Soil base deformation features of the pile foundations on loess and landsliding territories at static and dynamic loadings

Les spécificités de déformation de la base au sol des fondations sur pieux sur terrain en lœss ou sur des terrains sujets à glissements sous l'impact de charges statiques et dynamiques

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ABSTRACT

The features of interaction between the pile foundations (stress strain state) and the soil base deformation, depending on the type of soil (loess soil, sliding zones, seismic zones), typical of Ukraine, are analyzed. Authors suggest to search the form and the place of a potential slip surface by fixing the localization of zones of plastic deformations in the soil massif. The experimental results of parameters' definition of loess thickness at static and dynamic loading impact are shown. Features of pile interaction in a soil massif, which depends on their sizes and their location under the building, are revealed. The differences of the stress strain state formation, which result from combinations of various loadings, either static or dynamic, in the elements of « soil basis – foundation – building » system, are exposed, depending on the chosen simulation model (soil massif, coefficient of rigidity).

RÉSUMÉ

L'article analyse les spécificités d'interaction (déformation) entre les fondations sur pieux et la base au sol, en fonction des types de terrain (lœss, terrain sujet à glissement, zone sismique), caractéristiques de l'Ukraine. Les auteurs proposent de chercher la forme et l'emplacement d'une surface de glissement potentielle, en repérant la localisation des zones de déformations plastiques dans la masse de sol. Les résultats expérimentaux de définition des paramètres d'épaisseur de loess sous l'impact de charges statiques et dynamiques sont exposés. Les caractéristiques d'interaction de pieux (piles) dans la masse de sol selon leurs tailles et leur emplacement sous le bâtiment sont expliquées. Les différences de formation de l'état de contrainte résultant de la combinaisons de différentes charges statiques et/ou dynamiques, dans les éléments du système « base – fondations – bâtiment », sont exposées en fonction du modèle de simulation choisi.

Keywords: mathematical modeling, stress-strain state, loess soil, collapse deformation, dynamic, pile foundation, anti-seismic constructions, landslide, sliding surface.

1 INTRODUCTION

Due to the specifics of soil conditions, pile foundations are widely used for industrial and civil objects in Ukraine, especially for loess soils settled under moistening, on landsliding territories and in seismic areas. In each case, the reliability and performance of pile foundations is determined by the behavior of it interaction with the base.

The major factor to define modern conditions in the city of Kyiv is its glacial activity. Frequent alternation of different layers has led to forming of several aquifer horizons that have become the reason for the wide development of landslide processes.

Significant increase in the real estate investments during last years led to sharp increase in use of territories with complicated soil conditions for the construction purposes. The main concerns for these territories during the construction period and sequential usage are maintenance of the slope stability and the durability of superstructures.

Dynamic properties of the elements of the "base-foundation-building" system, the existence of the real data on dynamic load and parameters of dying oscillations in various environments are very important for the the reliable design of bases and foundations in seismic regions. Such problems require the creation of models, which take into account the real allocation of seismic waves in the soil environment. Finding solutions for such problems requires development and realization of the calculation methodics with the help of up-to-date computer technology [Boyko 2005, Fialko 2003].

Solving such problems is the subject of this paper.

2 PROBLEM DESCRIPTION

Performance of the pile foundations in loess soils depends on the amount of the additional load on the lateral surface deformations caused by the soil settled under moistening. An interaction between the pile and the thickness of the loess soil depends on soil properties, the type and technology used during piles installation, the amount of the construction-related load on a pile, and the recent direction of moistening – the bottom-up or top-down.

Construction characteristics of loess soils in natural and saturated states essentially vary by physical and mechanical parameters, which determine the interaction between the pile and the base.

The additional base deformations due to loess saturation can affect both building as a whole (a tilt) and it separate parts (a deflection, a structure hogging). When taking into account non-uniform base deformations, analysis of construction deformations becomes significantly more complex. In practice, sometimes even insignificant base deformations may result in the loss of building structural integrity. Base plays important role here since it strain capacity ensures that building frame will not experience significant changes in effort applied to its elements. Depending on deformation intensity and rigidity of both the soil base and the structure itself, some areas will experience increased pressure, others - decreased and some foundation areas may even break away from the base. Such redistribution of the contact pressure influences a pressure changes in the soil, affecting it deformations. Analysis of such systems is usually done using mathematical modeling. In this case, problems were solved using software complex "VESNA" that allowed analysis of the the stress-strain state of the

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"building – foundation – base" system. Used model and calculation scheme encompasses all elements: buildings, foundations and soil base [Zhuk V. 2006]. The analysis of calculation results has shown that there is a significant redistribution of load in bearing elements of a multi-story building frame. Load on corner columns an increased by a factor of two. In a collapse zone there is an unloading of columns which caused occurrence of stretching efforts in vertical elements. Bending moments in some columns increased up to 9 times while at some elements force vector reversed its direction.

The additional deformations of the loess saturated base under the seismic influence occur at soil collapse from a soil's own weight. The reason of these deformations is the decrease of structural strength of a loess soil while under vibrations. According to laboratory tests, the structural strength of a loess saturated sample in odometer under vibrations can be decreased by 10-15%. For soils in a natural state such change does not occur.

It important to distinguish different behavior of the loess soil during an earthquake, as it experiences instant deformations of destructive character developing under the action of a soil's weight. At the same time deformations developed in the compressed zone of the base under the foundation are plastic in nature.

While designing bases and foundations in seismically dangerous territories it is necessary to take into account the reduction of structural strength, the decrease of the deformation characteristics of a loess soil under influence of saturating and dynamic loads. In numerical modeling of such processes it is difficult to take into account all parameters of strength and deformation. Therefore solutions to such problems traditionally use models based on update of the structural strength value on each step.

It is of primary importance to recognize various conditions that cause slopes to become unstable and the factors that trigger their displacement. Only than, an accurate diagnosis can be made to appreciate the extent of the possible dangers and to propose effective remedial measurements. Such detailed analysis that takes into account the actions of different factors together or separately is possible to execute by using numerical modeling. It enables us to analyze the evolution of the stress strain state of an earth mass on landslide-prone territories that are important problems to solve in determining the slip surface location.

Existing calculation methods such as circular arc have no opportunity to estimate the stress strain state of a slope.

3 CONCEPT OF NUMERICAL MODELLING

To analyze the influence of dynamic oscillations on the construction's behavior it is necessary to describe the interaction process as the system of differential equations. Oscillating construction, which was taken out of the balance under the action of seismic waves in base, makes damped oscillations. The relative displacements of such oscillator can be subscribed by the differential equation [A. V. Perelmuter 2001]:

$$\ddot{x} + 2\varphi\omega\dot{x} + \omega^2 x = -\ddot{x}(t),$$

where ω – radial eigenfrequency of the system without damping, φ– relative damping, *x*– relative displacements.

For discrete systems with many degrees of freedom for FEM, taking into consideration dying according to the hypothesis of Kelvin – Foight, we have system of ordinary differential equations:

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

where *[M]* – mass matix, *[C]* – dissipation matrix, *[K]* – rigidity matrix, *{U}* – displacements' vector, *{Q(t)}* – loading vector represented as a time function.

From the mathematical point of view the problem reduces to solving the spectral problem for FEM matrices or direct integration in time [Bate K. 1982]. Current standards for the dynamic calculations allow usage of schemes with console building fixation [ДБН В.1.1-12-2006], that excludes the soil's work altogether. The use of 3D soil array allows much better precision while describing interactions within the system "base-foundation-building". Accelerograms of seismic oscillations are applied directly to the soil surface. When modeling, in most cases, it is accepted that the length of seismic waves is singnificantly greater than building size and related accelerations are applied to all points simultaneously. To estimate the influence of the inertial soil forces on the dynamic properties (eigenfrequencies and oscillation forms) the system "base-foundation-building" was analysed using real industrial construction as an example. The construction with profile dimensions 18x48 m has 36 columns with 40x40 sm profile which are placed in squares using 6 m steps in both directions. Finite-element model is shown in fig. 1.

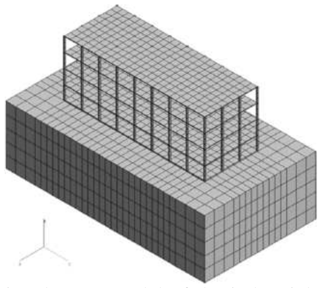

Fig. 1. Finite-element model of the industrial construction as a system "base-foundation-building".

The number of identified eigen oscillation pairs was limited by the following condition: the sum of the modal masses during oscillation in horizontal and vertical directions must be at least 90% and 76% of whole sum respectively. In order to verify the accuracy of the results the modeling was made on the two systems - ASSR «VESNA» and CC «SCAD», which utilize different types of the finite elements and calculation methods. Error did not exceed 7%. The analysis of the results has shown that for this problem in the case of weightless soil base, the number of necessary eigen pairs (16 and 113 oscillation forms) has been 7 times smaller and values of main eigenfrequencies decreased by about 30%. It is important to note that first three oscillation forms (longitudinal, transverse and rotational) are similar in both cases. Physical properties of the soil base are well founded to take into account mass forces of the soil base, however the difficult question is to how to consider dimensions and limit conditions [Ross M. 2004, Lysmer J. 1969], which would influence inner qualities of the soil.

4 FINITE ELEMENT ANALYSES

4.1 *Interaction between the pile and loess base*

Interaction between piles and foundation is always connected with the definition of the additional loading on their lateral surface, which occures at loess soil's saturation. For this purpose full-scale pile tests was carried out. The pile had 20 m length and 35x35 sm profile. The pile, with the exception of the upper portion, was submerged in the loess soil with thickness H_{sl} = 14,7 m. The measurement of soil resistance on the lateral surface of piles in natural and saturated states was made by using CPT diameter 127 mm. A numerical modeling of the "pile

- loess base" system interaction was calculated using ESSR "VESNA" based on the finite element moment scheme.

The results are shown in fig. 2. Fig. 2 shows the characteristics of tangential stresses σ_{12} (kPa) distribution on the lateral surface of pile at the time when it has reached the maximum friction force in the saturated loess soil.

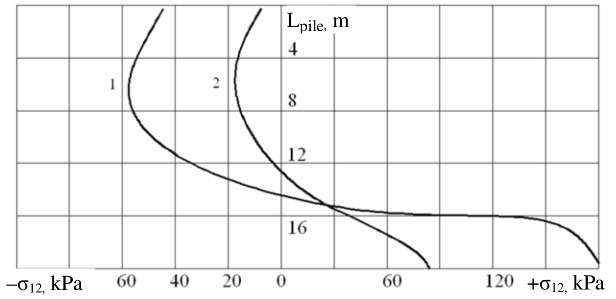

Fig. 2 Stresses' distribution on the lateral pile surface at maximum friction force values which are loaded in addition: 1 saturation's direction bottom-up; 2 saturation's direction top-down.

In the case "bottom-up" saturation direction the value of maximum resistance of loess soil in natural condition f = 56 kPa is changing to f_w = 25 kPa. Value of maximum resistance of loess soils on the lateral surface of piles according to the numerical modeling in natural and saturated conditions is in agreement with the results of experimental tests of loess soil by full-scale pile tests and CPT diameter 127 mm. The difference did not exceed 15%.

4.2 *Landslide development*

The idea of defining a sliding surface position and its subsequent form is based upon describing local zones of plastic deformations which may depend on several different factors.

Analysis was perfomed using finite element model. Initial conditions were set according to the original state of the slope. First stage consisted of performing analysis of the strain-stress state under slope's own weight. Distribution of zones of the plastic deformations determined a critical angle of the slope.

Next stage of calculations consisted of the stress strain state analysis of the soil base under condition that ground was excavated at the bottom of a slope to the depth of 4 meters. In such case displacement vectors are directed upwards. Zones of plastic deformations concentrate on its perimeter. Several cases with different soil parameters depending on various hydro-geological conditions were considered.

The main factor causing a landsliding was determined using the results of the stress-strain state evolution. Intensivity of the distribution of plastic deformations in the zone of the sliding surface has shown the beginning of the landslide process development.

4.3 *Foundation design in seismic areas*

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 eigenforms as a sum:

$$\{U\} = \sum_{i=1}^{N} A^i \{X_i\},$$

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. Taking into consideration this fact the number of used own forms was limited by standard recommendations [ДБН В.1.1-12-2006] as for accumulation of modal masses not less than Mx=0.85, My=0.85, Mz=0.75 in corresponding direction.

The explored object is a many-storied wireframe construction of the complex form, which is built on landslide territory AR Crimea. Building has 16 stores with parking area on the first floor projected on pile-plate foundation. The bearing over-foundational constructions are the floors of 220 m^2, square of which varies bottom-up from 900 m^2 to 300 m^2, the rigidity core with a stairwell situated inside, vertical columns with square profile 40x40 sm , the diaphragm of rigidity is only to the 5th floor and seamless wall (b=40 sm) along the parking perimeter.

The soil base is represented as layers of gruss-crushed rock soil with clayey stuff about 20 m thick (E=54 MPa, ν=0.25, ρ=24.8 kN/m^3); broken mudstones h=2.5 m (E=54 MPa, ν=0.25, ρ=22.1 kN/m^3), and mudstones in nature state (E=54 MPa, ν=0.25, ρ=23.1 kN/m^3). According to the seismic estimation this territory has 9 points on a MSK-64 scale.

The building configuration and high area's seismicity require application of special anti-seismic arrangements. Piles, which work on tension of "TITAN" type (fig. 3), are used as an anchor elements..

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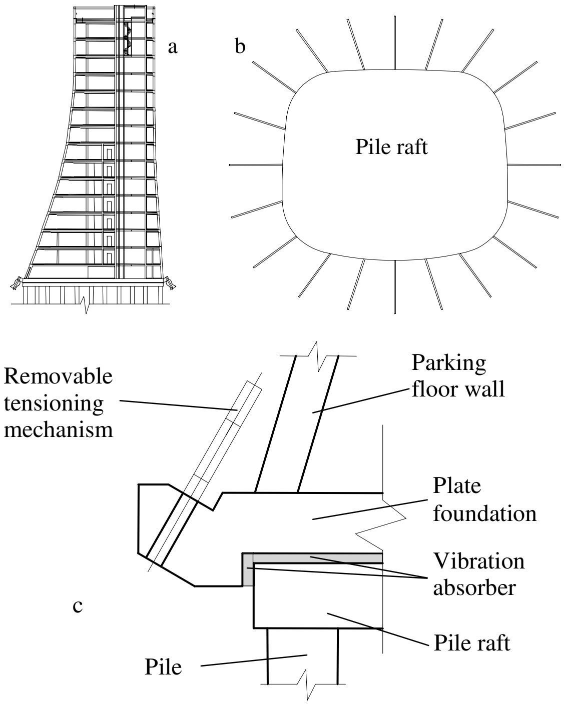

Fig. 3. Constructive scheme of anti-seismic arrangements for building: a – constructive section of the building; b- anchor disposition plan; c – foundations' construction.

During the modeling the calculated synthetic accelerograms were used to define the dynamic component in loading combination. Finite-element model is presented in fig. 4 and has 88209 degrees of freedom. Analysis of the eigenforms and eigenfrequencies of the construction shows that it is necessary to take into account 102 eigenpares in order to reach the required amount of modal masses. Under the norms the combination of synthesized accelerograms №8 (period of own oscillation of the construction according to the first form is T=1.845 sec^{-1}) and logarithmic decrement of oscillations δ=0.3 were used. The calculation takes into account the inertial properties of the soil base.

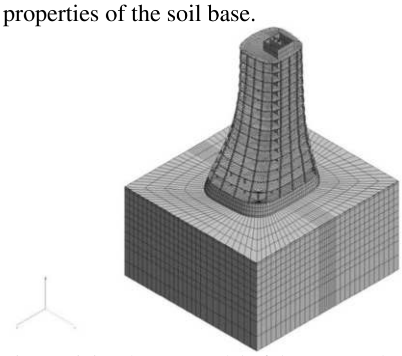

Fig. 4. Finite element model of the system «base-foundation-building».

The enveloping diagrams of the parameters of strain-stress state in time for the foundation were built as a result of calculations. The results are presented in fig. 5 a, b, the biggest intensity are fixed in local zones under the rigidity core, where the moment reaches the highest values up to 5 MN·m/m along Mx and about 6.8 MN·m/m along My. In other zone the moments changed between 0.40-0.6 MN·m/m in both directions. Analyzing enveloping moment diagrams of different signs, the qualitative differences in their distribution was not found. Such stress distribution is conditioned by resonance of seismic oscillations which affect system elements during significant period of time.

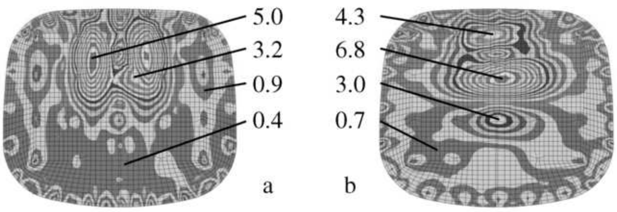

Fig. 5 The distribution of maximal enveloping moments of lower plate [MN·m/m]: a – along X; b – along Y.

The exploration of the influence of the oscillations' logarithmic decrement values to the stress-strain state of the foundations showed that with the decrease of the decrement to the value of δ=0.15 the maximum moments in rigidity core zone increase up to the values of Mx=6.6 MN·m/m, My=8.6 MN·m/m. In the case of using the decrement of δ=0.5 the moments are decreasing to Mx=4.04 MN·m/m, My=5.02 MN·m/m. Variation of the characteristics of dying oscillations don't influence the qualitative stress distribution, but changes only peak moments' values. This evidences the resonance origin of these extremums.

This way, the normative technique is oriented on the search of synthesize accelerograms, that leads to the resonance effects' and appearing of significant stresses in the bearing constructions. This makes impossible the estimation of anti-seismic arrangements effectivness, which aimed at the change of eigenfrequencies different from resonance range. Usage of various calculational schemes determine the choice of the corresponding seismic accelerograms, which differ by spectrum, frequencies and acting time.

The realized explorations point to the needs to make the additional geophysical research for the intensity corrections and making real accelerograms for the specific building site.

5 CONCLUSIONS

- The technique for determination of the additional load on a pile in the loess soil, which has collapsed settlements due to the moisture saturation, allows detection of the maximum soil resistance on its lateral surface without splitting soil into the separate layers using soil types provided by norms.
- Analysis of the evolution of the local plastic deformation zones allows to determine the sliding surface location and its form.
- Obtained results allow possibility to optimize solutions for the landslide territory stabilization.
- The effectiveness of the proposed anti-seismic arrangements that can be recommended for multi-stored buildings, was shown on the example of real construction.
- It was demonstrated that the method of choosing accellerograms (varying in spectrum, amplitude of acceleration and time of action), suggested by norms, is dependent from dynamic properties of the decision algorithm.
- Normative methodic does not provide the possibility to estimate the role of anti-seismic arrangements in decreasing the influence of the resonance seismic oscillations on the elements of the system «base-foundation-building».

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