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Geotechnical supervision in complex reconstruction of city areas

La supervision geotechnique en reconstruction complexe de zones urbaines

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ABSTRACT: Reconstruction of coastal cities usually presents complications owing to thin strata of weak marine deposits found in the underlying soils. Reconstruction experience in Saint-Petersburg reveals deformations of the adjacent buildings in most cases, 90% of which are ushered in by failure to predict joint subsoil-foundation behaviour as may be occasioned by negligible design, as well as by application of the inadequate construction techniques. The article features setting forth of a unified concept of geotechnical support of urban reconstruction comprising complex research, numerical modelling of various reconstruction situations, actual monitoring, design assessment, safety provisions and cofferdam protection.

RÉSUMÉ: D'habitude la reconstruction des villes marines produit des difficultés à cause de minces couches de marines dépôts faibles qui se trouvent dans les sous-sols. L'expérience de la reconstruction à St. Petersbourg fait voir que en plupart du cas des bâtiments contigus se déforment à cause de projets négligents ou inadéquate technologie de construction qui est incapable de prédire la conduite jointe de sous-sols et fondement. L'article décrit le conception unifié du appui geotechnique de reconstruction urbaine qui consist en recherches complexe, modelage numérique de divers situations de reconstruction, monitoring, estimation des projets, approvisionnement de sûreté et stabilisation des murs de fouille.

1 INTRODUCTION

1.1 *Geotechnical problems during reconstruction of coastal cities*

Lots of contemporary cities originated in coastal areas near seas and rivers where the ground conditions are specifically complicated. For instance, the boundaries of Saint Petersburg historical city centre correspond quite remarkably to those of the underlying weak clays. From surface [+2...+4 m absolute level] the strata distribution is generally as follows: made-up ground [≈ 2 m], deltaic sands [2 m - 6 m], post-glacial Baltic clays, glacial (moraine) loams and clay-sands [at 20 to 30 m from surface].

Deltaic and glacial strata possess construction friendly properties, whereas Baltic marine clay-sands and loams are counted amongst weak and structurally unstable soils.

Until 2-nd half of the 20-th century buildings in Saint-Petersburg used to be erected on shallow foundations with the bearing strata composed of the surface sands, though quite rarely short (max. 10 m) timber piles were employed. Being the capital of the Tsarist Russia, Saint-Petersburg had quite a peculiar limitation 'imposed' on the subsoil bearing pressure, whereby no ordinary building was permitted to surpass the cornice level of the Imperial Winter Palace. This, naturally, was entirely based on ethical and aesthetic grounds, the resulting subsoil bearing pressure nonetheless being comparatively low. However, the older buildings still used to tilt towards the heavier neighbouring ones just constructed. Despite most of the buildings now reaching the age of 100-150 years, many of them continue suffering from uneven settlement conditioned by the increase of technically generated loads on subsoil. The most powerful effect is that of the new construction in their immediate adjacency.

Apparently, the agreeable quality of both design and construction in the described circumstances is only attainable based on the full-fledged scope of relevant geotechnical research, including geological and geodetic, (in congested areas complemented by meticulously conducted condition surveying of the existing structures), designed to identify the most sparing construction solutions and methodology. Considering high costs of the preliminary research, which, however, is incomparable with the expense spent on recovery of buildings damaged as a result of unaffordable negligence, attention is needed to identify the necessary work scope in each individual case. An attempt at such subdivision may be seen as trying to identify the degree of geotechnical complexity of a given building and the corresponding scope of preliminary research and monitoring during construction. This will allow adjustment of both design solutions and construction methods.

1.2 *Geotechnical categories*

The most expedient approach towards such an assessment of geotechnical complexity would be such based on a combination of criteria distinguishable into 3 groups. Group 1 – traditionally accepted *importance subcategory* of new construction or reconstruction (ordinary, considerable or unique). Group 2 – *condition subcategory* of the adjacent structures or of the actual reconstruction site (poor, satisfactory or fair).

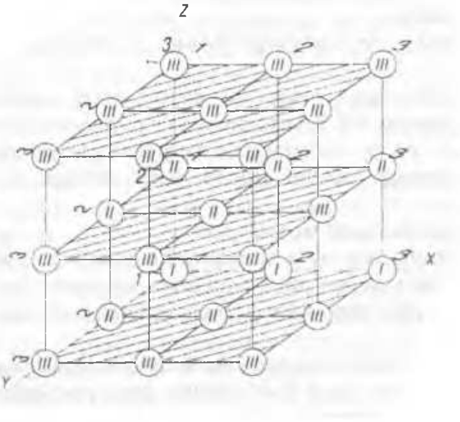


Figure 1. Identification of geotechnical complexity of new construction or reconstruction in city areas: *x* - technical *condition* of adjacent structures; *y* - *risk*, *z* - *importance* of new construction or reconstruction.

To predict the aftermath of this or that design solution Group 3 is needed to identify the risk area (an area where the influence of any of the extraneously generated loads is expected) and the degree of such influence (degree of risk). An option for identifying the geotechnical complexity of a site in relation to its complexity features is drafted in *Fig. 1*. For each group of criteria a subcategory is established and finally it is the combination of those subcategories that decides the Category of geotechnical complexity (geotechnical category) in each given case.

Geotechnical category I shall include:

• reconstruction of a building with no subsoil bearing pressure increase and no corresponding change in the way the subsoil behaves statically (e.g. when no new foundations are constructed or basement areas expanded, etc), provided that the condition subcategory is I.

• new construction of buildings, structures or services, provided that the importance subcategory is I and no static or other loads are generated in relation to the existing buildings.

Geotechnical category II shall include combinations of subcategories not included into categories III or I.

Geotechnical category III shall include cases where at least one of the components is of subcategory 3. The exceptions will occur when the risk subcategory is 1 and the importance subcategory of a new construction or condition subcategory of a reconstruction is 1 or 2, where *geotechnical categories I* or *II* would normally apply.

Geotechnical category of a new construction or a reconstruction will be adjusted at all stages of geotechnical monitoring.

2 THE PRINCIPAL FACTORS CAPABLE OF CAUSING UNEVEN SETTLEMENT OF THE GROUND BULK

To properly assess geotechnical situation it is necessary to first consider the principal factors capable of causing uneven settlement of the ground bulk, thereby generating defects in the adjacent buildings. For a new construction or a reconstruction in a city centre such factors will include the following:

- *Weak clay strata in subsoil.*

Such soils have considerably high compression characteristics and low saturation ratio. Their uneven settlement conditioned by excess loading may go on for decades and even centuries. Weak silty clays are extremely sensitive in terms of remoulding which leads to increase of their deformation capabilities and reduction of their bearing characteristics.

- *Silty saturated sands in subsoil close to foundation.*

Sands have the property of transformation into floating state at extraneously generated loads. They are also compacted at dynamic loads. Their seepage resistance is weak even at low water pressure gradients.

- *Excavation below the foundation footings of the adjacent buildings.*

When doing the design below the ground level special shoring/propping options will have to be taken into account with the intention to rule out any movement of the ground outside the excavation and seepage of the ground water through the cofferdam.

- *Foundations methods and technologies.*

The construction practice in the specific ground conditions of Saint Petersburg centre demonstrates no a priori settlement free foundation technologies being offered by either foreign or local contractors.

For an individual geotechnical situation such techniques may be divided into two types. Type I will include those practically not capable of ruling out negative influence on the ground bulk and the adjacent buildings. Type II will include those with the provisions available to accommodate safe construction method. The latter will be referred to as 'sparing' techniques.

- *Surcharge on subsoil generated by new structures.*

The design solution for the new foundation is produced with the additional settlement of the adjacent structures borne in mind, being:

$$S_{ad} \leq S_{adu} \tag{1}$$

where S_{adu} – permissible settlement as per TSN 50-302-96 (local construction standards and norms). This settlement is a sum of the following components:

$$S_{ad} = S_{ad}^{load} + S_{ad}^{w} + S_{ad}^{slope} + S_{ad}^{tech} \tag{2}$$

where S_{ad}^{load} – is conditioned by surcharge on subsoil by weight of the building under construction; S_{ad}^{w} – is related to compaction and mechanical suffusion (washing out of fines) in silty sands at dewatering; S_{ad}^{slope} – is occasioned by the cofferdam deflection and related movement of the ground bulk outside excavation; S_{ad}^{tech} – is contributed to by influence of particular method of construction.

Components S_{ad}^{load} and S_{ad}^{tech} cannot be totally reduced to zero values, whereas S_{ad}^{w} and S_{ad}^{slope} can be avoided by means of pertinent design and construction solutions.

Definition of each of the above components is rather difficult and cannot be attained by the basic standard engineering methods. Numerical assessment of those values is only possible if the modern physically and geometrically non-linear models of soil mechanics are applied. To identify components S_{ad}^{load} and S_{ad}^{slope} it will be necessary to solve elastoplastic, visco-elastoplastic and seepage consolidation tasks (the latter two are used when it is necessary to predict the development of deformations in time). For weak clay a model of structurally unstable medium may be used [Shashkin A.G., 1988]. Definition of value S_{ad}^{w} is attainable by solution of seepage tasks.

Value S_{ad}^{tech} is the most difficult as it is related to the selected construction techniques. It is only very recently that this value started to be taken into account owing to unavailability of any method to calculate the influence of the chosen technique on the ground bulk. This gap has now been partly bridged by solution of geometrically non-linear tasks in soil mechanics [Paramonov V.N., 1998] and partly by development of weak clay model where it is represented as structurally unstable medium.

3 DEFORMATIONS OF BULIDINGS IN SAINT PETERSBURG

In 70-s and early 80-s two major methods of protecting old buildings from the effects of nearby construction were generally employed: cantilevering and dividing sheet piling. The former was generally grounded on the practice of locating foundations of constructed buildings as far away from those of the existing ones as possible, with whatever parts above the ground level propped by cantilevers in the "void" area, whereby it was attempted to achieve reduction of any unfavourable influences from the constructed building unto the existing one. The positive effect of that measure had been insignificant mostly due to the fact that construction of cantilevers with more than 4 m outreach was technically rather troublesome. As was demonstrated by calculations, any agreeable result would only be effected in case the cantilever outreach was nearly the same as the depth of the suppressed ground mass (around 20 m) which is absolutely impracticable.

Dividing sheet piling along the boundary of the adjoining buildings is likewise only effective in case the piles cut through the whole of the suppressed ground mass and have their toes fixed in less suppressible layers. As those layers are usually located deeper than 20 m, sheet piling becomes rather problematic both in terms of technology and provision of safety to the surrounding buildings. Moreover, the sheet pile wall changes conditions of the suppressed ground in the base, which may easily cause additional settlement.

Construction of buildings on piled foundations with the pile toes resting on comparatively strong glacial strata is by far the most radical. In such cases the static load of the new building onto the bases of the existing ones with the upper level foundations is minimal. Development of this technology up to the late eighties was halted by no sparing piling methods being available on the Russian construction market. Bored piling is definitely the one to be referred to as such. However, those methods, as has been demonstrated by the recent construction experience, require adjustment to the regional ground conditions, which, without sufficient knowledge of some specific properties of soft clays, is impossible to accomplish.

For instance, introduction of Bauer piling to Saint Petersburg started with a quite drastic failure during construction of the Nevsky Palace Hotel when the three neighbouring buildings were ruined by applying the Bauer method. Bauer is a casing protected method with the casings jacked into the ground by means of alternating turns and the spoil extracted by either a bucket or an auger. When drilling through the supple clay, its access into the bore was mindlessly overlooked whereby completely uncontrolled amounts of spoil were taken out. This resulted in settlement of the neighbouring residential buildings exceeding the critical 30-mm and evacuation of all the tenants. This situation was repeated at yet another Saint-Petersburg site (Malaya Dvoryanskaya Street, 4-6) after which occurrence the question was raised as to whether such piling method was at all applicable to the geotechnical conditions of the city. Once the matter was looked into by the local experts the causes for the above mentioned mishaps were revealed and safe piling regimes worked out. A method for calculating the necessary size of the ground lock was introduced, this lock ensuring stability at the bottom of the bore. The dynamic loads created in the process of pile construction were also eliminated. Thus, the necessary adjustment of the Bauer piling made it possible to successfully use this method on St. Petersburg reconstruction sites.

4 NUMERICAL MODELLING

4.1 *Numerical modelling of reconstruction situations*

One of the most basic components of geotechnical monitoring is geotechnical support. At the heart of it there is so called 'FEM-models' software which has a *bank of models* containing the complete list of models referred to above [Ulitsky V.M. & others, 2000], thus providing for the possibility to model virtually any geotechnical situation. Based on solution of multiple tasks where various models are studied through altering their parameters, the foundation options least *statically* harmful towards the existing buildings and, naturally, acceptable for the needs of the project under design.

The next series of tasks defines the temporary works solutions, such as the cofferdam option, anchorage, ties, etc, based on the requirements to safeguard the adjacent areas from settlement as may be related to the cofferdam movement and dewatering.

Following selection of the foundation and the temporary works options, the last set of tasks is solved to develop a sparing technique of foundation construction for the given case.

Naturally, the sequence of the calculation procedures described above has been simplified, whereas in reality the geotechnical assessment of the situation is accomplished through a series of progressive approximations. As a result of such procedure the options compliant with expression (1) above are selected.

Contemporary construction norms provide a broad field of opportunities to perfect numerical methods of subsoil-foundation design. Particularly in Saint Petersburg an entire chapter of the geotechnical norms provides for the necessity to envisage and predict joint action of buildings and their subsoils which is only attainable through numerical methods. Unfortunately enough, it should be noted that the requirements contained therein remain practically void and are usually ignored in routine design. For this the following explanation may be given:

- The overall reduction of quality in design due to collapse and disappearance of big design bureaux and emergence of smaller firms who in many cases do not employ experienced designers and lack novelty instruments prerequisite for provision of quality design.
- Design software produced by local research laboratories and universities is in most cases targeted at an extremely limited range of tasks and is difficult to modify. The same holds for the western software products distributed locally mostly as pirated copies.
- An obvious hindrance to the appropriate distribution of numerical assessment methods in design is the fact that the initial premises, assumptions and the options of practical implementation of a model are totally unintelligible in the existing software products. Practically, reliance on numerical software amongst the specialists in Russia and elsewhere is founded mainly on the reputation of product developers or referees, including the ones authorised to issue the appropriate certificates. This in no way precludes production of deficient results, as the software part of a product is unintelligible to a designer. It is only quite natural that in the described circumstances people lean towards simplistic, foolproof and verifiable calculation types preferring those to modern but not quite so transparent software products.
- Software distributed as intruder restricted non-modifiable systems is extremely inert in terms of utilising state-of-the-art research products.

Finally, one more hindrance on the way of numerical calculation methods development is the troublesome nature of 'digital' realisation of the new models. Researchers know only too well how time and labour consuming it may be trying to develop their own specific software which, naturally, often appears far from being perfect on account of the authors being mere amateurs.

The problems outlined above may be appropriately dealt with by a software product designed to set forth a unified standard for finite element models. The above mentioned 'FEM models' software presents itself to be such a product.

The programme comprises the following components:

At the core of the programme there is a *'solution finder'* responsible for the procedure of forming the solution matrix of the finite element system by means of compiling the matrices of individual finite elements followed by solution of the appropriate linear algebraic equations. The peculiarity of the 'solution finder' is its capability of solving physically and geometrically non-linear tasks by means of progressive approximations with the ability to modify the finite element grid. The tasks can be interpreted in plane, axisymmetric or spatial settings with the account of time variation factor if necessary. As the 'solution finder' was developed, a detailed analysis of various algorithms of linear algebra tasks solutions was carried out and the most effective methods in line with the current state of computing were selected.

Another major component of the programme is a novelty *'graphics editor'*, being a system capable of creating spatial finite element schemes variable in time. Thus the user is enabled to work in virtual four-dimensional space-time. The 'graphics editor' is designed to simplify the procedure of the finite element schemes creation to the largest possible degree and to reduce it to the visually manageable drawing procedure in three-dimensional time. It also enables the user to analyse the calculation results in simple and convenient format (as isolines, patterns, charts, deformed schemes, etc). The device has been developed in light of the most recent achievements in 3-D graphics currently employed mostly in computer games.

The third major component is a 'developer medium' for the finite element models which allows the user to create, test and analyse various models of calculation. The user is enabled to create finite element models at almost no previous expertise in programming required. The model is described almost entirely in the language of maths.

The fourth component is a 'bank of models' which is basically a storage facility for the individual finite element models. During solution of practical tasks the adequate model is selected out of this 'bank'.

The binding unit of the programme that holds all listed components together is a 'universal finite element structure'. It gives the opportunity to describe practically any possible finite element model. The finite element described within the framework of this structure possesses unlimited number of freedom degrees in any point (movements, acceleration, water pressure, temperature, etc). Introduction of new unknown values into the points of an element at the user's discretion is possible. Forces or other loads may also be represented in the points of an element. Each element is described by a set of user defined parameters the number of which is specified by the author of the model.

When operating in the 'developer medium' the author fills in the structure of the universal finite element with the particular information about the model he or she is creating. The author thus imparts a range of 'skills and capabilities' to the element, like the ability to create the element's stiffness matrix, define the most convenient display view option, calculate internal loads by the movements of points defined based on the solution results, etc. The structure of the universal finite element thus filled in is converted into a real finite element, corresponding to the description of the model supplied by the author, following which it is automatically entered into the 'bank of models' thus becoming one of the programme's components.

'FEM models' is user friendly and may be employed either by researchers of medium models or by designers doing calculations based on the available model patterns.

Currently a range of models has been developed describing joint subsoil-structure behaviour including the following:

- linear and non-linear elastic models (isotropic, orthotropic and anisotropic media), incompressible media models;
- elastoplastic models (ideal elastoplasticity, pyramidal models);
- rheological models;
- geometrically non-linear continuum models;
- pressure and gravity seepage;
- stationary and transitional thermal conductivity task;
- thermo-visco-elasto-plastic tasks;
- structurally unstable media models;
- dynamic continuum tasks.

The described 'FEM models' programme incorporates a new approach towards finite element models creation. Its basic features follow:

- intelligibility, i.e. free access to all details of a given model realisation complemented by mathematical clarity of the actual model description for the author, user or anyone else;
- openness, i.e. the possibility of adding new models to the programme;
- easy to understand nature of the designed models in terms of their application for practical calculations;
- no inertness towards practical application of the newest scientific findings.

Below we shall consider one of the practical applications of calculation-based analytical research using the example of a retrospective assessment of a geotechnical situation.

4.2 *Example of numerical modelling*

The building in question has the following characteristics: 4 levels, skeleton type, 3-flights, rectangular, basement floor, the frame of reinforced concrete, exterior walls of clay-dite concrete panels, intermediate floors of reinforced concrete of hollow slabs, two staircases with lift pits at gable ends, staircase bearing walls of bricks. The foundation constructed as a solid 500-mm slab with solid 500-mm concrete ribs along the slab perimeter and solid 1200-mm concrete ribs at longitudinal column sections. Staircase foundation constructed as solid 500-mm reinforced concrete slab with 400-mm foundation blocks positioned on the slab for the brick walls.

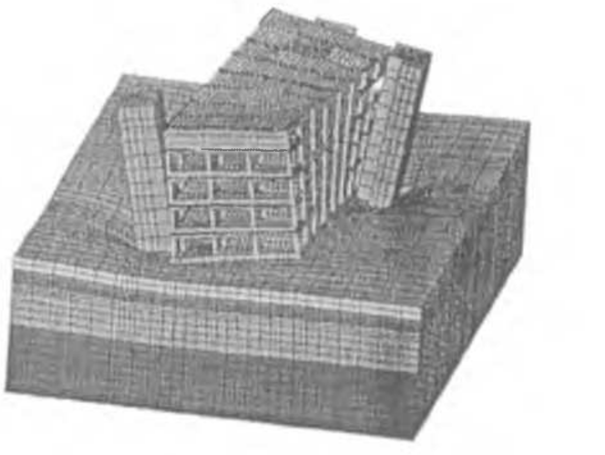


Figure 2. Deformations of the building as shown by the calculations (deformation scale enlarged by 50)

The footing levels at the main block and the staircases are at 3.9 m and 3.2 m respectively. There is a 65-cm drainage layer of coarse sand underneath the building. The staircases are separated from the body of the building by a movement joint.

In 1995 one of the staircases with the protruding brickwork of the building body displayed a tilt identifiable by a 130-mm gap in the floor tiling on level 4. The gap was concreted following 1995 condition survey. In 2000 a new 80-mm gap appeared. Based on the surveying level results the average tilt on the outside staircase walls amounted to 25.75 and 11.9 cm. The outside corner settlement grew by as much as 8 mm over the past 5 years at no corresponding movement in the juncture point between the staircase and the building body, which means the tilt of the staircase has increased. The influence from the staircase has affected the entire building and is causing it to twist.

A series of calculations was carried out to identify the causes for deformation and to select the strengthening option. To identify the nature of the deformation correctly the following had to be taken into account:

- spatial action of subsoil in light of its physically non-linear nature;
- foundation structures behaviour (body of the building and staircase slabs);
- superstructure behaviour (reinforced concrete frame and brickwork on the staircases).

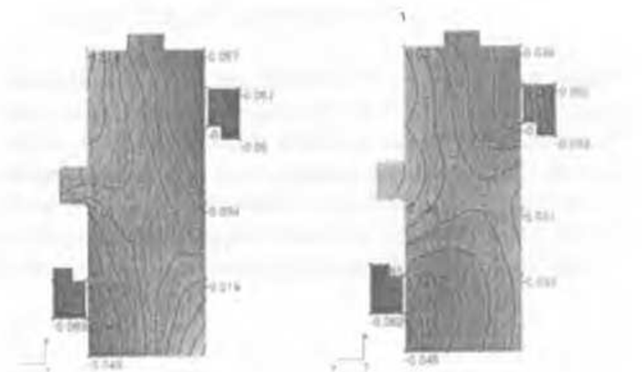
Mises-Schleicher-Botkin elastoplastic limited surface model was employed to represent the subsoil with the plastic potential surface taken as parallel to the hydrostatic axis. The superstructure was represented by the standard core-type finite element with 6 freedom degrees per point (for the frame) and by plain shell-type elements combining the plain stressed condition in plain of the element and the torsion of plain (for the foundation slabs, stiffness diaphragms, intermediate floors and staircase walls). Results below.

-The most considerable settlement is on the staircases. The nature and the absolute values of settlement correspond almost entirely when calculated and surveyed, suggesting that the selected calculation scheme and the physio-mechanical ground characteristics assumed in calculation were appropriate *(Fig. 2, 3)*. The settlement increase in the areas adjacent to staircases is caused by the influence of the latter. In general, this influence results in twisting of the building, however, the settlement differential (except for the staircases) is still within the norms.

- As demonstrated by the calculations, in case the movement joint between the staircases and the building body and also the blinding for the foundation slabs had been constructed correctly the tilt on the staircases would not have exceeded the permissible values. Besides, it would have been directed towards the building, which, according to the survey is not the case.

- The observed tilt of the staircases directed away from the building may only occur in case of complete or partial 'dangling' of the staircase structures on the body slab. In reality the condition survey identified lack of alignment in the movement joint layouts in the foundation and the superstructure which resulted in the observed uneven settlement. Calculations show that if such 'dangling' is taken into account the observed deformations will fully correspond to the calculated ones *(Fig. 2)*.

- Calculations suggest there is a limiting state area in the staircases subsoil which may be significant of continuously ongoing settlement. This corresponds to the survey results according to which the settlement on monitoring points on the building body gradually dies out but the points on the stairs keep settling (on the outside wall).



a b

Figure 3. Settlement isolines: a) by calculations; b) by survey results

Simulation of the staircases underpinning by means of bored piles proved that it would be possible to avoid future development of the uneven settlement should such strengthening options be resorted to. If the underpinning had been conducted at the initial stage of the deformations development the observed tilt of the staircases would not have occurred. At the moment such underpinning may help reduce the danger of the limited state areas development in the subsoil of the staircases curtailing the future development of persistent deformations.

The developed software thus proves to be a reliable tool for modelling complex geotechnical situations, identifying the causes of negative effects and determining the ways to cope with them most effectively.

4.3 *References*

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