MOTROL. COMMISSION OF MOTORIZATION AND ENERGETICS IN AGRICULTURE – 2014, Vol.16, No. 8, 37-44

Interaction Study of the Frame Building With Foundation Weakened by the Underground Mines Under the Seismic Load

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Summary. These article describes the researching results of the underground man-triggered cavities' influence on the stress-strain state of the «soil base – foundation – structure» system elements under the seismic loads using the numerical simulation.

Key words: non-uniform deformation, frame, numerical modelling, mine, underworked area, seismic load, SFSI.

INTRODUCTION

Today we need to increase the reliability and the safety of the buildings and the facilities usage (especially) in the seismic regions of Ukraine. It can be reached if we will do complex analysis with the numerical simulation with the usage of the seismic affection on the buildings components.

In the most cases there is the one special loading in force combinations is being considered at the designing [1]. At that time, as the other special loading can be added in practice, and this also can lead to the increased (total) impact. The proposal of the additional effects accounting was made at the new edition of the design standards [2], which can arise during the construction on the collapsible soils. There are a lot of the scientists agree with this point of view. The European design standards [3] give the designer opportunity to consider emergency combinations of the loading at his own discretion.

The one of such problem is the task of the accounting the underground cavities, which can affect on the behavior of the soil base. This article doesn't describe the common problems of the surface treatment at the coal and other minerals underground extractions, because they are related to the specific man-triggered processes. The main question is the necessity of the accounting the mutual influence of the buildings and facilities on the built up areas with the anthropogenic or natural origin voids. All this can be concerned to the subway lines, underground transport tunnels, man-triggered premises, communications tunnels and cavities which historically formed in these areas (the catacombs, the underground passages and structures). The solution cavities have their own characteristics of the underground cavities forming.

This paper describes the problem of the influence of the man-triggered underground cavities on the stress-strain state of the buildings and soil base by the actions of the seismic loads.

PURPOSE OF WORK

The purpose of the researching was the qualitative and quantitative estimation of the influence on the strain-stress state of the frame structures from the presence mines in the soil base and the consideration of their possible destruction.

ANALYSIS METHODS OF EXTRACTION

The existing engineering calculation methods strongly limit the possibility of the excluding the impact of the mines on designed and operated building or structure. These tasks are difficult because of the necessity of the verifying the theoretical propositions; obtaining the detailed baseline data for the materials and loads as well as the time-consuming calculations. Such researches today are possible to carry out only by the numerical modeling.

NUMERICAL MODELING CONCEPT

Modern development of the mechanic of massive medium relies on the phenomenological models for load and deformation determination in the soil base, oriented on opening of deformation processes in the massive medium. Algorithms of the mechanic of massive medium use mathematical set of theories of elasticity, plasticity and creep, based on the experimental parameters. To determining baseline data and choosing deformation models, soil base modeling is related to the problem of the iterative solving of high-order equation systems, which requires massive computer resources. As a result, in most cases, calculations on seismic impacts are limited to the use of simplified models and computational methods, which prevents consideration of the real properties of a soil base (e.g., the Winkler soil model and similar models).

Such approach requires the use of the numerical simulation methods of the processes of soil deformation on various stages of loading as a necessary condition for prognosis of stress-strain state of the soil base. The finite element method (FEM), boundary elements method (BEM) and others are used successfully for calculation of stress strain state (SSS) of the soil base. Also it is necessary to emphasize new problem of the identification of the functions defining change of parameters that correspond to the soil state depending on stress gradient in this zone and the character of loading (static or dynamic).

For discrete systems with many degrees of freedom for FEM we have system of ordinary differential equations:

$$[M]\frac{d^2}{dt^2}\{U\} + [C]\frac{d}{dt}\{U\} + [K]\{U\} = \{Q(t)\}, \quad (1)$$

where: $[M]$ – mass matrix, $[C]$ – dissipation matrix, $[K]$ – rigidity matrix, $\{U\}$ – vector displacement, $\{Q(t)\}$ – loading vector represented as a time function.

To estimate the stress-strain state of the constructions under the seismic loads presented as three-component calculation accelerograms.

In the deformation of soil under the influence of dynamic oscillations, a significant role is played by the internal and external processes associated with energy dissipation. For structural constructions and bases, the main role is played by forces of internal resistance caused by the rheological characteristics of the material behavior.

To describe the decay processes should be used dependencies obtained from experimental data. However, given the complexity and high cost, and in some cases impossible to conduct experiments using different models of damping. In this work one of the commonly used Foight model, where dissipation $[C]$ represented by the expression:

$$[C]=\beta[K], \quad (2)$$

where: β – damping coefficient with stiffness matrix.

To describe β damping the slide-decrement oscillations δ used in standards [2]. To apply the parameter of the overall viscosity ξ should be determine due to decrement of oscillations δ:

$$\xi = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}} = \frac{\beta \cdot \omega_0}{2}, \quad (3)$$

where: ω_0– natural frequencies.

Value ω_0 was adopted with first natural (eigen) frequency of the construction.

External factors for energy dissipation include the interaction of the system with elements of the environment in which the oscillations occur – the surrounding soil, air, special damping devices, seismic isolation systems, and so forth, designed for oscillation damping. These processes are not directly related to deformation of soil or of the construction's material, but affects the overall energy. In this paper we used one of the most common options for incorporating energy radiation into outer space – the limiting damping method proposed by Lismer [14] and based on the use of viscous damping of degrees of freedom on the boundary elements. The method provides absorption of energy approaching the border, and prevents the processes of wave reflection at the boundaries of the body corresponding with actual conditions.

To estimate the stress-strain state of the constructions under the seismic loads presented as three-component synthetic calculation accelerograms the method of the direct integration of incomplete spectrum of the own pares is used. Vector of full displacements can be factorized by forms of the eigen-oscillations and written through the amplitude and eigen forms as a sum:

$$\{U\} = \sum_{i=1}^{N} A^i \{X_i\} \quad (4)$$

,

where: A^i – amplitude of the oscillations, $\{X_i\}$ – vectors of the eigen oscillation forms, N – number of eigen oscillation forms.

Characteristics were defined through Duhamel integral for each component of the spectrum during the period of seismic oscillations validity. While the number of the own pares is increasing, their contribution to the displacement value is decreasing.

SOIL – FOUNDATION – STRUCTURE INTERACTION

Let us consider the research of the mutual influence on the system elements «soil base – foundation – structure» in the case of the real object – the residential complex (Fig.1) the erection of which was planned on the potentially underworked area.

The multistoried residential complex with the underground parking is the complex of three 23-storey buildings, and the last two from those building are the three-section constructions, which have the expansion joints between the sections. The complex of the three buildings unites the solid two-storey underground parking under the entire area of the complex (Fig. 1). Each section of the residential buildings is the multistory construction: two underground floors of the parking, 23 aboveground floors and technical attic floor. The frame of buildings is designed in a monolithic form. The foundation of the residential complex is the pedestal footing with the jacked-in piles, the length of piles is 13m, cross-section of piles is 350×350mm. The height of the grillage for the altitudinal part of the building is 1.5 m, for parking – 1.0 m.

Fig. 1. A multi-storey residential complex with underground parking:
1 – adult zone, *2* – children's area, *3* – flowerbed, *4* – border of the parking

The geological structure of the site (Fig.2) is represented by the quaternary settlement, the Neogene soils are located below. The entire stratum of the surface is covered with the filled soils.

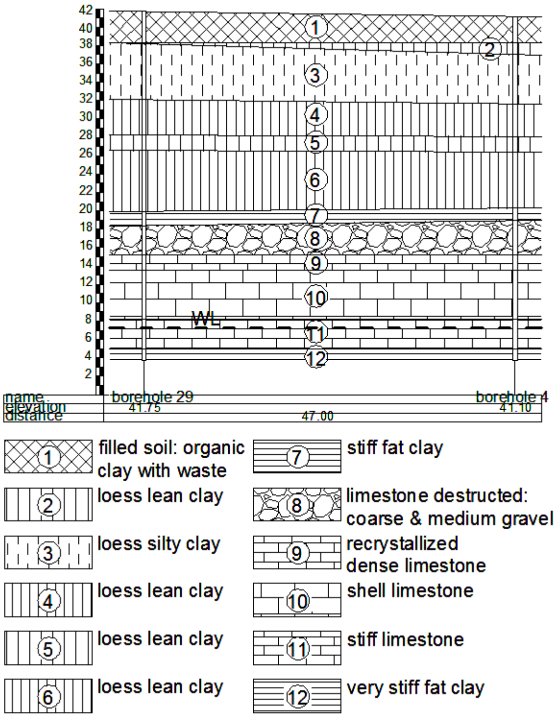

Fig. 2. The geological conditions of the site

The presence of the underground mines which eventually possible can cause the crash of the ceiling coving is fixed near to the excavation of the building in the shell limestone's layer (EGY – 10). The planning and vertical characteristics of the mine are shown in Fig. 3. This can cause the collapse deformation and surface dips at the larger destructions. Some reasons of the ceiling coving collapse are the pressure from the new buildings and the dynamic load (seismic intensity of territory is 7 balls). Therefore, the researches of the mutual influence of the building and the soil base with the mines were conducted with the considering emergencies.

Odessa mines are the underground quarries, where the stone buildings formerly dig. There was the widespread in the central part of Odessa region shell limestone layer extracted in that place for the building purposes. It was only durable and affordable building material in the steppe zone of southern Ukraine. At the present time the Pontian shell limestone cover all the central part of Odessa region. The average stratum of the limestone layer varies from 5 to 12 m near Odessa area. The structure of the limestone strata is following: the lower part is represented by the uniformly cemented saw limestone, the top part is composed by the strongly recrystallized dense limestone - coarse gravel. The sawing limestones are the enough light formation (the volumetric weight is 1100...1500 kg/m^3).

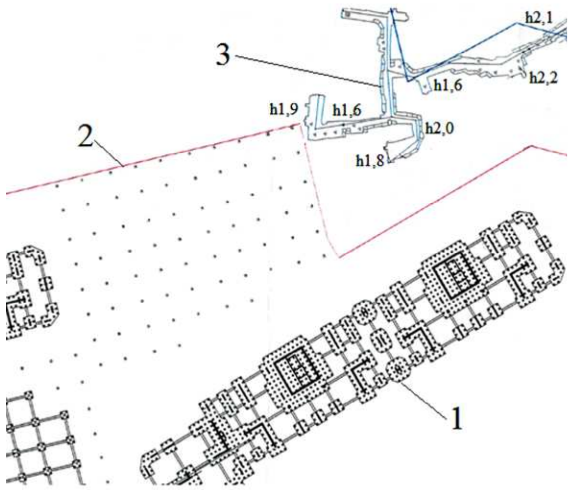

Fig. 3. Location of mines that were detected nearby the pit of the residential complex: *1* – altitudinal part of residential complex, *2* – border of the parking, *3* – underground cavities (mines)

The researches of the mine influence and the residential complex are conducted by using the numerical modeling of the teamwork of the system elements «soil base – foundation – structure», this model was made by the finite elements method based on the automated research system «VESNA» in the three-dimensional model. The soil base was considered as an elastic laminated soil according to the geological section (Fig. 2). The soil parameters are the following: the deformation modulus E, the specific gravity γ, the Poisson coefficient ν, the specific cohesion c, the angle of the internal friction φ. The minimal value of the deformation modulus for the limestone layers E=50 MPa has been accepted for the ensuring the reliability of the calculations. This value corresponds to the low compressibility soils (the uniaxial compression strength is Rc=0,8…1,0 MPa according to the research).

The solution of the problems on the effect of the static and seismic loads were provided for the consideration of the interference between the construction of the residential complex and the parking in terms of the potentially underworked territory based on the emergency situations:

– the interaction between the building and the soil base does not taking into account the presence of underground mines,

– the interaction between the building and the soil base including the presence of underground mines,

– the interaction between the building and the soil base forced by the destruction of the catacombs,

– the interaction between the building with the soil base under the action of the seismic loads.

The part of the complex (Fig. 4), which is located closer to the underground mines considered for the evaluation of the collaborative framework and the soil, which has the underground cavities.

The results of the numerical modeling collaborative system «soil base – foundation – structure» do not taking into account the presence of the underground mines based on the following: the predicted settlement below the center of the gravity of the building is expected to be not more than 4.8 cm; the settlement of the last row of the piles – is not more than 1.57 cm. Wherein, the settlement of the soil base in the area of underground cavities is not more than 2…5 mm.

The comparison of the bearing structures' strains of the building and the soil bases elements showed that the presence of the underground mines near the excavation complex actually doesn't cause changes. The calculations were made for the soil base does not taking into the account the presence of the underground mines, and with taking into account their availability. In this case of the vertical stresses in the elements of ceiling coving of the underground mines (zone nearby parking's corner) are expected not more than 50 kPa by the results of the calculations. This is not more than the domestic pressure and is perceived easily by the layer of the limestone, where the mine is made.

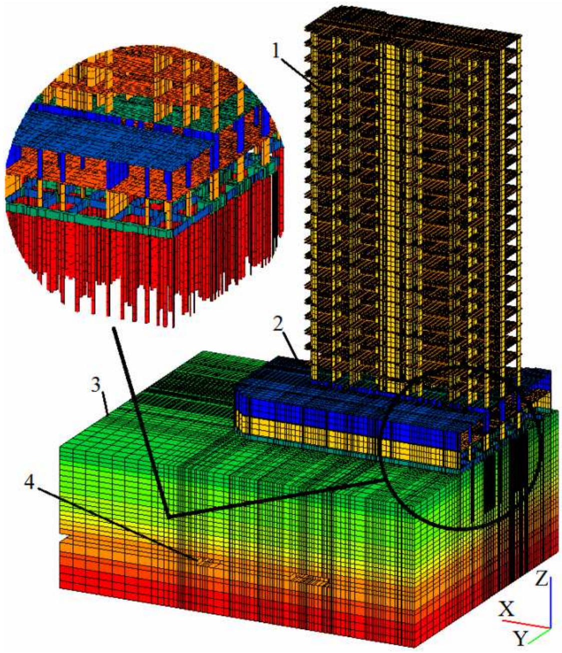

Fig. 4. Three-dimensional finite element model for solving the problem of teamwork structure with soil base by using «VESNA»: *1* – altitudinal part of residential complex, *2* – parking, *3* – laminated soil base, *4* – underground cavities (mines)

The stress-strain state soil mass on the weight of the building with taking into account the presence of the workings in the vicinity of the pit complex was accepted for the assessing the relative subsidence of the residential complex, with the possible ceiling coving mines' collapse. At the same time the stress and strain of the previous stage were considered.

The numerical modeling of the disaster collapse of the catacombs ceiling coving was showed that the deformation of the soil base fragments are expected in the area which does not cover the foundation of the altitudinal part of the residential complex. At the same time, the predictable additional displacements of the parking foundation (Fig.5) that are causing the destruction by the emergency mines are not essential. The corner zone of parking received the additional settlement by 0.2 ... 0.8 mm. The settlement of the piles on the contour is expected maximum value 0.8 mm. In this case the predicted relative difference of the settlements at grillage's corners (Fig.5) is $\Delta S/L$=0,00003 (the maximum value by Code [4] is $(\Delta S/L)_u$=0,002).

The numerical modeling for the system «soil base – foundation – structure» was made by the direct dynamic method in order to research the strain stress state of the bearing structures of the residential complex from the effect of the seismic loads. The Voigt model is used as the model for the energy dissipation for the soil and structures for solving this task. The own couples (for building structures with the soil base) were calculated to select the seismic loads and to determine the modes and the frequencies of the oscillations. These own couples were calculated in an amount which corresponds to a set of the modal mass in the directions *X*, *Y*, *Z* accordingly 85%, 85% and 75%.

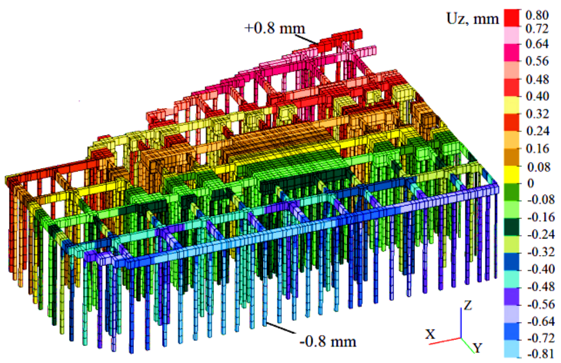

Fig. 5. The increase of settlement on the results of solving the problem of "soil-foundation-structure interaction" for the forced destruction of the catacombs

The damping parameter was adopted accordingly to the higher frequency oscillations of the system «soil base – foundation – structure», which amounted to ω_0=2,67 s^{-1} (*n*=0,425 Hz),), that corresponds to the period of natural oscillations T_1=2,353071 s. The logarithmic decrement of the oscillations was assumed such that corresponds to ξ=5% of the critical damping of the oscillations (δ=0,3145). Thus damping parameter was ξ=0,037.

The calculations of the system «soil base – foundation – structure» on the action of the seismic loads were performed using three-component calculation accelerograms.

Seismic load was modeled using special accelerograms designed especially for this site and derived from the actual earthquake records of Vrancea zone and local regions.

The oscillation amplitude for the designed earthquakes from the Vrancea zone is much more intense so the results using these accelerograms will be determined.

According to the results of the numerical simulation we got contour plots of the envelopes of the maximum and minimum pressure for the frame structures of parking in the directions *X*, *Y*, *Z*, which must be considered as the extra possible changes to the static stress state.

The analysis of the results showed that the additional vertical forces in the piles of the parking are expected to *N*=10…184 kN (extreme values). The efforts in the cover plate parking from the seismic load can reach values *Mx*=5,2…9,3 kN·m/m, *My*=5,2…11 kN·m/m. The increase efforts in the grillage of the parking lot is expected to *Mx*=33…112 kN·m/m, *My*=52…148 kN·m/m (momentary extreme values). Expected gain of the vertical pressure under the action of the seismic loads (dynamic composes) does not exceed 100 kPa in the walls and the ceiling coving of the underground mines near the complexes excavation. In this case, the total value of the vertical pressures in these elements is expected not more than 200 kPa, which does not exceed *Rc*.

The tracking moving of the control points were provided in the calculations for the seismic loads. These points are: the grillage corners and the cover parking (Fig.6); the point on the ceiling coving of the underground mines, which situated near the building; the bottom and pile head which is located closest to the underground mines.

The analysis of the received results showed that the maximum expected deviation of the pile head is *Ux*=37,3 mm (on 83 s), *Uy*=42,8 mm (on 71s), *Uz* =7,8 mm (on 68 s).

The maximum displacement of the grillage with the soil projected by the amount of *Ux*=38,0 mm, *Uy*=45,6 mm, *Uz* =9,7 mm. According to the results of the numerical simulation from the action of the seismic loads the slope roof slab parking is *Ux*=37,8 mm, *Uy*=43,0 mm, *Uz* =8,0 mm. The control point on the ceiling coving of the underground mines get displacement *Ux*=37,6 mm, *Uy*=44,1 mm, *Uz* =7,8 mm.

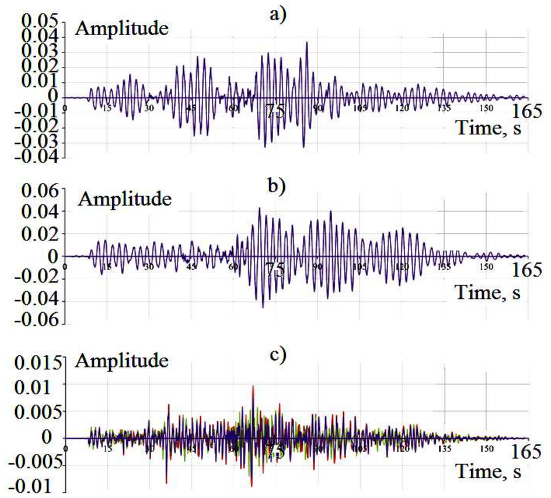

Fig. 6. Displacements of grillage corners on the results of calculations using the calculation accelerograms for the *7* – magnitude earthquake from Vrancea zone in directions: *a* – along *X*, *b* – along *Y*, *c* – along *Z*

Thus, the simulations were performed for the case of an emergency in order to be able to draw conclusions about the interaction of piles of soil base and the impact of their behavior catacombs.

CONCLUSIONS

According to the results of the research by using the numerical simulation was found:

- The presence of the underground mines in the soil base near the apartment complex almost does not cause the stress-strain state changes of the building load-bearing elements and the soil base. At the same time vertical stresses in the soil (the ceiling coving and the walls of mines) do not exceed 100 kPa. This pressure is sensed by the layer of the limestone where the underground mines are situated,
- The settlement of the mines' ceiling coving, relatived to the floor in the loads transmission from the building did not exceed 5mm and did not exceed the soil strength,
- The research of the emergency destruction of mine influence showed that the deformation occur within the radius 23 m and do not affect at the soil base of the altitudinal part of the building. However, due to the possible heterogeneity of the soils in such circumstances the usage of the pile foundations is justified,
- The influence of the mines destruction on the parking's foundation may lead to the additional settlement of the small amount of the piles, which situated near the mines due to low soil deformability. The usage of the grillage with cross straps enables the saving of the parking operating properties meet the requirements of standards [4],
- It is established that the seismic loads can lead to increase the pressure in the ceiling coving of mines up to 2 times, do not lead to exceed the strength of the soil and do not cause the destruction of the mine,
- We find that under the action of the seismic influence prevails rigid building foundation moving along with the soil. The maximum displacement of the grillage in the space was 50,4 mm at 71 s of load.

The numerical modeling results confirm the fact that the stress-strain state of the soil base and the load-bearing elements of the building significantly react to the impact of each element of the system: its own stiffness of the building, the components and the foundation stiffness, the characteristics of the soil base, the presence of the underground natural or man-made cavities, etc. All this confirms the necessity for a detailed study of the interference system «soil base – foundation – structure» in the designing for the reliable operation of the structures during the usage in the future by the numerical simulation considering the action of the seismic loads. This approach makes it possible to appreciate the character of the building interaction with the having cavities soil base: to assess the impact of the building load of the building on the underground structures; to assess the impact from the presence of the cavities on the stress-strain state of the load-bearing elements of structure.

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ИССЛЕДОВАНИЕ ВЗАИМОДЕЙСТВИЯ КАРКАСНОГО ЗДАНИЯ С ОСНОВАНИЕМ, ОСЛАБЛЕННЫМ ПОДЗЕМНЫМИ ВЫРАБОТКАМИ, ПРИ ДЕЙСТВИИ СЕЙСМИЧЕСКИХ НАГРУЗОК

Аннотация. В статье приведены результаты исследования влияния подземных техногенных пустот на напряженно-деформированное состояние элементов системы «грунтовое основание – фундамент – здание» в условиях сейсмических нагрузок с использованием численного моделирования.

Ключевые слова: неравномерные деформации, каркас, численное моделирование, подземные техногенные пустоты, подрабатываемая территория, сейсмическая нагрузка.