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INFLUENCE OF BASE SUBSTANTIAL DIFFERENTIAL SETTLEMENTS ON STRUCTURAL SYSTEMS SEISMIC STABILITY LEVEL

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Abstract

Introduction: *Urgent question of base substantial differential settlements influence by different origin on building structural systems seismic stability is considered in the article. The aim of research is estimate of such influence degree.* ***Selection of analysis method:*** *It had been suggested to use of nonlinear static analysis by the spectrum capacity method for analysis and then this method was used.* ***Numerical estimate of base substantial differential settlements influence on structural system seismic stability:*** *Numerical experiment which shows degree of seismic stability reduction depending of base differential settlements level is introduced. The experiment was made on the ground of wall system model of complex masonry and also reinforced concrete constructions. Nonlinear analysis was done on the consecutive influence of base differential slumping deformations and horizontal seismic loads.* ***Consideration of the analysis results and conclusions:*** *Consequently it was revealed, that force influence of base substantial differential settlements is able to significant reduce seismic stability of construction systems (from 1 intensity degree down to practically completely loss of seismic stability). This fact determines necessity of accounting of base substantial differential settlements and seismic force influence combination when there is capability of occurrence both of them. In this case, it is necessary to take into account sequential influence of the loads and also recommended using of nonlinear analysis by the principles of the capacity spectrum method. It is also necessary to specify level of inelastic deformations and damages evolution by experimentally confirmed values.*

Keywords: base differential settlements capacity spectrum; construction system; inelastic deformations; seismic stability.

1. Introduction

Large areas of Earth's surface are characterized by significant seismic hazard by tectonic activity. Territories of many countries are located wholly in earthquake-prone areas. Complex geotechnical natural and anthropogenic conditions which result in substantial differential settlements of base (SDSB) are widely spread too. They include, for example, slumping soils, karst and other suffosion kinds, undermined territories, creeps, new building influence, etc. Combination of such complex influences is natural. Thus, the question of SDSB influence on building structural systems seismic stability is relevant.

SDSB may create significant load influence on the construction system making its complex stress-strain state (SSS) with local plastic deformations and ruptures accumulation. These processes expectedly create slacking of construction system seismic stability, what causes necessity of estimating of such influence.

High complexity of questions of SDSB and seismic combination often results in avoidance of problem consideration by a standardized negation of such combination possibility (typical of the post-Soviet countries) or in all-out removal of SDSB causes (typical of West Europe or North America).

Individual attempts of seismic and different SDSB kinds combination studying occurred on the exSoviet Union territory, for example, were considered in papers [1-5 et al.]. Series of studies [6-9 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, questions of applied engineering analysis methods development including numerical estimate of seismic stability reducing for deformed buildings remained unexamined. In this connection the author conducts a complex of studies to solve the above problems and some results are presented in the article.

The article's aim is estimate of SDSB force influence degree on construction systems seismic stability.

2. Selection of analysis method

Different ways of deformed design models account for building seismic analysis are proposed [8,10,11 et al.]. They include:

- specify of construction system repositioning in space and shape modification;
- change of construction system elements rigidity;
- modeling of soil base slaking and deformations in difference ways et al..

By analysis of their suitability it is necessary to take into account influence of method on summary stress-strain state (SSS) of construction system and also calculation laboriousness. The last one is extremely important for applied engineering analysis methods, which are characterized by undertime and probable necessity of reiteration.

Taking into account all factors, nonlinear static analysis by spectrum capacity method (SCM) is one of the most effective. Its main points in different variants are presented in [11-17 et al.]. Despite great number of the method conditionality in comparison with the direct dynamic analysis, SCM is easy-to-use and intuitive for construction systems seismic stability estimate. Eventually, a number of dynamic effects, which can't be taken into account in SCM, for example, the upper vibration forms influence, may be taken into account by additional coefficients using and seismic loads allocation correction.

Universality of approach of the equivalent seismic loads application to a construction system nonlinear model is additional SCM advantage. It allows to do nonlinear analysis of various force influences jointly with seismic loads with lower computational laboriousness versus nonlinear direct dynamic methods. Taking into account this it is suggested by author of nonlinear static analysis by SCM using for analysis of SDSB influence on construction systems seismic stability.

3. Numerical estimate of SDSB influence on structural system seismic stability

Analysis by bearing wall of complex masonry and reinforced concrete nonlinear models example was made for obvious studying of SDSB influence (SDSB prestressing) on structural system seismic stability and development of their main rules. Software package LIRA-SAPR 2012 was used.

The type project 67c of residential buildings [18], which are widely spread in Odessa region in Ukraine, was generally used for selection of models elements sizes and structural specifications. Plane models of building complex masonry axial walls were considered in variants: with apertures (WA model, Fig. 1, a); without apertures (WOA model, Fig. 1, b); with additional reinforcing of window openings by reinforced concrete closed rigid frames along the contours (WAR model, Fig. 1, c). To supplement, variant of cast-in-situ reinforced concrete walls with same apertures and size configuration in plane was considered (WAC model, look like model in Fig. 1, a).

Models dimensions in plain: 30.4x15.6 m (size of finite element 0.4 m), thickness of plain finite elements is 1.4 m (total thickness of three building axial walls).

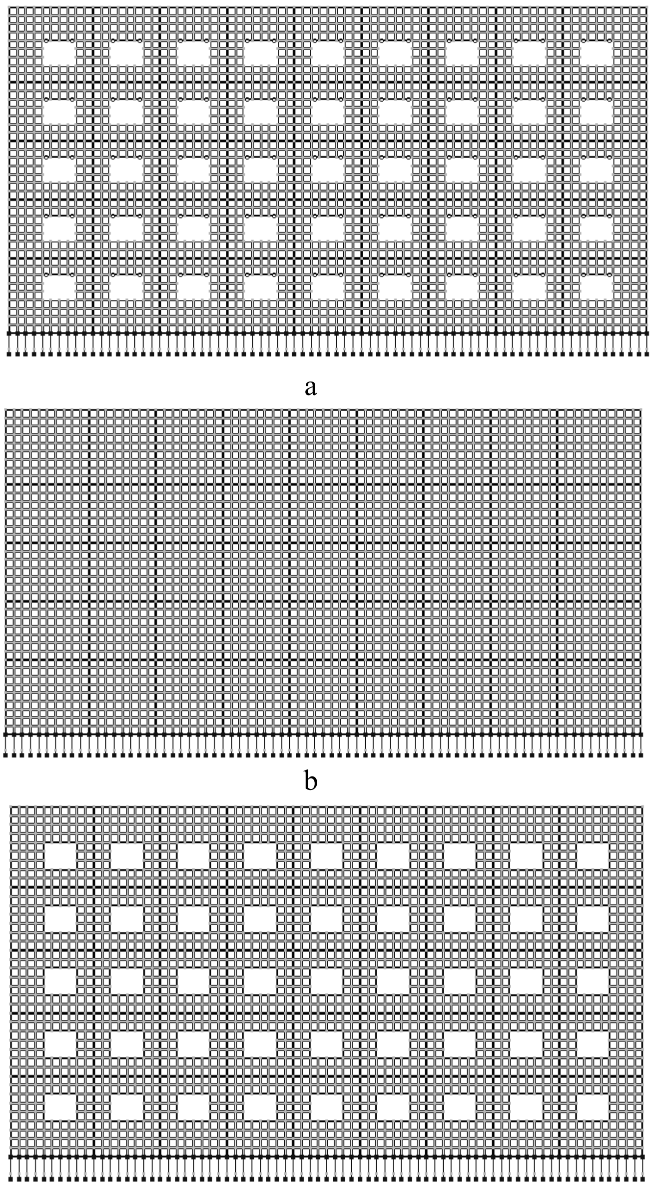
Reinforced concrete elements for WA and WOA models conform to design concepts of the type project 67c by materials and dimensions (cast-in-situ reinforced concrete vertical and floor horizontal elements, foundation tape with total width 4.4 m, precast lintels).

The main differences of model WAC: constructions are completely from cast-in-situ reinforced concrete C12/15 (B15); thickness of plain finite elements is 0.6 m (total thickness of three building axial walls bearing parts); reinforcement of wall – double mesh ø6 A240C (AI) with cell 100x100 mm for each 200 mm off thickness; additional reinforcement of A400C (AIII) was provided at the sections of reinforced concrete elements for WA model.

Standard for LIRA-SAPR exponential laws of material nonlinear straining with characteristic values of material properties were used for concrete and reinforcement.

Straining law of Onishhik [19] was used for masonry:

$$\varepsilon = \frac{1{,}1}{\alpha} \ln\left(1 - \frac{\sigma}{1{,}1 R_u}\right),$$



a

b

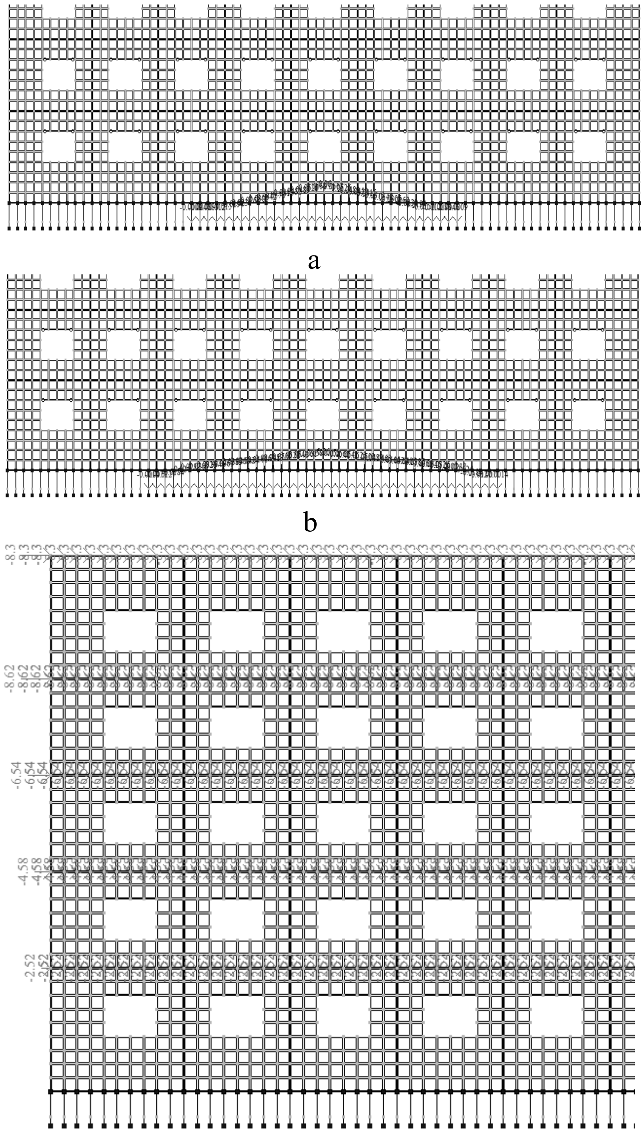
c

Fig. 1. General view of models for numerical experiment: a – of complex masonry with apertures (WA model); b – of complex masonry without apertures (WOA model); c – with additional reinforcing of window openings by reinforced concrete closed rigid frames along the contours (WAR model)

were $\alpha=a$ – the masonry elastic characteristic; σ – stresses in masonry; $R_u=f$ – the mean compressive or tensile strength for masonry.

Following loads were employed:

- characteristic values of proper weight of model structural elements (loading 1), that approximately corresponds to the using of coefficients 0.8…0.9 for design values of dead loads for seismic analysis (loads at the time of an earthquake) according to DBN [11];



a

b

c

Fig. 2. Some special loads imposed to the models: a – 1st stage of slumping crater evolution by length; b – 2nd stage of slumping crater evolution by length; c –seismic loads imposed to the floors levels

- characteristic values of other dead loads (loading 1), which contain the proper weight of floors, partition walls and floor slabs imposed to the floors levels;

- live static loads according to DBN [11,20] for residential buildings at the time of an earthquake (design values with coefficients 0.5), imposed to the floors levels (loading 2).

- base differential settlements by soil proper weight slumping (it can be several loadings subject to degree of slumping crater evolution, Fig. 2, a, b);

- horizontal seismic loads imposed to the floors levels determined by spectral method (Fig. 2, c).

All loadings were imposed step-by-step with parting up to 100 steps in the following sequence:

- dead loads (10 steps);
- life loads (10 steps);
- differential base settlements (up to 100 steps per stage of slumping crater evolution);
- horizontal seismic (100 steps).

Maximum soil proper weight slumping evolution – 300 mm, slumping crater evolution by length – turning-point (possible widening – in 4 m from 13 m up to 29 m by length every 60 mm of slumping, total – 5 possible stages). In this case average one-way rigidity of soil base 10000 kN/m^3 was taken into account with its increase to 1.43 times under the extreme points according to laws from [21]. Before seismic loading, rigidity of soil base was increased up to dynamic (to 5 times) by insertion of additional springs with 4 times stiffness at the remained junction points of foundation–soil base contact.

Models were step-by-step brought to collapse by nonlinear analysis of SDSB influence (to appearance of substatic system). In this cases relevant SSS was gotten (Fig. 3).

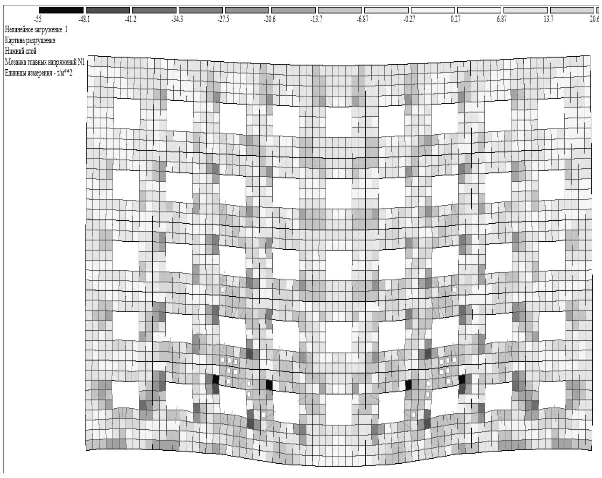


Fig. 3. Typical view of model stress stain state by destruction from SDSB (by example of WA model)

Received diagrams of construction system generalized straining (by analogy with capacity spectrum for seismic analysis) without taking into account of material creep is shown in Fig. 4. For their creation, conditional bounds of carrying side zones for wall-beam were allocated by comparing of initial pressure under foundation subgrade and values by slumping evolution:

$$V = \int_{x_{cz}}^{x_{mb}} \Delta P(x)\,dx ,$$

were x – coordinates by horizontal axis;

x_{cz} – the coordinate of inside bound of carrying side zone;

x_{mb} – the coordinate of model bound;

$\Delta P(x)$ – pressure gain at point x of the carrying side zone.

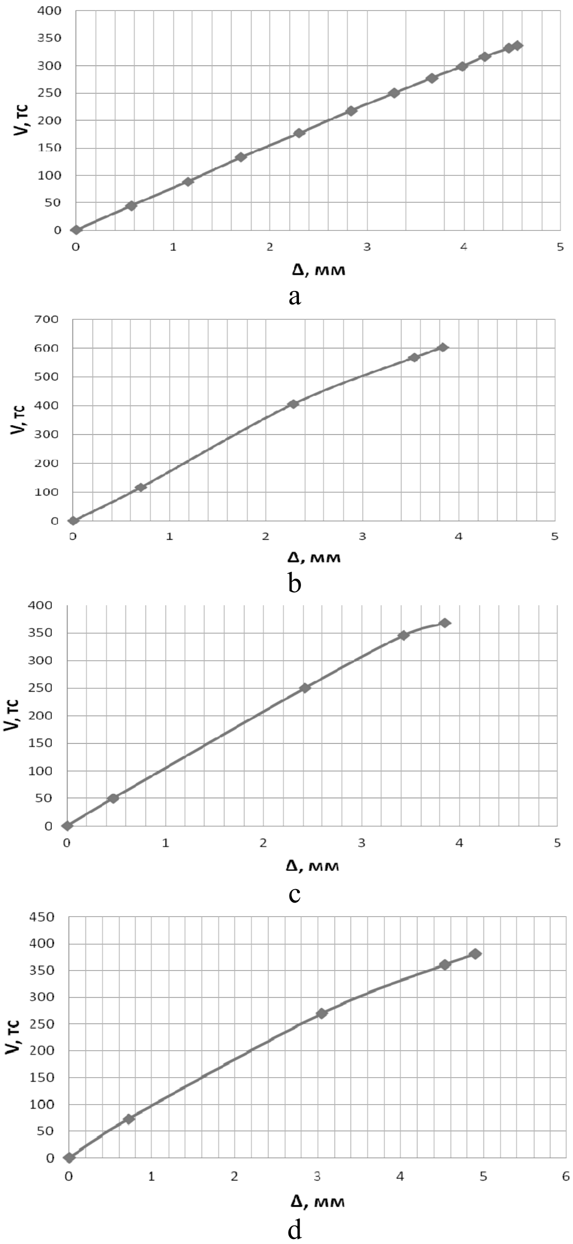


Fig. 4. Diagrams of construction system generalized straining by soil base slumping: a – for WA model; b – for WOA model; c – for WAR model; d – for WAC model. Notes: V – generalized shear forces (unit measure тс = 10 kN); Δ – vertical deformation of the wall-beam middle (unit measure мм = mm)

As a result of models analysis by soil base slumping, bearable (crushing) generalized shear forces were determined and are represented in the table 1. Also relevant maximal comparative settlements of construction system foundation level were estimated (table 1), in this case creep deformations of construction system were taken into account by using relevant enlarging coefficients for initial deformations [22,23]. Values of soil slumping force influence for subsequent analysis of seismic stability are also shown in the table 1.

Table 1. Overall results of models analysis by soil base slumping influence and its levels for seismic estimation

Model	V^{bd}_{max}, kN ($(\frac{\Delta s}{L})_u$)	V^{bd}_1 / V^{bd}_{max}	V^{bd}_2 / V^{bd}_{max}
WA	3363 (0,0021)	0,648	0,941
WAR	3686 (0,0017)	0,679	0,939
WOA	6020 (0,0012)	0,674	0,943
WAC	3818 (0,0023)	0,708	0,947

Note: results were gotten for characteristic values of material properties, for maximal comparative settlements of foundation level – with taking into account of construction system creep deformations.

In the sequel, horizontal seismic forces were imposed at the models in 3 variants of soil slumping level (according to the table 1): V^{bd}_1 (results WA-1, WAR-1, WOA-1, WAC-1), V^{bd}_2 (results WA-2, WAR-2, WOA-2, WAC-2) and without influence (results WA-0, WAR-0, WOA-0, WAC-0).

Typical view of deformed design model by destruction from combination of SDSB and seismic loads is represented in Fig. 5.

Examples of received superposed diagrams of seismic influence and capacity spectrum (for characteristic values of material properties) in the coordinates S_a-S_d are shown in Fig. 6 and 7. Sizes of capacity spectrum horizontal branches were specified by allowable plastic deformations, which had been estimated with using of the coefficient of admissible damages for according design types [11].

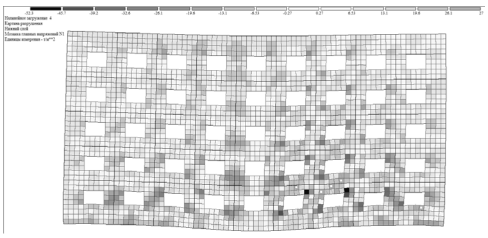
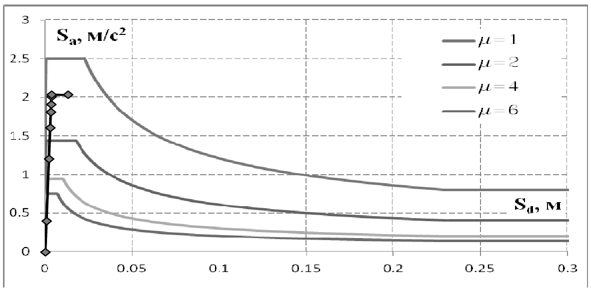


Fig. 5. Typical view of model stress stain state by destruction from combination of SDSB and seismic loads (by example of WA-2 model)



a

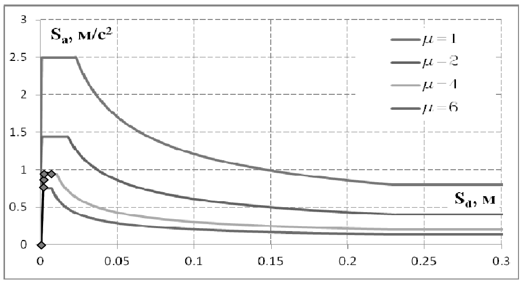


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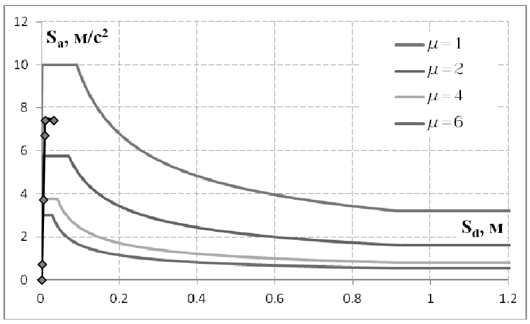
Fig. 6. Diagrams of capacity (with markers) and seismic influence spectrum (by [11]): a – for WA-0 model and seismic intensity degree 7 (II soil category); b – for WA-1 model and seismic intensity degree 7 (II soil category). Notes: S_a – spectrum acceleration; S_d – spectrum displacement; μ – elastic coefficients for single degree of freedom (SDOF) systems; units measure: м = m, м/с^2 = m/s^2



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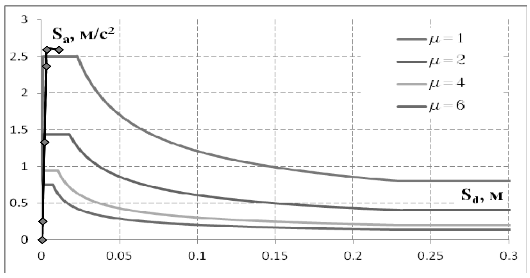

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Fig. 7. Diagrams of capacity (with markers) and seismic influence spectrum (by [11]): a – for WOA-0 model and seismic intensity degree 9 (II soil category); b – for WOA-1 model and seismic intensity degree 7 (II soil category). Notes: similar for Fig. 6

Generalized analysis results are represented in the table 2.

4. Consideration of the analysis results

Consideration of the results generalized represented in the tables 1 and 2 shows the following. SDSB evolution creates complex SSS of construction system with constructions elements overload and local plastic deformations and damages. As a result, combination of stresses from seismic and SDSB occurs by unfavourable direction of seismic forces. The situation with availability of already damaged elements creates significant reducing of construction system seismic resistance. For example, SDSB evolution up to level 65…70% from maximal (by generalized efforts) results in seismic stability reducing of 1…1.5 intensity degree. SDSB approaching to the maximal level practically completely deprives system of seismic stability (reducing of 2 and more of intensity degree).

Table 2. Results of the models analysis by sequential influence of soil base slumping and seismic loads and also residual seismic stability of the construction systems

Mod. sign	T_1, s	$S^k_{a,y}$, m/s^2	$S^d_{a,y}$, m/s^2	μ	γ_s	Seismic stability, intensity degree
WA-0	0.264	2.02	0.89	3.63	0.88	6.5
WA-1	0.275	0.94	0.47	-	1.00	<6.0
WA-2	0.298	0.34	0.17	-	1,00	<6.0
WAR-0	0.253	3.52	1.41	2.07	0.80	7,0
WAR-1	0.259	1.36	0.64	1.95	0.95	6.0
WAR-2	0.274	0.35	0.17	-	1.00	<6.0
WOA-0	0.210	7.40	2.59	2.36	0.70	8.0
WOA-1	0.213	2.58	1.14	3.08	0,88	6.5
WOA-2	0.221	1.08	0,51	3.50	0.95	6.0
WAC-0	0.245	5.21	2.92	1.96	0.70	8.0
WAC-1	0.271	2.99	2.10	1.26	0.88	6.5
WAC-2	0.294	0.56	0.44	-	1.00	<6.0

Notes: T_1 – period of SDOF system vibration; $S^k_{a,y}$ – spectrum yield point of SDOF system by characteristic values of material properties; $S^d_{a,y}$ – spectrum yield point of SDOF system by design values of material properties; μ –elastic coefficients for SDOF systems by relevant seismic influence level; γ_s –coefficient of materials strength reducing by alternating-sign seismic loads [11].

Adequacy of the received results is confirmed by their proximity to physical full-size experimental data, specifically:

- received maximal values of SDSB evolution with material creep accounting are proximity to the relevant experimental data from [24];
- periods of SDOF system vibration (without SDSB influence), that conform to 1st vibration form of relevant building, are also proximity to the experimental data [25 et al.];
- average level of seismic stability of models WA-0 and WOA-0 conforms to type project 67c.

Uncovered necessity of using of experimentally confirmed allowable levels of inelastic deformations and damages evolution (for example, from norms) for capacity spectrum diagrams construction (for analysis in software packages) is additional result.

5. Conclusions

Force influence of base substantial differential settlements is able to significant reduce seismic stability of construction systems (from 1 intensity degree down to practically completely loss of seismic stability). This fact determines necessity of SDSB and seismic force influence combination accounting when there is capability of occurrence both of them. In this case, it is necessary to take into account sequential influence of the loads and also recommended using of nonlinear analysis by the principles of the capacity spectrum method. It is also necessary to specify level of inelastic deformations and damages evolution by experimentally confirmed values. Next studies in this direction must concern of development and explanation of universal methods for analysis of construction systems jointly with soil base on the combination of SDSB and seismic influences and also according measure of building resistance.

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Вплив значних нерівномірних деформацій основи на рівень сейсмостійкості конструктивних систем

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Вступ: У статті розглянуте актуальне питання впливу значних нерівномірних деформацій основи різного походження на сейсмостійкість конструктивних систем будівель. Метою дослідження є чисельна оцінка ступеню такого впливу. **Вибір методу розрахунків:** Для розрахунків запропоновано використання нелінійного статичного розрахунку методом спектру несучої здатності, використаного у подальшому. **Чисельна оцінка впливу нерівномірних деформацій основи на сейсмостійкість:** Представлений чисельний експеримент, що демонструє ступінь зниження сейсмостійкості системи в залежності від рівня розвитку нерівномірних деформацій основи. Експеримент виконаний на основі моделей стінових систем кам'яної комплексної, а також залізобетонної монолітної конструкцій. Нелінійний розрахунок проводився на послідовний вплив нерівномірного просідання основи та горизонтальних сейсмічних навантажень. **Аналіз результатів розрахунків та висновки:** В результаті виявлено, що силовий вплив значних нерівномірних деформацій основи здатен суттєво знизити сейсмостійкість конструктивних систем (від одного бала до майже повної втрати при наближенні до граничних значень деформацій). Даний факт визначає необхідність врахування сумісного силового впливу значних нерівномірних деформацій основи та сейсміки, при можливості виникнення обох. При цьому слід враховувати послідовний вплив навантажень, а також рекомендується використання нелінійного статичного розрахунку за принципами методу спектру несучої здатності. При побудові графіків спектру несучої здатності на основі розрахунків в програмних комплексах слід уточнювати рівень розвитку непружних деформацій на основі експериментально підтверджених значень.

Ключові слова: конструктивна система; нерівномірні деформації основи; непружні деформації; сейсмостійкість; спектр несучої здатності.

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Влияние значительных неравномерных деформаций основания на уровень сейсмостойкости конструктивных систем

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Вступление: В статье рассмотрен актуальный вопрос влияния значительных неравномерных деформаций основания разного происхождения на сейсмостойкость конструктивных систем зданий. Целью исследования является числовая оценка степени такого влияния. **Выбор метода расчетов:** Для расчетов предложено применение нелинейного статического расчета методом спектра несущей способности, примененного в дальнейшем. **Численная оценка влияния неравномерных деформаций основания на сейсмостойкость:** Представлен численный эксперимент, демонстрирующий степень снижения сейсмостойкости системы в зависимости от уровня развития неравномерных деформаций основания. Эксперимент выполнен на основании моделей стеновых систем каменной комплексной, а так же железобетонной монолитной конструкций. Нелинейный расчет проводился на последовательное воздействие неравномерной просадки основания и горизонтальных сейсмических нагрузок. **Анализ результатов расчетов и выводы:** В результате выявлено, что силовое влияние значительных неравномерных деформаций основания способно существенно снизить сейсмостойкость конструктивных систем (от одного балла до почти полной потери при приближении к предельным значениям деформаций). Данный факт определяет необходимость учета совместного силового воздействия значительных неравномерных деформаций основания и сейсмики, при возможности возникновения обоих. При этом следует учитывать последовательное воздействие нагрузок, а так же рекомендуется применение нелинейного статического расчета по принципам метода спектра несущей способности. При построении графиков спектра несущей способности на основании расчетов в программных комплексах следует уточнять уровень развития неупругих деформаций на основании экспериментально подтвержденных значений.

Ключевые слова: конструктивная система; неравномерные деформации основания; неупругие деформации; сейсмостойкость; спектр несущей способности.

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