Interaction between structures and compressible subsoils considered in light of soil mechanics and structural mechanics

Etude de l'interaction sol- structures à la lumière de la mécanique des sols et de la mécanique des stuctures

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ABSTRACT: Authors developed '*FEM Models*' software, which allows solving soil-structure interaction problems. To speed up computation time this software utilizes a new approach, which is to solve a non-linear system using a conjugate gradient method skipping intermediate solution of linear systems.
The paper presents a study of the main soil-structure calculations effects and contains a basic description of the soil-structure calculation algorithm. The visco-plastic soil model and its agreement with in situ measurement results are also described in the paper.

RÉSUMÉ : Les auteurs ont développé un logiciel aux éléments finis, qui permet de résoudre des problèmes d'interactions sol-structure. Pour l'accélération des temps de calcul, une nouvelle approche a été utilisée: qui consiste a résoudre un système non linéaire par la méthode des gradients conjugués, qui ne nécessite pas la solution intermédiaire des systèmes linéaires. Cette communication présente une étude des principaux effets des calculs sol-structure, et une description de l'algorithme de calcul sol-structure . Le modèle visco-plastique pour le sol et la bonne concordance avec les résultats des mesures sont également détaillés. .

KEYWORDS: soil-structure inrteraction, soil non-linear models, numerical modeling

1 INTRODUCTION

Necessity soil-structure interaction calculations (SSI) is becoming more and more obvious to a majority of both geotechnical and superstructure designers. SSI produces one major effect that can be expressed by a simple formula "subsoil behaviour considered = superstructure loads changed". The effect has been certainly known for a long time. Indeed, a theoretical epure of contact stresses under an absolutely rigid plate is a parabola with infinite values under plate edges. A real epure is of a characteristic trough shape. Stresses at the plate foot are a reflection of this epure. Correspondingly, stresses inside the plate itself will be equally non-uniform. However, the essence of the matter is that loads distribution in this or that structure depends on a whole range of factors, including, but not limited to, structural layout, spatial rigidity, deformation characteristics of structural materials, and subsoil yield properties.

The degree of difference between an SSI-based calculation and that for traditional non-yielding supports can be expressed as factor $K_{ssi} = \sigma_{ssi}/\sigma_{tr}$, where σ_{ssi} – stresses in a certain point based on SSI, σ_{tr} – stresses in the same point based on traditional separate calculation. Based on our sample numerical analyses that factor may reach the value of 4 for typical building layouts (Fig. 1), which establishes practical necessity for SSI design.

Factor K_{SSI} tends towards 1 with subsoil rigidity increase, i.e. on condition that subsoil approaches a non-compressible state. With decrease of subsoil rigidity the factor increases to certain limits following which it no longer displays any significant change (and, of course, the greater the subsoil yield, the greater the settlement). The highest stress concentration is observed in the lower edge of transverse walls in layout *a*, because in this layout stresses cannot be transferred to longitudinal exterior walls.

The dependency shown in Fig. 1 cannot certainly be used directly in practical design applications in view of the fact that it was obtained for some generalized and simplified structural building layouts. Practical SSI effects are considerably more difficult and versatile.

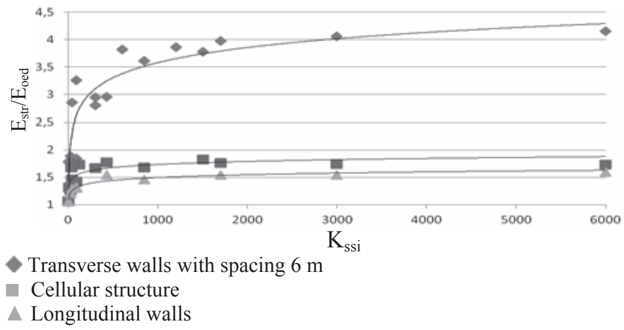

Fig. 1. Dependency of K_{SSI} value on relation of superstructure and subsoil stiffnesses E_{str}/E_{oed} for various building layout types

2 MAJOR PROBLEMS OF PRACTICAL SSI APPLICATION

So, expediency of SSI application in practical analyses seemingly being beyond doubt, one should simply go ahead using SSI-based computations in one's routine design activities. However, when practically attempting analyses a designer faces several problems which we attempt to classify below.

2.1 *Technical problems*

Technical complicacy of SSI analyses. SSI analyses pose a challenge even for contemporary, rapidly advancing, computer technologies.

Commercial dearth of codes capable of SSI calculations catering to the interests of both superstructure and geotechnical engineers.

Closed-in character of commercially available codes: they are essentially "black boxes", never revealing the ways in which the models of materials and soils actually work.

Unavailability of an instrument with which to study behaviour of various models of soils and materials.

2.2 *Unsolved problems of soil mechanics*

Imperfection of models representing soil behaviour. It seems that there are dozens of models of soil-behaviour, however, often, in real life one is faced with situations of being unable to find a requisite model capable of effective and correct solution of a practical problem.

Insufficiency of initial input parameters submitted as results of site investigation.

Limitations of models and dearth of good quality input parameters often yields imprecise modelling results.

2.3 *Organizational problems*

Absence of unified data base on in situ monitoring of buildings and structures. Improvement of models and practice of analyses is impossible without comparison with in situ monitoring data. Nevertheless, despite many construction projects built all around the world, there are only single instances of well documented in situ monitoring.

Sharing responsibility between geotechnical and super-structure engineers.

3 NEW RELEASE OF FEMMODELS SOFTWARE (FEM MODELS 3.0) AS A POSSIBLE INSTRUMENT OF SSI PROBLEMS SOLUTIONS

The list of problems necessary to be solved in order to enhance SSI reality is a heavy one. Is there a possibility to overcome them?

Such instrument can be found in the new release of *FEM Models 3.0* software. Technical SSI problems can obviously be resolved by creating an efficient programme code capable of rapid SSI problems solutions. Additionally, creating an efficient software medium for such analyses can remove a number of other problems. For example, in when a convenient programme capable of catering to the interests of both superstructure and geotechnical engineers equally well is created organizational problems listed above are largely removed, because division of labour and sharing responsibility can be realized within the framework of a single analysis profile "soil-structure".

The new release is being created under the auspices of ISSMGE TC 207 "Soil-Structure Interactions and Retaining Walls". The larger portion of the software is structured as an "open source", involving maximum openness and availability.

3.1. *3-D modelling medium*. The medium is created based on a very effective open software source OpenCascade, capable of performing solid modelling using logical operations with figures, their geometric transformations, etc. The profile editor contains rather simple modelling instruments, perfectly accessible to engineers who are the end-users of the software. An important task is introduction of adaptive finite-element meshes into the modelling medium architecture. Adaptive meshes move a significant portion of the task to provide solution accuracy to the computation algorithm.

3.2. *Non-linear equations solver*. When using finite element method, non-linear differential equations within the limits of investigated areas are reduced to solution of systems of non-linear algebraic equations. The task of this software component is an effective solution of large systems of nonlinear equations.

3.3. *Integrated Engineering Environment (IEE)* provides a possibility to perform engineering computation (in the form of formulas and simple algorithms), as well as solution of parametric problems by finite elements methods using components 2.1 and 2.2 described above. IEE is a *java* based tool and provides all possibilities of a state-of-the-art high-level programming language aimed at simplifying writing of mathematical formulae and algorithms (work with matrices, numerical modelling and so on). The codes of finite-element models and materials models are written in the same environment in the most transparent and accessible form. The objective of this environment is to make complex non-linear models more accessible for study and improvement.

3.4. *Library of finite elements and materials models*. All models of elements and materials are stored in the library with an open source, which makes their analysis and verification easier. This library makes it possible not only to use preset finite elements solutions, but also to add some of one's own design.

3.5. *Library of parametric problems to be used in design practice*. This library provides a possibility for engineers to solve specific practical problems without an in-depth study of finite-element programmes. For instance, the way SSI analyses are performed by the authors is such that numerical analyses are always correlated with available analytical solutions, which yield approximated results. Such approach eliminates potential for significant errors. Using the library of parametric problems the user is given a possibility, for instance, to make both an ordinary analytical calculation of settlements and a numerical computation, following which both results can be collated.

All parts of the programmes (except the solver) are of open source type. To ensure a fastest possible solution it is suggested to use a special highly effective server. To increase computation quality, collection of data on well-documented case histories is actively underway with participation of ISSMGE TC 207 «Soil Structure Interaction». In future based on this work it is planned to build a method of testing soil-models as regards their correspondence to in situ data.

4 USE OF NON-LINEAR SOIL MODELS FOR MODELLING SUBSOIL IN SSI APPLICATIONS

The issues of adequate choice of soil model to properly represent subsoil action are covered in every detail in the paper (Shashkin, 2010a).

The most promising approach to building the model in our opinion is the so called Double Hardening, which perhaps would better be referred to as *Independent Hardening*. In this approach hardening zones during isotropic and deviatoric loading develop independently, which is confirmed experimentally. An example of the model, built based on that principle is he Hardening Soil Model (HSM). However, the idea of independent hardening in it is not brought to its logical conclusion.

Additionally, the standard HSM model assumes isotropic hardening, which can not be proved experimentally. At multidirectional, specifically, cyclic loading (Fig. 2) the model yields results radically different from the experiments.

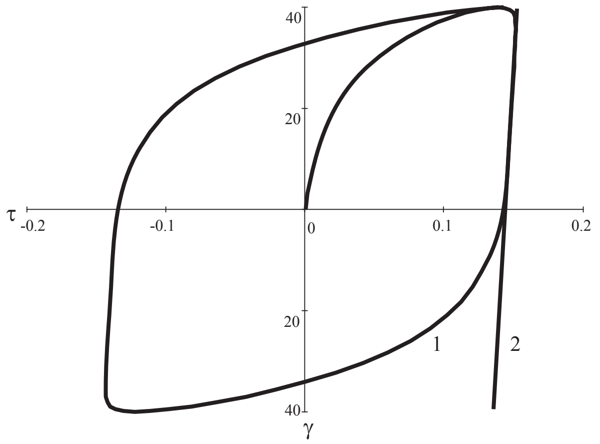

Fig. 2. Strain-load dependency at cyclic loading: 1 – as evidenced by experiments; 2 – according to isotropic hardening models

To remove the above-described discrepancies the present authors developed their own model featuring independent anisotropic hardening. Compared with the HSM model the dependencies for hardening in volumetric and deviatoric directions have been significantly simplified and purged of contradictions. Somewhat more detailed equations for the model are contained in the paper of Shashkin (2010a). A fundamental addition is introduction of anisotropic hardening (Fig. 3).

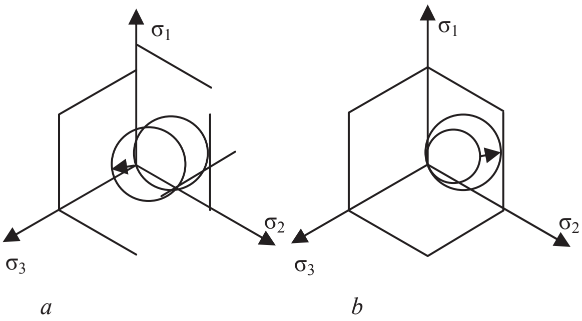

Fig. 3. A diagram of development of hardening area according to the assumed model featuring anisotropic hardening: (*a*) hardening during first loading, (*b*) change of location of hardening during reverse loading

During deviatoric loading the hardening zone in the model develops anisotropically and is directed towards loading. When the loading direction is changed the hardening zone moves, and its size does not increase until the hydrostatic axis remains within that zone. At translational movement of the hardening zone, with loading ongoing in the opposite direction, the strain is doubled, according to the Masing rule. As a result, the model provides a correct representation of soil behaviour at multidirectional loading. In that, taking into account anisotropy of strain hardening, according to the assumed approach, does not require introduction of any additional model parameters in contrast to the isotropic hardening model.

A correct representation of soil behaviour under loading following unloading and under multidirectional loading is relevant not only for cyclic loading tasks (as it may initially appear). Multidirectional loading of subsoil is encountered in modelling of any building with a complex underground part, which is very common in contemporary design. Indeed, when bulk excavation is performed subsoil experiences a reduction of volumetric stresses and a corresponding increase of deviatoric stresses. As the superstructure is being added, volumetric stresses increase, whereas deviatoric stresses at first decrease and then increase in the opposite direction. Any model that does not take into account hardening anisotropy, as shown by Fig. 8, will radically underestimate strains present at the stage of building the superstructure. Therefore, a proper account of anisotropy hardening appears rather important as regards SSI.

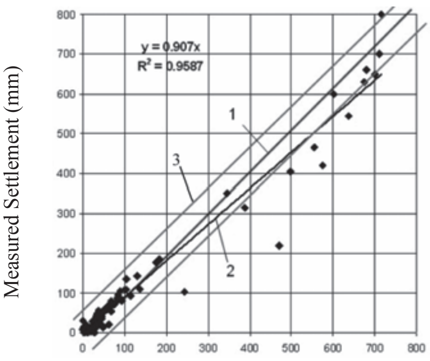

Fig. 4. Comparison of numerical analyses of settlements performed through the offered non-linear independent hardening model and monitoring results: 1 – perfect fit between computed and observed settlements, 2 – linear approximation, 3 – standard deviation

The model was tested based on the settlement database created under the auspices of ISSMGE TC 207, under the programme of data collection for well-documented case histories. Numerical analyses and monitoring results are collated in Fig 4. As one can see from the figure, this model provides a good accuracy of settlement calculation, and, accordingly, can be used in day-to-day SSI analyses.

5 EXAMPLE OF SSI ANALYSES USED IN CONTEMPORARY DESIGN PRACTICE

Below we shall give an example of how effectively SSI analyses can be used in real day-to-day design applications.

St. Nicholas Naval Cathedral is located in the town of Kronshtadt (Fig. 5). It was built in 1902-1913 according to the project of V.A. Kossiakoff. In this cathedral an idea of a classical cruciform church with a domed roof was fulfilled. This idea was realized first in the famous St. Sophia Cathedral in Constantinople. In fulfilling ancient architectural traditions new structural materials, introduced in the beginning of the 20 century, have been used. The main dome is supported by the system of steel beams. The dome is made of the reinforced concrete. Four big pillars are the main supporting elements of the cathedral. Due to the presence of the boulders the author of the project decided to construct foundations made of cast-in-place reinforced concrete avoiding construction of piles.

Immediately after the construction completion the differential settlement was recorded with the value of about 4 cm.

Fig. 5. St. Nicholas Naval Cathedral in Kronshtadt

During the Cathedral's life a lot of cracks have been developed. In May 2009 a sharp local increase of a crack in one of the abutments was observed. This endangered the stability of the whole structure. A special programme of cathedral structural survey, research and development of salvation measures was put forward. The key issue of this investigation was to find out the reasons of cracks development.

Some dangerous cracks in the cathedral's structures are shown in Fig. 6.

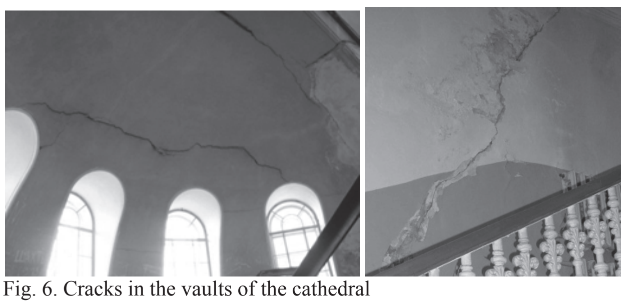

Fig. 6. Cracks in the vaults of the cathedral

Full structural survey of the cathedral was completed. The condition of the foundations and subsoil was estimated. Dynamic sounding of the subsoil was made and detailed geophysical investigation was performed. Soil samples from the holes were taken; main properties of soil were determined.

A series of soil-structure interaction computations has been. The computation profile is shown in Fig. 7. All main structural elements, foundations, and subsoil layers have been incorporated in the computation profile. All main findings during the condition survey of structural elements, foundations, and subsoil have been taken into account in computations.

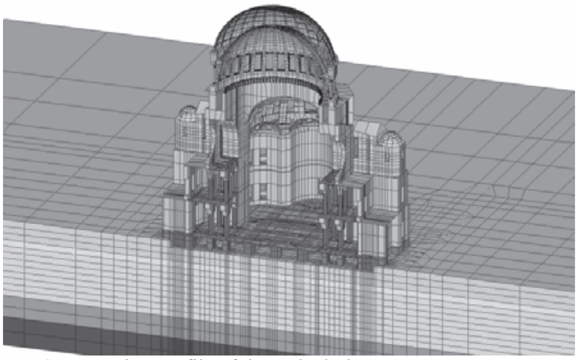

Fig. 7. Computation profile of the cathedral

Soil-structure interaction calculations showed that the cathedral is subject to non-uniform settlements. The reason of these settlements is the different loads acting to the main bearing structures of the Cathedral (Fig. 8-9). Such non-uniformity of loads is quite typical for the temples characterized by cross-cupola structural scheme. The most heavily loaded are central pillars by which the central cupola is supported. Hence, the pillars are subject to bigger settlements. The calculated non-uniform settlements (Fig. 8) correspond well to the results of the geodetic measurements. The observed settlement differential is about 13-22 mm.

Computations show that the zones of development of tensile stresses in brickwork well agree with the locations of actual cracks. In particular, taking into account non-uniform settlements we have a characteristic system of cracks in the semi-domes in altar and Western parts of the Cathedral (Fig. 9).

The main conclusion of the conducted investigations and SSI computations is that currently there is no danger of an immediate collapse of the Cathedral. Local mostly endangered structural elements are: the main dome, its supporting elements and semi-domes in Eastern and Western parts of the cathedral. Local reinforcement must be provided as soon as possible. This reinforcement must be based on the detailed analysis.

General strengthening of the monument was executed on the basis of SSI computations as required both by local codes (TSN 50-302-2004) and International codes.

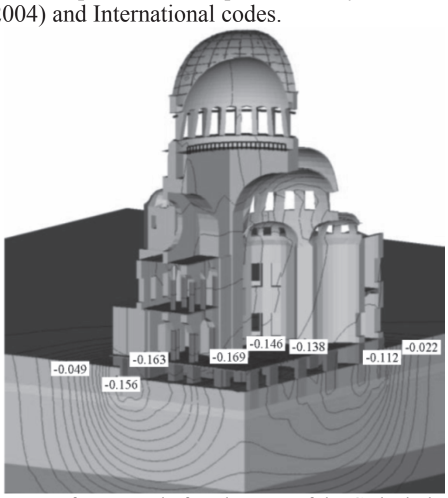

Fig. 8. Contours of computed of settlements of the Cathedral, cm

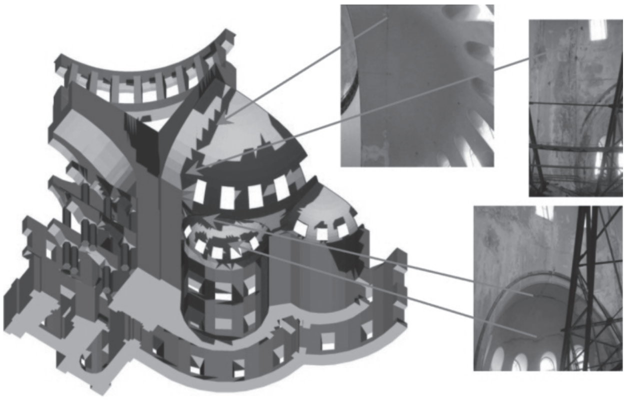

Fig. 9. Location of possible calculated cracks development and real observed crack locations

The given example demonstrate that SSI calculations can become an important tool in design practice, ensuring the most effective design solutions without compromising overall safety and reliability of buildings and structures.

6 CONCLUSIONS

1. Proper engineering account made of soil-structure interaction is essential not only for unique projects but also for run-of-the-mill buildings and structures. Analyses of typical buildings' layouts show that SSI computation may reveal stress increases exceeding 4-times the stresses computed for rigid subsoils.

2. Application of soil-structure interaction analyses in design practice is associated with a number of problems, which can be mostly resolved by means of *FEM models 3.0* release. The former releases of the software used by Georeconstruction Institute in their design practice for 10 years revealed efficiency of the unified approach towards combined soil-structure modelling within a single software package.

3. The algorithm for solution of non-linear equation systems targeted at cracking highly complex non-linear SSI problems does not contain an enclosed cycle for solution of linear subproblem while tackling a linear problem, which significantly reduces solution time. Convergence of the algorithm is proved for rather general and relatively easily met conditions.

4. The offered non-linear soil model is able to accommodate strain hardening anisotropy, which feature is of high importance for soil-structure interaction analyses used for design of buildings with a complex underground section.

7 REFERENCES

Golub G., Van Loan, Ch. 1999. *Matrix Computations*. Moscow, Mir Publishers.

Munksgaard, N. 1980. Solving Sparse Symmetric Sets of Linear Equations by Preconditioned Conjugate Gradients, *ACM Transactions on Mathematical Software (TOMS)*, Vol. 6 No. 2, pp. 206-219

Shashkin, A.G. 2010a. Critical analyses of most widely used non-linear soil models. *Engineering Geology*. Moscow. No 3,. pp. 29-37 (in Russian)

Shashkin, A.G. 2010b. Depicting deformation behavior of clay soil with visco-elasto-plastic mdel. *Engineering Geology*. Moscow. No 4,. pp. 22-32 (in Russian)

Shewchuk J.A. 1994. An Introduction to the Conjugate Gradient Method Without the Agonizing Pain

Voevodin, V.V. and Kuznetsov, Yu.A. 1984. *Matrix and calculations*. Moscow. Science Publishers (in Russian)

Wolfe, P. 1969. Convergence conditions for ascent methods. *SIAM Rev.* 11 (2), pp. 226–235.