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Overall regularities of soil-structure interaction

Les conformités de l'interaction d'un bâtiment et son sou-sol

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ABSTRACT
Subsoil–superstructure interaction is conducive to changes in stress-strain condition of the bearing elements of a building different to stress-strain values predicted by means of traditional calculations. The paper contains an outline of major effects brought to light by means of numerical modelling of soil-structure interaction.

RÉSUMÉ
L'interaction d'un b•timent et son sou-sol conditionne le changement d'etat stressant-déformant dans les structures gros en comparaison avec le pronostic fondé â calculs séparés traditionnels. Dans l'article il y a les effets fondamentals déterminés par modèle numérique de l'interaction des bâtiments et lear sou-sol.

1 INTRODUCTION

Nowadays in calculation practice one can observe a certain 'division of labour' between subsoil and foundation specialists on the one hand, and superstructure engineers on the other. Moreover, the latter often consider a building as constructed on an inflexible subsoil ('solid rock-subsoil'), whereas the former tend to over-approximate superstructure stiffness, taking it to be either absolutely elastic or absolutely rigid. It is quite clear, however, that such 'tops or butts' division of a building is rather relative and that in reality the subsoil and the superstructure will always exist as a system. In order to offer a more precise analysis of how this system will function, combined calculations are indispensable, because then it becomes possible to take into proper account both the specific superstructure behaviour and the complex non-linear action of the subsoil.

Until very recently such joined-up calculations have been practically unrealizable owing to enormous scope of mathematical material to be processed in order to solve these problems (one must go through systems of linear equations with about a million of freedom degrees). Even with the current state of computation techniques such solutions pose almost insuperable complexity. Also, the majority of computational software now in existence are predominantly directed either at superstructure (in which case subsoil models are wanting) or at geotechnical solutions (in which case there would be an inconvenience if one wanted to calculate superstructure).

In this respect, to facilitate joined-up solutions using the finite elements method we developed our *FEM Models* software [Ulitsky et al, 2003]. The software was designed to unify soil-structure calculations in one system which would have been valid both for foundation and superstructure design. The software features a previously unused approach to computation of linear algebraic equations which will deliver a confident performance of challenging soil-structure calculations with detailed division of analytical models on common semi-sophisticated personal computers over an acceptable amount of time.

The software comprises various models with which to analyse subsoil action (elastic, elasto-plastic, and reological models; stationary and non-stationary thermal conductivity models including those with account of phased transitions to calculate frost penetration in subsoil; models to describe frost heave effects; models to analyse non-linear soil action when exposed to dynamic impact, etc). At the same time the software features an affluent array of instruments responsible for superstructure modelling and capable of performing effortless analyses of structural behaviour when affected by subsoil action.

Below we shall consider the main effects brought to light through joined-up soil-structure calculations for static loading. As these effects invariably manifest through modelling of subsoil by means of a vast diversity of models, both comparatively simple elasto-plastic and more complex reological, etc, we shall dwell here on the overall regularities, rather than describe the subtleties of various possible solutions.

2 INTERACTION OF A BUILDING AND NATURAL SUBSOIL

When calculating foundations on natural subsoil with no account of superstructure rigidity one normally arrives at considerable settlement differential. In most cases owing to spatial action of subsoil there is usually a flexural deformation with an increase of absolute settlement of the building towards the centre of the loaded area (Fig. 1).

Evidently, such situation is seriously unfeasible because the walls of a multi-storey building possess significant rigidity which will preclude any considerable settlement differential. Indeed, as becomes evident from the calculations, whereby superstructure rigidity is taken into account, the building's action approaches that of a rigid box (Fig. 2). It would seem that under what looks like practically symmerical settlement superstructure calculation for a rigid subsoil should hold true. However, this appears far from being the case when one approaches the matter more closely.

The transverse walls taking on the flexure of the superstructure develop concentrated loads in the three lower floors, whereat the vertical loads three times exceed those arrived at through calculations of a rigid subsoil. Such effect manifests both through calculation of the simplest possible elastic model of subsoil and through taking into account non-linear action of the latter. Simple explanation of this effect may lie in irregular distribution of stress underneath the footing of an absolutely stiff box in solving an elastic theory problem. When calculating through non-linear models, certain redistribution of contact stress is observed during formation of plastic strain fields underneath the edges of the loaded area. However, no dramatic change in the character of contact stress epures is whereby effected, as may be shown by a host of calculations for buildings constructed on slab foundation in various ground conditions. In majority of cases plastic deformation areas underneath slab foundations are of limited development, on which account concentration of stress underneath the edges of a building gets changed only very insignificantly compared to the elastic solution. The most considerable consequences of non-linear soil action is that values of bending moments around foundation slab edges are whereby affected. In the central part of the building span moments in these areas may increase whereby moments in support also tend to increase in the central part of the building in locations of the bearing walls embedment.

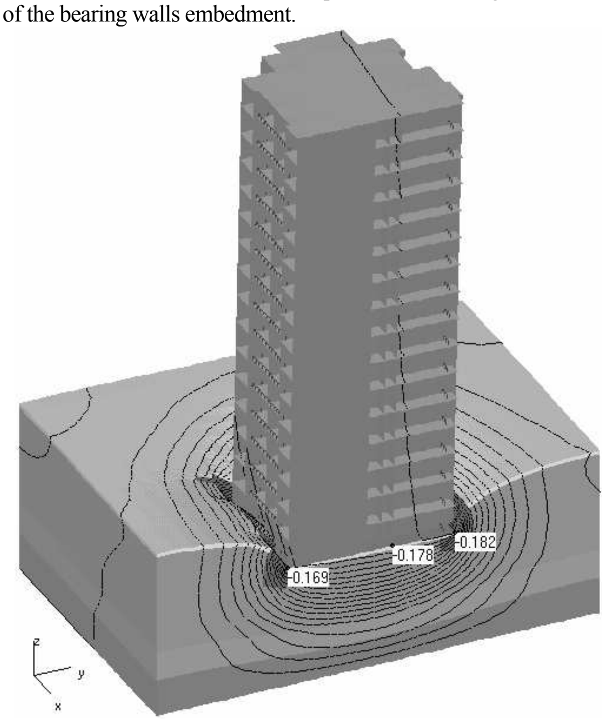

Figure 1. Deformation profile and isolines of settlement (m) of foundation and surrounding soil (cross-section). Shaded areas designate the zones of limiting state development in soil

Bearing in mind lengthy character of subsoil strain processes, as a rule considerably exceeding the period of time over which the building is constructed, it would be expedient to consider time dependent loads redistribution in the structures through solution of either an appropriate rheological problem or of a series of problems modelling subsoil behaviour at different times. In the simplest possible case an elastic problem with subsoil deformation moduli approaching dynamic characteristics can be applied to model incipient loads distribution, whereas to model finite stressed-strained condition of subsoil and superstructure it would be reasonable to use an elasto-plastic problem. Solution of two such problems will allow to assess the limits, wherein values of loads in the superstructure vary throughout deformation of the building. That solicits an implication that both the foundation and superstructure should be designed in such a way that no loads in excess of the permissible may be allowed therein at any certain moment of time.

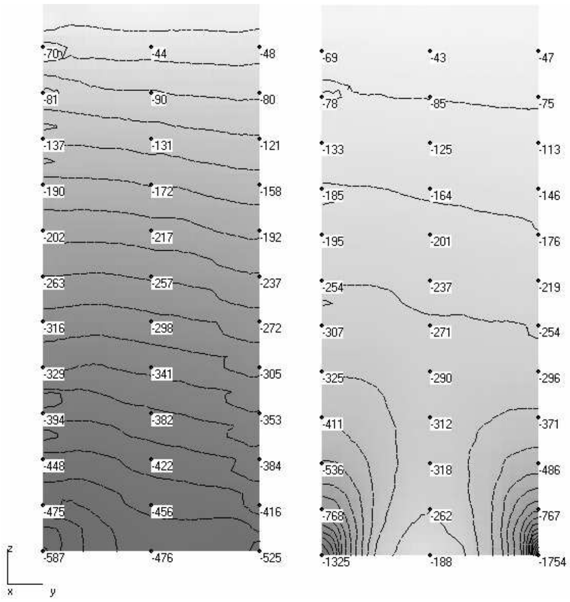

Figure 2. Isolines of vertical normal forces in the transverse wall: a - irrespective of soil-foundation deformability; b – according to soil-structure interaction calculations (kN/linear m)

3 INTERACTION OF A SUPERSTRUCTURE AND A PILED FOUNDATION

When considering interaction of a superstructure and a piled foundation loads redistribution effect is also manifested being conditioned by reduction of settlement differentials owing to the stiffness of the building. First and foremost, loads redistribution affects loads on piles creating certain unevenness.

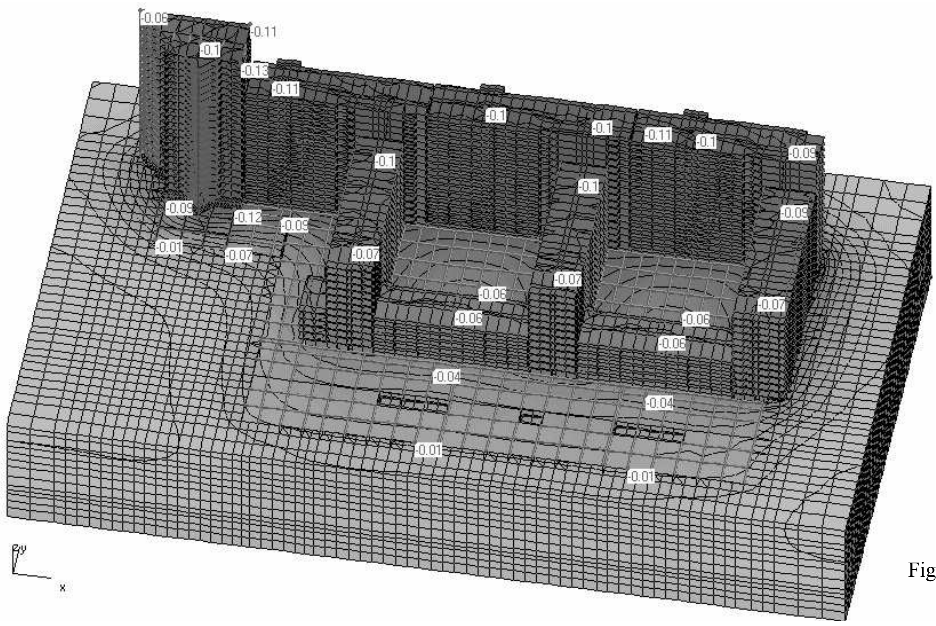

Figure 3. Isolines of vertical displacements (m)

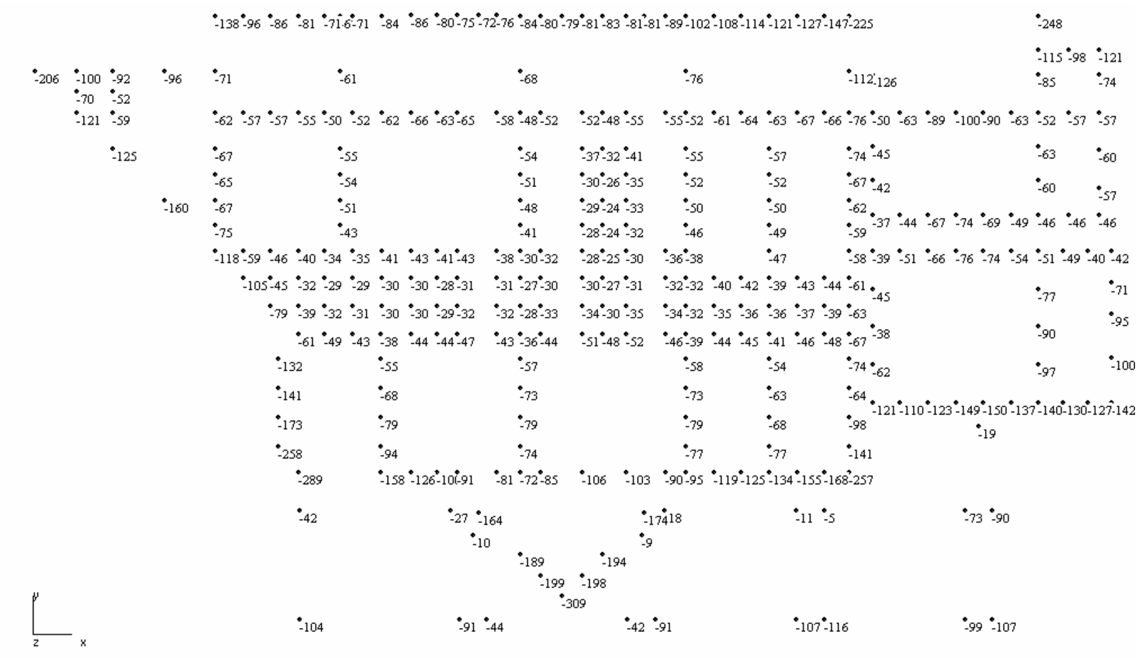

Figure 4. Loads on piles (tonne/force) under a building section

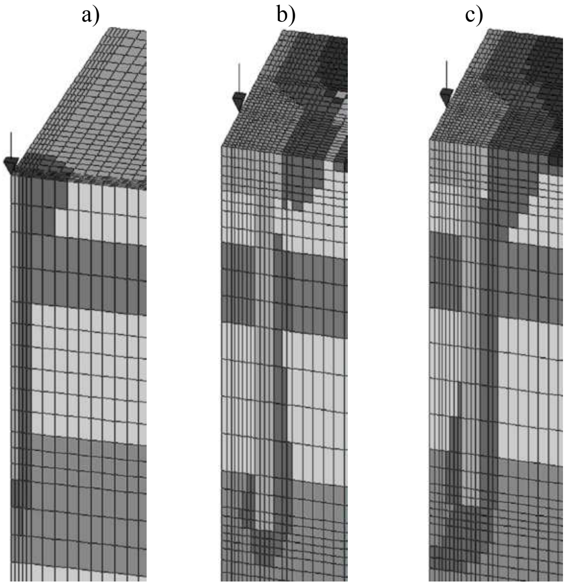

Figure 5. Zones of limit state development in soil (shaded): a – for a single pile test model; b, c – for a pile-cap interaction model. The load on pile is 50 t (a); 37.5 t (b) and 50 t (c)

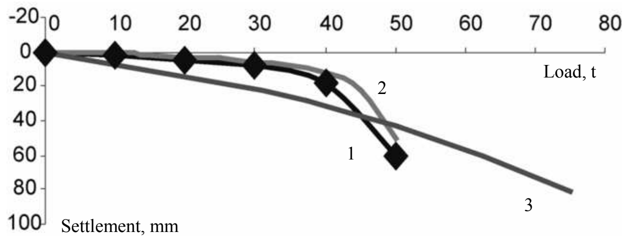

Figure 6. Load–settlement curve: 1 – pile displacement as per classical single static test; 2 – pile displacement as per calculation for a single static pile test model; 3 – pilecap settlement as per calculations

Fig. 3 contains isolines of settlement registered on a group of buildings constructed on piled foundations. It is to be noted that the absolute settlement values on the piled foundation is rather significant (nearly 12 cm) which is a feature of complex local ground conditions of St. Petersburg.

Loads in piles as shown in Fig. 4 considerably differ from a conventional calculation of a building on so called ‘elastic supports’ or from a calculation through ‘loaded areas’.

The load is transferred from the central to peripheral piles. Such effect of uneven load distribution in piles under a rigid structure is considerably well known [Katzenbach et al, 2003] and is related to the fact that the soil between the piles is engaged in action resulting from which it is only the periphery piles that work as skin-friction. Combined calculation allows more precise value definition of the loads differential depending on the type of the structure. In skeleton systems, where spatial rigidity is considerably low, loads redistribution value appears to be at its minimum. In buildings with rigid bearing walls the effect of uneven loads distribution in the piles is the more apparent, the longer the piles and the shorter the distance between the piles. As becomes evident from our calculations, application of various non-linear soil action models entails no significant changes in the character of loads distribution in the piles.

In a number of cases based on the calculation-proved data the loads in peripheral piles exceed the bearing of a single pile obtained through a standard static load test. Here a logical question naturally solicits itself as to whether it is feasible that such loads may appear in reality. Pile tests under existing rigid structures convincingly lead one to believe that the presence of a rigid structure and the reciprocal effects piles render on one another significantly alter pile behaviour, leading to an increase of its bearing. In a number of cases a bearing increase 1.5-2 times exceeding the bearing values of single piles obtained through a standard static load test has been revealed (Fig. 5).

We shall study such bearing increase of piles underneath a rigid superstructure using pile action in a rigid pilecap. As one can see in Figure 6 the limiting state areas with allowances made for reciprocal pile action in a pilecap develop in accordance with utterly different patterns to those present in testing of a solitary pile. There is a 'shearing' not of a single pile but of an entire group of piles together with the soil wherein they are embedded. As a result the 'load-settlement' curve for a pile within a pilecap (or other rigid structure) differs considerably from the same curve for a solitary pile (Fig. 6). Thus a test result on a solitary pile can be understood as the lower limit of pile bearing. Within the boundaries of a pile field the bearing may appear to be higher, however, to render a more precise assessment of such reserve, further research is required.

On the other hand the considered effect may also have an adverse effect on the function of the structure. Growth of loads in the piles leads to a corresponding growth of loads in pilecaps and superstructure, which may not have been designed to take on such a load and in the event undergo dilapidation. Thus, the uneven loads distribution effect amongst the piles should especially be considered in superstructure design, pilecap design, as well as in calculation of pile strength in relation to material. There one should also take into account the changes in loads pattern during deformation as in the case of a foundation on a natural subsoil.

4 SOIL-STRUCTURE INTERACTION UNDER DYNAMIC LOADS

For areas with low-key seismic activity the principal source of dynamic loads is the man-made impact generated during the works below the ground level, as well as other extraneous factors. Very often it presents a significant difficulty when in such cases one tries to fully rule out any possible dynamic impact on the existing buildings, hence the paramount importance of vibration values assessment in the subsoil and the superstructure. One must ensure the permissible vibration level in the superstructure together with the permissible sanitary vibration level, as certainly as one must provide for no settlement of the adjacent structures which may be occasioned by vibration-initiated creep of the subsoil, this sad eventuality being a prominent feature of St. Petersburg. *FEM models* software contains specific models realising solutions of spatial problems featuring dynamics of solid media with account for non-linear soil behaviour to perform soil-structure calculations for conditions of extraneously generated technical influence. Such models permit, for example, to represent the entire pile driving sequence complete with analysis of displacement wave fields in any location of the subsoil.

The influence of the seismic wave onto the superstructure depends significantly on the ratio of Rayleigh wavelength to building dimensions. Having relatively short waves, commensurate with building dimensions the pattern of vibration propagation differs dramatically from that of waves propagation in unlimited ground space: one observes a considerable waves reflection conditioning the overall character of the influence rendered onto the building. Superstructure develops serious transverse oscillations (directed out of plane). The walls undergo vertical compression-extension strains and horizontal shear-bending and torsion-bending strains. The part of the building closest to the dynamic source develops the most extensive vibration amplitude whose peak is located at the level of the top floor.

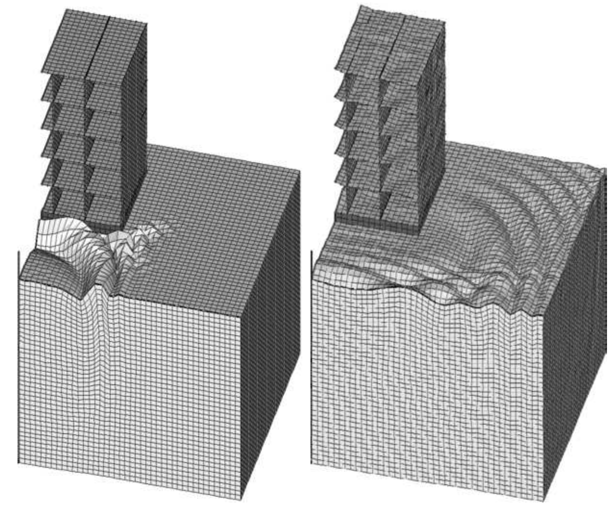

Fig. 7. Deformation profile. Waves propagation with account of interaction with superstructure at different time intervals

5 CONCLUSIONS

Our implementation of soil-structure interaction calculations under both static and dynamic loads has revealed the following principal regularities:

- Spatial rigidity of superstructure conditions reduction of settlement differential compared with the traditional elastic load calculations;
- Resistance to settlement differential is rendered by the lower part of the building, commensurate in height with its width; here a considerable (times and times) growth of loads, predominantly on the periphery, precluding irregular deformations development, occurs;
- The same effect inculcates the periphery areas of the pile field with utmost loads correspondingly relieving its central area; the increase of forces in edge piles has to be taken into account in designing pile grillage and structural elements of buildings
- In soil-structure interaction analyses it is necessary to account for redistribution of forces in time caused by settlement development; foundations and superstructure must be designed to avoid inadmissible forces during the building life
- When calculating dynamic loads rendered unto a building one should necessarily make allowances in respect of soil-structure interaction as this dramatically alters the overall pattern of vibration propagation.

Consideration of the studied particulars of soil-structure interaction quite often tends to become a predominant feature while selecting the principal building layout, foundation type and the method of the earthworks. Implementation of '*FEM models*' allows prediction of how the structures will act as early as the design stage, as well as to furnish multifaceted analysis of the structures' behaviour. Indeed, for the first time in history of calculation practice this instrument offers the opportunity to solve complex soil-structure interaction problems in spatial setting in terms of both static and dynamic loads, ensuring reliability of design solutions.

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