Features of base substantial differential settlements influence on structural system seismic stability

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Summary. The problem of possible combination of soil base substantial differential settlements and seismic action is characterized. This theme is extremely urgent subject to significant negative influence of soil base substantial differential settlements evolution on the construction system seismic stability. The article's aim is to consider features of such influence. The considered spectrum of the influence aspects includes: initiation of a complex stress-strain state, which loads additionally structural system when seismic loads are emerging; reduction of the structural system energy capacity to take and absorb the seismic vibration energy; abatement and rupture of seismic stability elements in the construction system; substantial change of a dynamic analytical model. The version of soil base substantial differential settlements occurrence before earthquake is selected for being studied as the most probable and destructive. Design procedure for construction systems under combination of soil base substantial differential settlements influence and seismic action on the basis of capacity spectrum method proposed by author is shortly introduced.

Key words: differential base settlements, seismic action, combination, construction system, capacity spectrum method.

INTRODUCTION

Large areas of Earth's surface are characterized by significant seismic hazard that is basically associated with a tectonic activity. Complex geotechnical natural and anthropogenic conditions which result in substantial differential settlements of base (SDSB) are widely spread too. They include slumping soils, undermined territories, karst and other suffosion kinds, creeps, new building influence, etc. Combination of such complex influences is natural and common. Thus, the protection of constructions affected by such combination is relevant.

Both earthquake and substantial differential settlements of base create significant load influence on the construction system and respective stress-strain state (SSS) with a high risk of the constructions or all system collapse. Taking into account its extreme hazard, it is logical to consider a possibility of such influences combination.

An increased complexity of research and consideration of SDSB and seismic combination results, as a rule, either in all-out removal of SDSB causes (typical of West Europe or North America) or in avoidance of problem consideration by a standardized negation of such combination possibility (typical of the post-Soviet countries).

Individual attempts of studying seismic and different SDSB kinds combination occur on the exSoviet Union territory, for example, papers [1 – 5 et al.]. Series of studies [5 – 9 et al.], which had been performed by Ukrainian Zonal Scientific and Research Design Institute of Civil Engineering (KyivZNIIEP) from 1982 to 2009 with interruptions, was the most thorough. This series was started for the purpose of developing protection methods for buildings in the slumping soils conditions of Odessa seismic region. Eventually, the range of problems had thoroughly been highlighted, the series of substantial differential base stiffness influence effects on the building seismic reaction had been revealed and the propositions for building analysis and resistance in the slumping soils conditions in seismic areas had been suggested. However, a great number of questions and problems, for example, consideration of other SDSB causes, taking into account a standardized prohibition of peculiar (abnormal) influences combination, applied engineering analysis methods development, more solid theoretical substantiation of the problem and its solutions, etc. remained unexamined. In this connection the author conducts a complex of studies to solve the above problems (some results are presented in the article).

MATERIALS AND METHODS

The article's aim is to consider SDSB features influence on the building structural system seismic stability. Methods of building literature analysis, inspection of existing buildings, modelling in bundled software, theoretical analysis, quantitative and qualitative data handling are applied in research whose results are introduced in the article.

RESULTS AND DISCUSSION

Sources analysis and the author's research have shown the following features and effects of SDSB influence on the building structural system seismic stability:

Initiation of complex SSS, which additionally loads the structural system under seismic effects.

Reduction of the structural system energy capacity and ability for taking and absorption of the seismic vibration energy.

SDSB high level involves abatement and rupture of seismic stability elements including the reduction of overloaded structure elements rigidity with efforts redistribution in the construction system.

Plastic deformations and ruptures accumulation in the construction system and probable residual changes in the soil base rigidity distribution may cause a substantial analytical model change.

Three variants of the seismic and SDSB combination are theoretically possible: SDSB occurrence before earthquake; earthquake during the active phase of SDSB; SDSB influence after structural system abatement by seismic loads. The first variant is the most probable and destructive, because earthquake probability during the active phase of SDSB (the largest duration – up to 1…2 years till complete attenuation), all the more its peak, is considerably less. And SDSB influence after earthquake applies "only" to risk of their loads on damaged buildings until their repair or dismantling completion.

Damage and rupture of building structures and elements responsible for seismic stability (main wall's sites, reinforced-concrete inclusions of walls, beams, columns, nodes, etc.) are the most apparent effects of SDSB influence. These effects initially drew attention to the problem of base deformations influence on construction system seismic stability, specifically, damages of residential and other buildings by slumping of soil base at the South-west of Odessa region in Ukraine or in countres of Central Asia, which are considired in research works [10 – 13 et al.]. Typical examples of damages in walls of masonry buildings are represented in Fig. 1.

The conclusion about causes of revealed building damages was made on the ground of analysis of cracks allocation and trajectories around sites of base slacking and availability of SDSB evolution causes. Cracks allocation in this case correlate good with generalized table of deformations variants in Fig. 2 [14].

Fig. 1. Damages of buildings bearing walls in seismic areas by substantial differential settlements of soil base

Reduction of rigidity in the construction system and, as a result, increase in natural vibrations periods and change in its mode become obvious consequences of plastic deformations and damages in bearing structures. Residual slacking of the soil base, for example, by a stable high level of subsoil water or sluggy formation may also lead to such effect. Numerical effect of the nature vibration period increase resulting from rigidity reduction of elements in the dynamic design model generally obey the well known law: $T = 2\pi\sqrt{M / K}$. That is the system natural vibration period increase is directly proportional to square root of the system overall rigidity reduction. Influence of construction system slacking goes down by soil base suppleness influence when rigidity of the base is taken into account (that is particularly important for the rigid buildings with low natural vibration period).

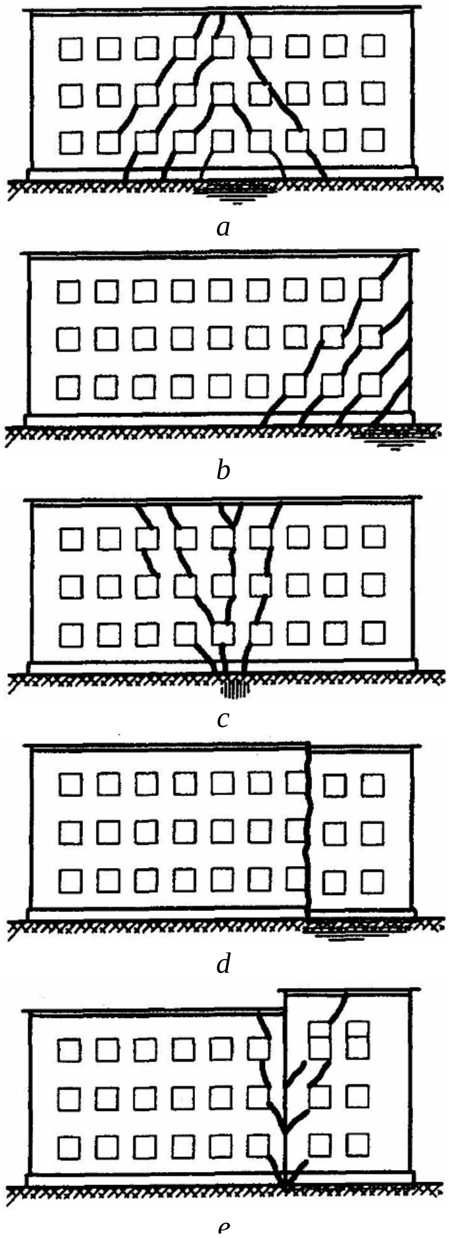

Fig. 2. Kinds of cracks allocation in masonry walls and causes of their occurrence: *a* – soil base slacking under the building midsection; *b* – soil base slacking under the shorter side of a building; *c* – hard spot in soil base under the building mid-section; *d* – stepped soil base slacking; *e* – different pressures under attached building blocks

According to the author's numerous experiments, SDSB occurrence causes reduction of general rigidity in masonry rigid building construction system up to 30% (down to 70% from starting values) due to their slacking and relevant increasing of summary periods of the natural vibration basic form up to 15% (subject to soil base rigidity). To that end nonlinear analysis was used by the principles of the capacity spectrum method (CSM) [15], specifically, generalized formulas for single degree of freedom (SDOF) systems (Fig. 3) were used for building slacked by SDSB influence.

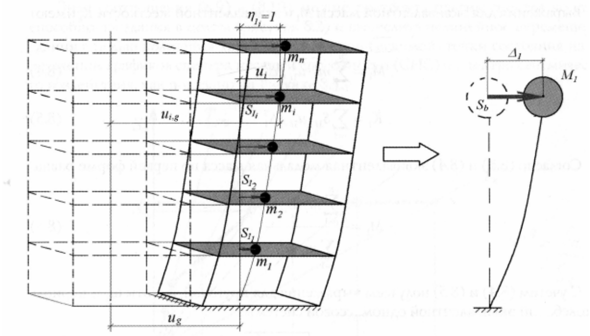

Fig. 3. Transformation of dynamic multiple degree of freedom (MDOF) system to single degree of freedom (SDOF) system

Slacking of certain masonry constructions as a result of overloads or damages by SDSB and seismic influence, in spite of a final collapse absence, reaches according to experimental data (for example, in [16]) increasing of period of the natural vibration basic form 4 times (2 times in average), and rigidity (which determines dynamic behavior and effect in general system) goes down to 10% of the initial values according to calculation data.

As regards a residual reduction of soil base rigidity after SDSB evolution completing (except sluggy formation), numerical studies indicate that a significant (more than by 10…15%) increase of periods of the natural vibration basic form occurs in low-rise rigid buildings during reduction of soil base parts rigidity down to 65% of the initial value. With an increased building flexibility and for the upper vibration forms the influence of such slacking is substantially lower or is practically absent. For detection of such regularities series of numerical experiments in software package LIRA-SAPR with models of building with up to 10 stories height (Fig. 4) were made. In the process resulting dynamic parameters were compared for the models with and without slacking of soil base.

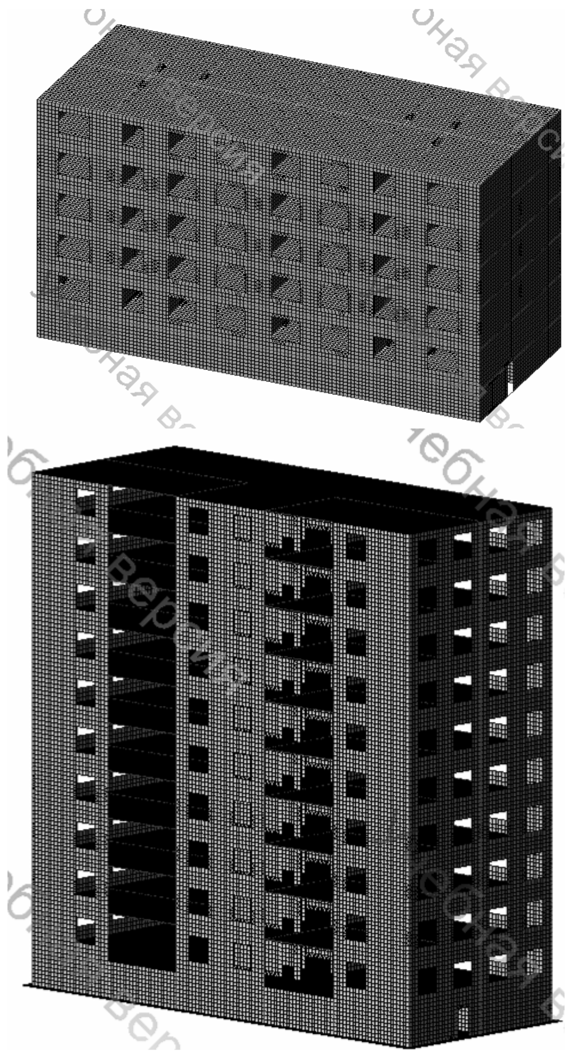

Fig. 4. Examples of building models for studies of influence of residual reduction of soil base rigidity after SDSB evolution completing

Determination of laws of changes in rigidity and periods of buildings natural vibration in general and of their individual structures depending on damages development enables to estimate a degree of damage and slacking of various parts of the "building-soil base" system on the bases of measured dynamic characteristics, as well as to locate areas of their development.

On the grounds of features of under load materials (except perfectly brittle) deformation diagrams it is commonly known, that rigidity reduction in constructions is sign of their active or occurred before (with partial damage of material structure) overload. It can be also non-mechanical damages by a chemical or biological aggression, freezing-defreezing cycles and other occurrences [17 – 19]. These occurrences affect on constructions, as a rule, in the form of cross-section loss, inner damages and material microstructure disruption. All of that are origin of construction rigidity reduction too. Thus in-situ measurements of dynamic characteristics of construction system and their elements are universal method of technical state assessment and have gotten certain development in practice of inspection and monitoring of buildings and structures [16, 20 – 23]. It is important in this case to have base values of dynamic characteristics based on initial measurements or analysis of building with out accounting of damages and defects.

Application of dynamic characteristics monitoring also can be utterly effective for estimate of reduction of seismic stability (resistance) of structural system damaged by both earthquakes [16, 20 – 23] and other influences, including SDSB. Series of calculations has to be done for quantitative estimation of extent of structural system seismic stability reduction by SDSB, for example, with application of CSM. As a result, generalized numerical laws between increase in natural vibration periods and seismic stability reduction of different kinds structural systems will be determined for estimation of extent of structural system seismic stability reduction by SDSB.

It appears that efforts and stresses by SDSB (residual) and seismic combine with each other and bring to a substantial increase in their level in comparison with separate effect of the influences. Overall load-bearing effect by such influence on partial sites of vertical bearing elements of construction systems can be described as sidesway in two directions: vertical and horizontal. Theoretical numerical experiments show that level of efforts and stresses in this case may rise up to 2 times (by commensurability of vertical and horizontal shear forces of sidesway).

For example, a significant efforts increase in some frame constructions elements by adverse variant of combination of shear sidesway forces directions occurs. Particularly, efforts increase for shear forces and bending moments in some elements amount to 1.5…2 times. The most expected variants of construction destructions depending on its features are: by eccentric compression of columns; bending or bending with tension of beam; by shear force in beam.

For flat wall constructions adverse variant of combination of shear sidesway forces directions involves the occurrence of:

- increase of shear stresses up to 2 times;
- increase of normal stresses in the central zone approximately to 2 times;
- additional boundary normal stresses by bending action in the vertical direction.

In this case the most expected variants of construction destructions depending on its features are: by normal tension stresses in the boundary or central zones for a material with low tension strength; by normal compression stresses in the boundary or central zones (as a rule, exceed modulo of normal tension stresses); by shear stresses in the central zone.

One of the seismic analysis features is allowance of significant plastic deformations and controlled construction damages. Positive effect by plastic deformations consists in absorption of seismic vibration energy by relevant destruction of material microstructure. According to Ukrainian, Russian and other post-USSR countries building norms such effect is allowed by reduction coefficient of admissible damages for seismic forces (as a rule, $k_1 \leq 1$ [24]). Physical interpretation of this coefficient can be presented on the base of Fig. 5.

Determination of the admissible damages coefficient k_1 and other similar factors which describe the ability (capacity) of seismic vibration energy absorption for construction system under SDSB influence is a separate problem. However, on the one part, there develop plastic deformations and construction material local damages, which reduce energy capacity of the system. On the other part, due to SDSB prestressing and local damages the evolution a yield point stress (force) P_y for horizontal shear forces perception decreases. This combination generates conditions for the lack of fundamental changes of the system ductility and coefficient k_1. For example, both values P_y and P_e in the formula $k_1 = P_y/P_e$ decrease. Indirectly, this effect is confirmed by lack of the coefficient k_1 variation in the norms for equivalent type construction systems by the same level of seismic influence, though specifications of specific constructive solutions for the same type may be numerous. Thus, standard set of the admissible damages coefficients k_1 and elastic coefficients (of yielding) μ can be used for seismic analysis of construction systems under SDSB influence.

Design procedure for construction systems under combination of SDSB influence and seismic action on the basis of CSM was proposed and then improved by author. It involves following stages:

- Generation of construction system non-linear model with accounting of soil base (its rigidity or massif of finite elements). Creep of materials isn't taken into account except case of its significant influence on change of construction system design model.
- Stepwise application of static loads according to norms for seismic analysis.
- Preliminary seismic calculation of construction system without SDSB influence. Main result – diagrams of CSM and seismic spectrum in $S_a – S_d$ (ADRS) coordinates.
- Non-linear analysis on the most likely variants of SDSB influence. It is performed by special stepwise loading (by displacements or equivalent forces) or by soil base rigidity changing.
- Determination of horizontal seismic forces allocation (vibration modes) is performed by spectral method. Analysis must be done for independent orthogonal horizontal axes of building, in the line of which rigidity and stability of construction system can be considerably different. In this case stabilized rigidity of soil base (base characteristic after SDSB evolution completing can be corrected) must be used except sites with loss of contact between soil and underside of foundation. These sites have to be determined subject to creep of construction system materials (directly or indirectly). Multiplied dynamic rigidity of soil base have to be taken into account by appropriate coefficients of rigidity or by generation of soil base finite elements massif.

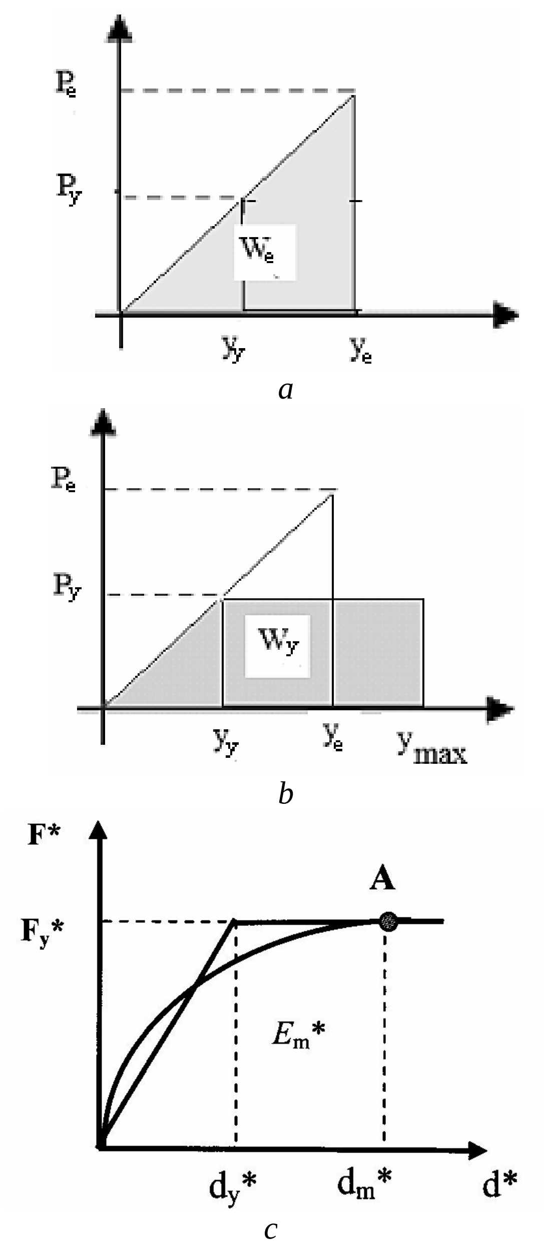

Fig. 5. Energy by: equivalent elastic (*a*) and elastic-yielding (*b*) behavior of system ($W_e=W_y$); CSM diagram construction (*c*). Indexes: *e* denote elastic, *y* denote yielding

- After determination of horizontal seismic forces allocation they are imposed in non-linear model after SDSB influence (SDSB postaction is allowed). Total value of seismic loads has to be assumed "with reserve" for obtaining of collapse of construction system. By stepwise application of seismic loads it is necessary to determine floor displacements with its following converting in the general equal spectral displacement S_d for SDOF with floor masses and seismic forces. Then appropriate spectral accelerations S_a is estimated. Overall result must be generated in the form of CSM diagram $S_a - S_d$.

- Plastic deformation's horizontal branch of CSM diagram $S_a - S_d$ (from limit of liquidity point a_T) can be made on the basis of experimental data. Also allowable by norms limits of elastic coefficients (of yielding) μ and limit constructive floor sidesways (without additional rotation by soil base rigidity) can be references for the horizontal branch of diagram. Before this it is important to convert CSM diagram to the bilinear form and to estimate limit of liquidity a_T.

- It is necessary to choose the most likely (to predictable building seismic stability) peak level of seismic influence spectrum according to area seismic hazard for searching of cross point of CSM and seismic influence spectrum diagrams in $S_a - S_d$ coordinates. Selected diagram of seismic influence spectrum can be corrected subject to calculable building features.

- Reduced diagram of seismic influence spectrum is made corresponding to μ. Final cross point of CSM and reduced seismic influence spectrum diagrams is generated.

- If necessary, vertical component of vibration is estimated by spectral method according to norms subject to changing of construction rigidity by SDSB influence and to capability of loss of contact between soil and underside of foundation (these sites have to be determined subject to creep of construction system materials). Simplified accounting of the vertical component by addition or subtraction of portion of vertical static loads (15% for 7 and 8 points of earthquake intensity, 30% for 9 points and no accounting for 6 points) can be used for rigid buildings by SSS analysis of their walls (or other similar braced systems). Level of seismic load vertical component is estimated by preliminary analysis of building under horizontal seismic loads. The vertical component in non-linear analysis is specified by separate loading, which is simplistically imposed before horizontal seismic or specifically stepwise in breaks of horizontal seismic. After such correction by additional loading analysis of horizontal seismic loads is carried out repeatedly and for refinements of preliminary results.

CONCLUSIONS

1. Despite a widespread disregard of the problem of possible combination of soil base substantial differential settlements and seismic action that is observed in regulations and practice, this theme is extremely urgent subject to significant negative influence of SDSB evolution on the construction system seismic stability.

2. The considered spectrum of such influence aspects includes: initiation of a complex stress-strain state, which loads additionally structural system when seismic loads are emerging; reduction of the structural system energy capacity to take and absorb the seismic vibration energy; abatement and rupture of seismic stability elements in the construction system; substantial change of a dynamic analytical model.

3. The version of SDSB occurrence before earthquake is selected for being studied as the most probable and destructive.

4. Design procedure for construction systems under combination of SDSB influence and seismic action on the basis of CSM proposed by author is shortly introduced.

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ОСОБЕННОСТИ ВОЗДЕЙСТВИЯ ЗНАЧИТЕЛЬНЫХ НЕРАВНОМЕРНЫХ ДЕФОРМАЦИЙ ОСНОВАНИЯ НА СЕЙСМОСТОЙКОСТЬ КОНСТРУКТИВНЫХ СИСТЕМ

Аннотация. Охарактеризована проблема возможного совмещения значительных неравномерных деформаций основания и сейсмических нагрузок. Данная тема является крайне актуальной по причине существенного негативного влияния, которое оказывает развитие значительных неравномерных деформаций на сейсмостойкость конструктивных систем. Целью статьи является рассмотрение особенностей такого влияния.

Рассмотренный спектр направлений воздействия значительных деформаций основания на сейсмостойкость включает: создание сложного напряженно-деформированного состояния, с дополнительным догружением конструктивной системы при сейсмическом воздействии; уменьшение энергетической емкости конструктивной системы для восприятия и поглощения энергии сейсмических колебаний; ослабление и разрушение элементов, отвечающих за разные аспекты сейсмостойкости конструктивной системы; возможность существенного изменения динамической расчетной схемы. Теоретически возможны 3 варианта совмещения воздействий неравномерных деформаций основания и сейсмики: возникновение деформаций до землетрясения, землетрясение на этапе активной фазы деформаций и действие деформаций после ослабления конструктивной системы при землетрясении. Как наиболее вероятный и опасный для рассмотрения в исследованиях выбран вариант возникновения деформаций основания до землетрясения. Коротко представлена предложенная автором методика расчета конструктивных систем на совместное действие значительных неравномерных деформаций и сейсмики на основе метода спектра несущей способности.

Ключевые слова: неравномерные деформации основания, сейсмика, совмещение, конструктивная система, спектр несущей способности.