that taking into consideration the availability, costs and commonness of individual instruments (KUWANO and KATAGIRI [6]), an advanced triaxial apparatus equipped with a local system of sensors for specimen deformation measurements and a set of bender-type components to measure the velocity of transverse and longitudinal wave passing through the specimen is still a leader.

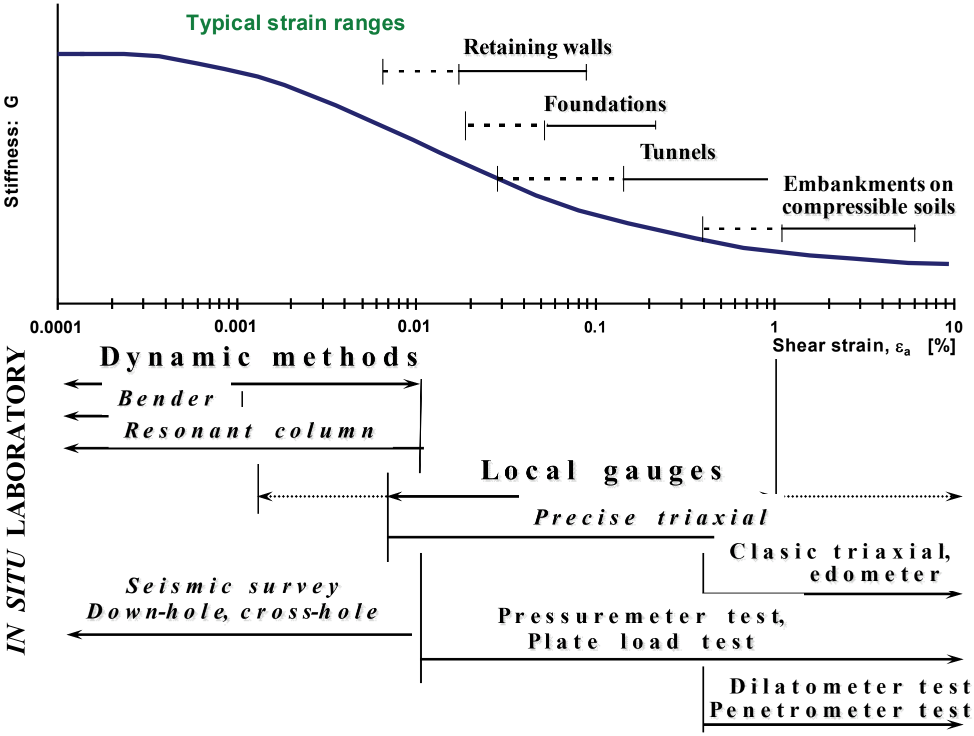

Fig. 3. Approximate ranges of reliable application of various measuring techniques for soil stiffness characteristics

3. THE MATERIAL TESTED AND COURSE OF TESTS

A series of triaxial tests was carried on kaolin from the Semi-Vitreous Chinaware Factory in Tułowice. A triaxial test features a soil density $\rho_s = 2.64$ t/m^3, natural water content $w_n = 35\%$ and plasticity index $I_P = 22.2\%$. Its other parameters, quoted many times, may be found, inter alia, in JASTRZĘBSKA's dissertation [2]. All tests were carried out on specimens, 50 mm in diameter and 100 mm high, which after installing in the chamber of triaxial apparatus were moistened initially gravitationally and then using the so-called back pressure method which allows a high value of the Skempton parameter $B = 0.95$–0.98 to be obtained. After completion of specimens moistening and their isotropic consolidation they were subjected to triaxial undrained compression. All experiments were carried out at a constant rate of displacement increase equal to 0.22 mm/h. Because of a local system of measuring a specimen deformation it was possible to determine the values of Young's modulus E in the strain range of 0.001%–10%.

4. ANALYSIS OF FOUNDATION SETTLEMENT

4.1. CALCULATIONS

The study was aimed at considering the fact that in engineering analyses the Young's modulus describing the subsoil behaviour does not have a constant value, but features a very high variability (a decrease by even a few dozen times) in the strain range of 10^{-5}–10^{-3}. To this end the settlement of three uniformly loaded foundations was analysed. The behaviour of two small footings was considered: a smaller (of 0.5 m × 0.5 m dimensions) loaded with 600 kPa and a larger (of 2.0 m × 2.0 m dimensions) loaded with 400 kPa as well as a raft treated as a large foundation (of 40 m × 40 m dimensions) loaded with 200 kPa. In the first stage of simulation, an assumption was made that the subsoil under the foundation is made of stiff silt ($I_L = 0.10$). In accordance with nomographs given in standard PN-81/B-03020 very often used by engineers, the value of Young's modulus for this soil is 18 MPa. In addition, an assumption was made that the subsoil considered is uniform and a linear elastic material model was used for its description. The analysis performed was used primarily to estimate the value of settlements for standard data. Moreover, its results allowed us to assume a model, taking into account the modulus variability, depending on average stresses (indirectly – on the depth) and on the value of main maximum strain. To this end, based on the results of the first part of the analysis, the subsoil was divided into areas of similar values of average stress and shape deformation. At a further stage, appropriate values of Young's modulus, determined from precise triaxial tests, were assigned

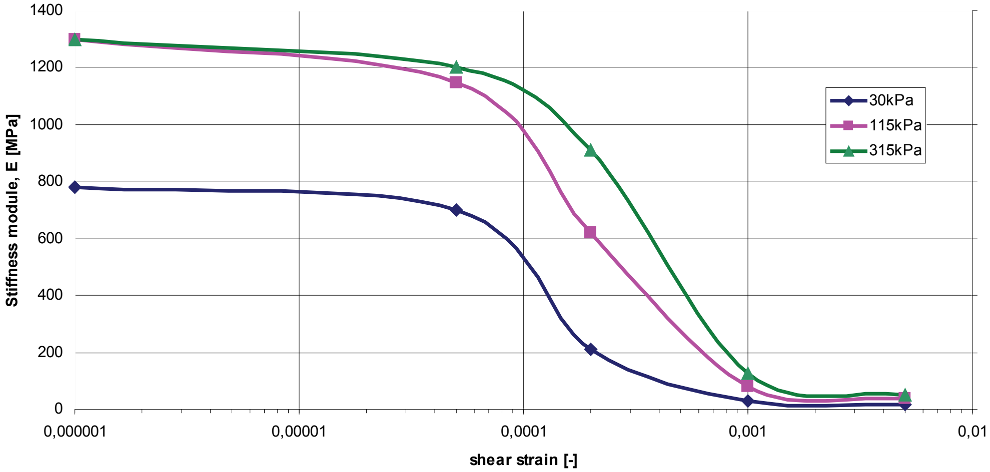

Fig. 4. Young's modulus taken for analysis vs. average stress
and main maximum strain

to those areas (figure 4). Because of that the fact that the stiffness of a substantial part of the subsoil is much higher compared with that of the area immediately under the foundation, which has a decisive impact on the settlement values obtained, has been considered in the numerical simulation.

4.2. NUMERICAL MODEL ASSUMED IN THE ANALYSIS

The foundation type analysed (a raft and small and large footings) was selected in such a way as to check the influence of its size on the results obtained. It is not difficult to notice (ŁUPIEŻOWIEC [7]) that the influence of the load transferred to the subsoil depends both on the foundation size and on the value of the load applied. Calculations were carried out by means of the finite elements method using the Z_Soil software v. 2007 [9]. A 3D problem was analysed and a quarter of the subsoil body was assumed in the simulation. For each foundation two variants of the subsoil were considered: uniform and stratified, taking account of the variability of Young's modulus. The FEM model grid for the second variant is shown in figure 5. The numerical simulation consisted in assuming first the primary stresses and then the load

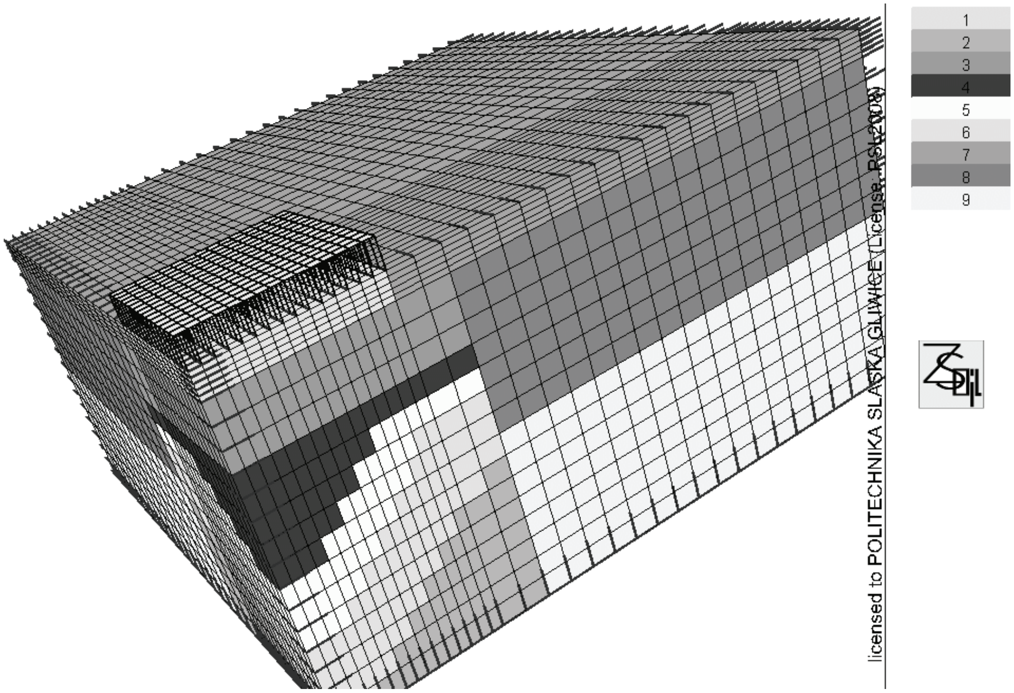

Fig. 5. Stratified numerical model of subsoil under foundation assumed in the analysis

imposed on the foundation. The latter was applied in one computational step – in accordance with the theory of elasticity assumptions. Based on the calculation results for the first variant (uniform subsoil), a model of stratified subsoil was designed, in which it was possible to assume variable values of Young's modulus (in accordance with experiments), depending on the depth and on the influence of load transferred by the foundation. The analysis results consisted of settlement values under the centre of each foundation considered.

4.3. RESULTS OF CALCULATIONS

Having performed the calculations described earlier, the results presented in the table have been obtained.

When analysing the above results it should be emphasised first of all that taking into consideration the described variable stiffness of the soil, strikingly different settlement results are obtained. In the case of strain moduli selected from the standard, the results obtained would disqualify a given type of foundation due to substantial exceeding the 2nd limit state conditions. Taking into account the variability of soil strain moduli, depending on the stress and strain state existing in specific place, the values of settlement are obtained, which – depending on additional requirements set for the structure – may be already considered permissible when designing foundations.

Table

Values of settlements under the foundations' centres (cm)

Foundation type	Calculations without considering changing stiffness of the subsoil (uniform model)	Calculations considering changing stiffness of the subsoil (stratified model)	Settlement reduction
Raft, 40.0 m ×40.0 m, $q = 200$ kPa	17.5	5.7	3.07
Footing, 2.0 m × 2.0 m, $q = 400$ kPa	19.9	6.7	2.97
Footing, 0.5 m × 0.5 m, $q = 600$ kPa	15.5	8.1	1.91

It should be noticed that much slighter influence of load on the subsoil settlement is observed in the case of considering the actual soil stiffness. A much limited range of the operating load influence is obtained taking into consideration a higher value of Young's modulus in deeper layers of the subsoil than in the case of analyses using a classical theory of elasticity. Based on that a much smaller zone, in which strains are calculated, can be assumed in engineering analyses, which definitely may contribute to more realistic settlement values.

The problem formulated here is the first approximation of a nonlinear problem resolution. To achieve a thorough analysis the next iterations should be performed, taking into account the zones of defined main strains – obtained in the previous calculation step – to which the values of strain modulus based on tests results are assigned. However, in typical engineering problems such approximations may be considered precise enough.

It also should be noticed that much higher settlement reduction is obtained in the case of larger foundations. For small, highly loaded footings the settlement values are reduced only twice. The fact that the range of load influence on the subsoil is relatively small is definitely important in this case and therefore layers under the influence of small primary strains are involved in the interaction. This makes that the increase in the strain modulus value is not so significant. However, despite that, the estimated settlement reduction approaches 2.0. In the case of larger foundations, this reduction is threefold.

It also should be noticed that the settlement reduction is visible only for small foundations. For a slightly larger footing (2.0 m × 2.0 m), the influence of foundations size is not that important. This results probably from the fact that in this case the dependence of the strain modulus on the deformations under the foundation has a decisive influence on the settlement values. Only for a small foundation the load transferred by it is much higher than the primary stresses existing in the subsoil and therefore the deformation originating just under its base has a slightly higher value. Therefore the modulus corresponding to those deformations may be even smaller than $E = 18$ MPa adopted according to the standard. However, also in this case a significant, i.e. around twofold, reduction of settlements is obtained. For a larger footing and also for a raft, the range of the influence calculated as dimension-dependent is similar. A slight difference is caused by the increase in stiffness with the depth and in the case considered this is a secondary influence compared with stiffness changes as a function of strain (figures 3 and 4). Different values of load transferred by the foundations to the subsoil also may play a role here. However, the values of the loads assumed correspond to the values observed in reality.

5. SUMMARY

The influence of the strain parameters selected on the values of settlements of engineering structures founded on the subsoil by means of a raft or footing has been analysed. In addition, the influence of stress history and the depth of settlement determination has been considered. For a small foundation, a twofold reduction of the settlements estimated was obtained, while for larger structures – a threefold reduction (comp. JASTRZĘBSKA and ŁUPIEŻOWIEC [4]). This property may have a decisive importance in the analyses of actual foundations, because the results much closer to reality are obtained. In some cases, a more thorough analysis of settlements may allow a specific solution, which – using the approach to settlement estimation resulting from the standard – could not be implemented.

A very simple method for considering complex deformation properties of soil has been presented, which may be used in typical engineering calculations. A more precise way of analysis according to the procedure suggested should obviously assume a change of the strain modulus in a few computational steps; however, this way of simulation would require extremely long time. This problem could be resolved by applying an automated selection of deformation parameters by a computer software; however, such a procedure is not available in FEM systems. Moreover, such an advanced analysis would require a more complex material model. This would be reasonable only in the case, where the parameter values taken for calculations would be estimated based on high-quality experimental tests performed and not assumed roughly on the basis of various correlations.

REFERENCES

[1] BURLAND J.B., *"Small is beautiful" – the stiffness of soils at small strains*, 9th Bjerrum Memorial Lecture, Canadian Geotechnical Journal, 1989, Vol. 26, 499–516.

[2] JASTRZĘBSKA M., *Calibration and verification of one-surface elasto-plastic soil model of strongly non-linear anisotropic strengthening* (in Polish), PhD Thesis, Silesian University of Technology, Gliwice, 2002.

[3] JASTRZĘBSKA M., *Investigations of the behaviour of cohesive soils subject to cyclic loads in the area of small deformations* (in Polish), DSc Monograph, Silesian University of Technology Publishers, Gliwice, March 2010.

[4] JASTRZĘBSKA M., ŁUPIEŻOWIEC M., *Foundations settlements taking into account the variability of strain moduli* (in Polish), 56th National Conference of KILiW PAN and KN PZiTB, Kielce–Krynica, September 2010, 145–152.

[5] KRIEGEL H.J., WEISNER H.H., *Problems of stress–strain conditions in subsoil*, Proceedings of 8th Int. Conf. on Soil Mechanics and Foundation Engineering, 1973, Vol. 1, No. 3, 133–141.

[6] KUWANO J., KATAGIRI M., *Recent state of laboratory stress–strain tests on geomaterials in Japan*, [in:] *Advanced Laboratory Stress–Strain Testing of Geomaterials*, A.A. Balkema Publishers, Tokyo, 2001, 47–52.

[7] ŁUPIEŻOWIEC M., *Analysis of large-size structures foundation taking into account a strong variability of soil stiffness in the area of small strains* (in Polish), Scientific Papers of Cracow University of Technology, Environmental Engineering series, Cracow, 2010.

[8] MAIR R.J., *Development in geotechnical engineering research: application to tunnels and deep excavations*, Proceedings of the Institution of Civil Engineers, Unwin Memorial Lecture 1992, Civil Engineering, 1993, Vol. 93, 27–41.

[9] ZIMMERMANN TH., TRUTY A., URBAŃSKI A., PODLEŚ K., *Z_Soil.PC 2007 3D user manual, Theory*, Tutorials and Benchmarks, Data Preparation, Elmepress International & Zace Services Ltd, Switzerland, 2007.