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Causes of some hazardous engineering-geological processes on urban territories

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Abstract. Population growth in cities, the need to expand the living space requires of rational use of territories within the existing boundaries of the city. The necessity of compliance with the functional zones of the city is shown on the example of a representative part of Kiev, that should be performed taking into account engineering-geological features of the territory. It is necessary to comply with the underlying zones in the underground space to ensure the bearing capacity of the soil mass. The changes in soil bases are defined as a result of changes in the stress-strain state under the construction, development of underground space, changes of soils water content as the result of soaking from the surface, formation of "perched water", raising the groundwater level. The vibration analysis of high-rise building – the main library building is made from the dynamic loads that arise during the movement of the vehicle, taking into account the work of the pile foundation as a rigid body relative to the longitudinal axis, which passes through the center of the building at the level of the cap of piles.

1 Introduction

The territory of any city can be divided into four main functional zones: residential, industrial, transport, recreational. The formation and placement of the objects is regulated by the planning documentation [1] and the Law of Ukraine "On regulation of urban development" valid in Ukraine. From the point of view of the engineering development of the territory for each type of functional zones according to natural conditions there are three categories: favorable, slightly favorable and unfavorable [2].

Each of the functional zones is characterized by a different degree of anthropogenic influence, ensuring the safety of residence / stay for a person and the mutual influence of objects from one zone to another (particularly in the underground semi- space).

The residential area is the location of buildings and constructions of permanent human habitation. The main influence on the geological environment in such zones is caused by a static load, which varies from 63 kN/m^2 (5-storey building of 1960-ies) to 380 kN/m^2 (modern high-rise buildings of 27 storeys). In industrial zones there are powerful industrial objects and power plants, which creating static and dynamic additional impacts on the soil,

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and also in case of accidents or improper operation of significant leaks from water supply networks.

The vibrations acceleration changes in the range 30-130 dB (0,05-1,8 in g) [3], that is transmitted to the soil from the movement of different types of transport in the transport infrastructure zones. Recreation zones such as parks and other recreational facilities, do not create significant negative influences. Generally for these zones within the city use areas with not the best engineering-geological conditions.

Large cities are characterized by non-compliance of functional zones, for example, energy objects are not systematically located, sometimes along with residential buildings; the road of categories with high traffic loads are close to residential neighborhoods. The close mutual arrangement of objects together with complex engineering-geological conditions can lead to an increase in the intensity of such influence and generation of hazardous engineering-geological processes.

The differentiation of the territory of Kiev in terms of the vulnerability of its geological environment to man-made influences was carried out. The method of quadratic evaluation was used, with the dimensions of a unit square of 300×300 m [3]. Factors such as static load, dynamic load, type of soil with load bearing capacity, ground water level etc., were taken into account. Squares with unfavorable engineering-geological conditions (60 % of the unit squares) have an intense mixing of functional zones in most cases.

The aim of this article was to show the occurrence of hazardous engineering-geological processes as a result of mutual influence of objects belonging to different functional zones, and to describe the conditions of violation of the geological environment under the urban planning activities, on the example of a high-rise building located on one of these sites.

2 The site description and methodology

The experimental site with a high-rise building – the building of the Vernadsky National Library of Ukraine is placed in the Holosiivskyi district of Kyiv and occupies 0.18 km^2. The objects of different functional zones are bordered on this territory: on the two sides at a distance of 50-80 m the building is surrounded by 12-16-storey residential buildings; within a radius of 60-100 m from different directions – roads with high transport load, including a traffic interchange and railway tracks; there are three food processing plants and a petroleum – petrochemical plant (Fig. 1a).

The site is located in the lower part of the right bank slope of the river valley Lybid within the Prydniprovs'ka upland, by geomorphologically. The absolute marks of the surface of the site are 115.5-120.7 m. The library complex consists of the high-rise 27-storey bookstore on a pile foundation and a 3-, 4-storey buildings on a strip foundation, set around the high-rise part (stylobate). The stylobate is separated from the high-rise book storage by expansion joints.

In 2008-2010, during the reconstruction of the traffic junction the Moscovs'ka Square and the construction of the subway, there were recorded the appearance of cracks on the constructions of the library building and damaging the covering on the facade (up to 20 % of the total area) that is associated with such building activities (Fig. 1b).

The documentations of engineering-geological exploration, a survey of the technical condition of the building, the simulation of the stress-strain state of the soil basis, the impact of dynamic loads, changes in water level were processed in order to determine the causes of the damages. Statistical, cartographic methods were used to build of all the charts using GIS technology and digital modeling. The mechanics and mathematical bases of engineering geology in combination with the approaches of system analysis and engineering-geological similarity theory were used.

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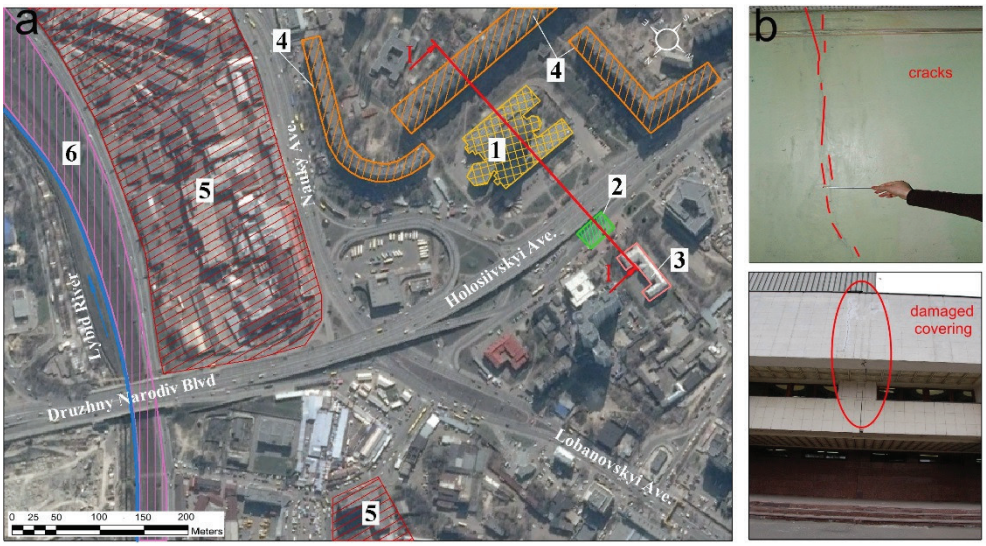

Fig. 1. The plan of the experimental site (a) and the damage on the constructions of building (b): 1 – the building of the library; 2 – the metro station; 3 – the school; 4 – residential buildings; 5 – industrial enterprises; 6 – railway tracks.

3 Results and analysis

3.1 The change of the stress state under the building and planning of underground space

The influence on the geological environment during urban planning is the stages of destruction of the natural environment (destruction of plant and soil cover, digging pits and excavation), the inclusion of new elements into the natural system (construction of buildings, underground structures, coverage areas, etc.).

Ensuring the stability of residential buildings, especially with the increasing number of floors, at the same time requires an increase in the depth of the foundation, the replacement of natural bases with artificial, which significantly changes the magnitude of stress in the first surface components of the geological environment. The general scheme of changing the stress state of the geological environment is shown in Fig. 2 on the example of the high-rise book storage.

Engineering constructions most actively affect on the soil layers close to the surface. The weight of the construction forms a compressed zone under the foundations at a depth of 10 to 100 m, respectively, and in lateral directions in the corners of the building up to 30 m.

The values of the compressed zones under the foundations of buildings along the line of the section I-I were established by the calculations, that is from 10 m (3-storey school building) to 50 m (27-storey library), according to building codes [4].

High-rise buildings with underground parking that built on piled foundations violate the hydrogeological regime of the first from the surface aquifer and create a barrage effect. The rise of the water level to the deep security zone or the zone of active compression under the existing objects generates the subsidence process in the loess types of soil. Similar conditions have developed on the territory of the reserve of world significance “Sophia of Kiev” during the construction of a high-rise building in its buffer zone [5].

Under the vertical protective zone of the building should be understood a zone around the bulb of the active compressed zone under it. Its size depends on the weight of the building

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and the depth of laying the foundations for different types of soils, and the intervention in which can lead to emergency situations.

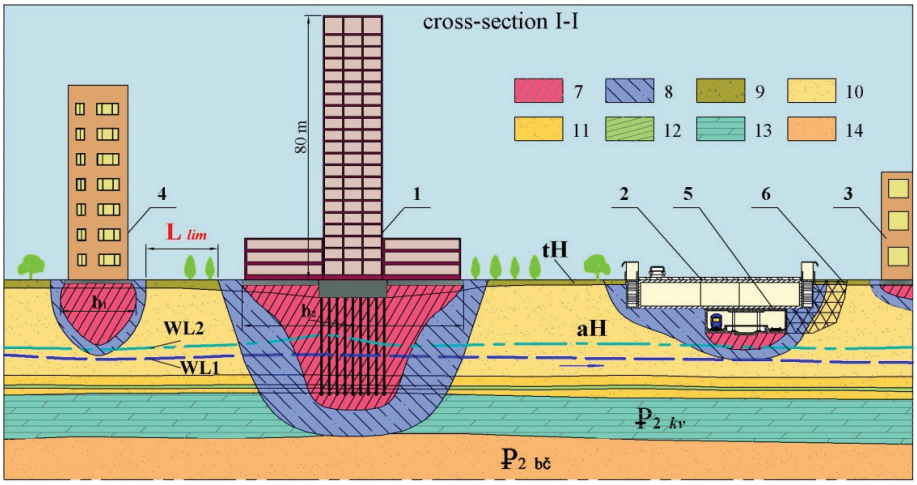

Fig. 2. The scheme of changing the stress field of the geological environment under the main objects of urban development along the line of the section I-I: 1 – the construction of the library; 2 – underground passage; 3 – the school; 4 – the residential building; 5 – the metro station; 6 – the place of the accident in 2006; 7 – a zone of active pressure under construction; 8 – the security zone; 9 – filling soils; 10 – loamy sand of loess-like type; 11 – fine sands; 12 – loam with organic matter; 13 – marl clay; 14 – dense sands; WL1 – water level; WL2 – changed water level due to the barrage effect; L_{lim} – the limit between protective areas of two buildings; b_1, b_2 – the maximal width of the compressed zone under the foundation; tH – filled soils, aH – alluvial soils, sands and loamy sands, $₽_{2\ kv}$ – clay marl of kyyivska suite, $₽_{2\ bc}$ – sandy soils of buchatska suite.

The distance from new buildings to existing buildings is a major parameter. A reduction in the distance threatens to changes in geological environment and leads to damage or destruction of the buildings. Therefore, the question of the limit distance (L_{lim}) between the security zone and the active compressed zones of new objects is relevant for the build at the intersection of various functional zones of the city (Fig. 2).

The appearance the barrage effect is most likely at a perpendicular location of long axis of new buildings with the direction of unloading of underground water. The value L_{lim} should be calculated taking into account the geometric parameters of the foundation and to consider depth of groundwater:

$$L_{lim}=(b_1+b_2)/2+W, \quad (1)$$

b_1, b_2 – the width of the compressed zone under the foundations of neighboring buildings, W – the distance at which the barrage effect is minimized.

3.2 Changes in soil water content

The territory of the experimental site refers to the potentially flooded by waters of the "perched water" and the main aquifer. There are two water levels. The first aquifer of the type "perched water" lies at a depth of 2.1 to 4.0 m, this layer is low-power. Its formation is associated with atmospheric precipitation, which are trapped in the relatively impermeable lenses of the loamy soil. The second aquifer formed in deluvial loam, sandy loam and alluvial sands is more powerful. The confining layer of this aquifer is the marl clay of the Kievan suite of the Paleogene.

Sandy-clay soils are the bases of all structures in this area, and change the bearing capacity depending on the soil water content. The changes in the strength parameters of soils depending on their humidity are shown in the diagram (Fig. 3).

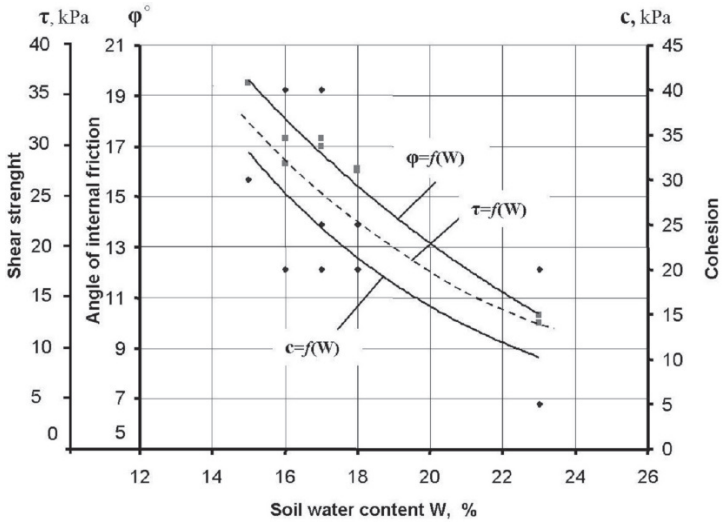

Fig. 3. The graph of the dependence of the shear strength, the angle of internal friction and the cohesion of the quaternary loamy sands from the water content.

In the modeling of the situation of saturation of the soil bases through raising the level of groundwater by 10 m (the appearance of the "perched water"), using the Coulomb-Mohr model, it was established that the value of the active pore pressure increased by 44 % (to -398.77 kPa), the effective stresses decreased by 16% (to 872.52 kPa), which led to an increase in deformations under the foundations of buildings up to 62 % (total displacement $182.45 \cdot 10^{-3}$ m). The modeling showed that the greatest influence on the formation of plastic zones and the development of processes of subsidence occurs under the construction of shallow laying, in particular the metro station.

The decrease of the strength as a result of additional moisture can lead to emergency situations [5, 6]. During the digging of the pit for construction of the metro station "Demiivs'ka" in January 2006 an accident occurred: wall which protected the foundation from the side of the school suddenly collapsed, and there was an ejection of the soil into the pit. The accident location is shown in the Fig. 2, (5). There was a failure of a number of communications and the traffic was blocked for a few days. The causes of the accident include the coincidence of anthropogenic and natural factors: as a result of the rising water content of the loamy sand by leakage from the water supply and further expansion of the soil after frost.

3.3 The influence of the traffic induced vibrations

The library complex with the high-rise building is located in the zone of influence of several dynamic sources: the traffic junction the Moscovs'ka Square; Holosiivskyi Ave. with heavy traffic (average value 3.8 thousand vehicles per hour) Nauky Ave. (average value 4.2 thousand vehicles per hour) and the metro station "Demiivs'ka".

The vibration level from automobile and rail transport generated in the range of 10-120 dB [3], which initiates the displacement of soil particles at high speeds (from 6 to 200 μm/s). The level of the oscillations in a geological environment from such number of

sources can be compared to weak earthquakes in the 1-2 level in the MSK-64 scale. The level of vibration from metro stations of shallow laying exceeds 4 times the seismic noise [7].

On the seismic noise, which is the result of either remote areas of earthquakes, or geodynamic activity of that area, vibrations from these sources are distributed in the soil environment, mainly in the upper part of a thickness up to 10-15 m, transmitted to the foundations and building construction of the library and other objects.

The basis of the foundations is the thickness of the loamy sand of loess-like type from 9 to 16 m. The velocity of propagation of seismic waves in loamy sand is 220 m/s, and at the additional moistening is increased to 275 m/s. If the water level rises to 4 or to 2 m, the seismic intensity will increase on 0.6 or 0.8 of the level in the MSK-64 scale, respectively.

If the oscillation frequencies from one or more sources come in resonance with the natural frequencies of the soil bases or foundations of the building, the amplitudes of the displacement can increase in 10-12 times [3], which may be affected by the additional expansion of the cracks or the increase of their number in the building structures.

Since the building is constructed in parallel with the axis of tunnel of the subway, therefore, its lowest resistance is in the plane normal to the longitudinal axis.

The vibration analysis of the high-rise building under the action of seismic waves based on the work of the pile foundation as a rigid body held relative to the longitudinal axis passing through the center of the building at the level of the cap. To determine contact stresses and forces acting on the construction from the piles, the soil is taken as the Winkler model to simplify the calculations. Dynamic impact from the metro station were determined by the parameters of the soil vibrations. Taking into account the shallow laying of the metro, it is possible to accept, that the maximal effect of the oscillation waves on piles is occur in the horizontal direction.

The vibration equation of the beam as the beam of vertical position under the action of horizontal wave is:

$$\frac{EI}{l^4}\frac{\partial^4 \upsilon}{\partial x^4} + \mu\frac{\partial^2 \upsilon}{\partial t^2} + \upsilon C_z D = C_z D(u_1 + u_2) \tag{2}$$

E – a module of elasticity of the beam material, MPa; I – a moment of inertia of the cross-section of the beam, m^4; l – the insertion length of the pile, m; μ – the linear mass of piles, kg/m; υ – the function of moving the beam; u_1, u_2 – the moving in the coming and reflected waves, m.

$$u_1 = u_2 = u_0 \cdot sin\omega t \tag{3}$$

ω – circular frequency of the coming seismic waves, s^{-1}; D – the diameter of the pile, m; Cz – the compression ratio for the Winkler model, kN/m^3.

The calculation of action on the building from piles, enclosed in the cap was done, not accepting to the calculation the horizontal moving of the cap in relation to piles at such boundary conditions:

$$x = 0 \qquad \frac{\partial^3 \upsilon}{\partial x^3} = \frac{\partial^2 \upsilon}{\partial x^2} = 0 \tag{4}$$

$$x = l \qquad \upsilon = \frac{\partial \upsilon}{\partial x} = 0 \tag{5}$$

The coefficients of the normal forms are determined by formulas:

$$a_i = \frac{2C_z D u_0 \int_0^1 X_i dx}{\mu(p_i^2 - \omega^2)}, p_i^2 = \frac{C_z D + k_i^4 \frac{EI}{l^4}}{\mu} \tag{6}$$

$$\int_0^1 X_i dx = \int_0^1 (V(k_i x) - \frac{T(k_i)}{S(k_i)} U(k_i x)) \cdot dx = \frac{chk_i \cdot cosk_i - chk_i - cosk_i}{2K_i S(k_i)} \tag{7}$$

the value of k_i^2 is given in the Table 1 (for four forms of oscillations), S, T, U, V – the function of N. Krylov [8].

Table 1. The coefficients of the *i*-th natural frequency.

i	1	2	3	4
k_i^2	3,516	22,03	61,67	120,9

For high-rise part of the building:

$$E = 3 \cdot 10^{10}\ Pa; l = 17{,}8\ m$$

$$I = \frac{\pi}{4} r^4;\ \ r = 0{,}4\ m;\ \ I = 200{,}96 \cdot 10^{-4}\ \ m^{-4}$$

$$\mu = 2{,}7 \frac{\pi D^2}{4} 10^3 = 1{,}36 \cdot 10^3\ kg \cdot m^{-1}$$

$$p_1^2 = 2{,}4 \cdot 10^4\ s^{-2};\ \ p_1 = 119{,}3\ \ s^{-1};\ \ f_1 = 19\ Hz$$

$$p_1^2 = 2{,}7 \cdot 10^4\ s^{-2};\ \ p_1 = 140{,}7\ \ s^{-1};\ \ f_1 = 22\ Hz$$

$$p_1^2 = 3{,}8 \cdot 10^4\ s^{-2};\ \ p_1 = 242{,}4\ \ s^{-1};\ \ f_1 = 38\ Hz$$

$$p_1^2 = 10{,}7 \cdot 10^4\ s^{-2};\ \ p_1 = 431{,}08\ \ s^{-1};\ \ f_1 = 68\ Hz$$

The reaction to the action of piles in the cap:

$$P_i = \frac{EI}{l^3} \cdot a_i X_i''(0) \tag{8}$$

$$P = \sum_{i=1}^{3} P_i = 1{,}5 + 4{,}7 + 61{,}3 = 67{,}5\ N$$

The moment acting from the piles on the cap:

$$M = \frac{EI}{l^2} \sum_{i=1}^{3} a_i X_i''(0) \tag{9}$$

$$M = \frac{3 \cdot 10^3 \cdot 200{,}96 \cdot 10^{-4}}{17{,}8^2} \cdot \left(0{,}49 \cdot 10^{-6} \cdot 8{,}45 + 0{,}27 \cdot 10^{-6} \cdot 54 + 0{,}53 \cdot 10^{-6} \cdot 147{,}5\right) = 184{,}4\ \text{Nm}$$

If this calculation continues for the option of free bearing of the cap on the pile, the effect of the horizontal force will decrease, and the bending moment is eliminated. However, in this case, since the building is high, the condition of enclosed of the piles into the cap is necessary.

Reduce of the influence of lateral forces depends on the ratio of the frequencies of piles and frequency of oscillations, which are excited by waves. It is possible only with a special arrangement of piles in any ratio between own and forced frequency. The piles are perpendicular to the front of the propagation waves and have distance between them equal integer number of waves.

4 Conclusions

Violation of the conditions of safe habitation in cities is connected with the unsuccessful placement of objects of different functional zones that have different degrees of safety of the inhabitation of people. It happens in case of hazardous engineering-geological processes, together with emergency situations. Changing the water level and change in soil water content have the most dangerous influence among the considered effects. The effect of soil water content is indirect and showed itself in the following:

– the increase of pore pressure at raising the water level leads to changes in the redistribution of stresses in the underground space, and the increase of vertical displacements of soil particles, decreases the maximum distance between buildings;

– the increase in soil water content leads to an increase in the velocity of propagation of longitudinal waves, therefore, in percolated soils, the distance distribution of the dynamic load increases and can reach the object, the distance to which from sources does not corresponds to the standards.

In built-up areas, leakages from engineering networks (water supply) that occur due to an emergency state of communications, and excessive atmospheric precipitation, which depend on the condition of storm drains and drainage structures are main sources that lead to changes in soil water content.

The close location of high-rise buildings on piles to residential buildings on shallow (tape or slab) foundations is hazardous in the case of high occurrence of the first aquifers. The raising of the groundwater level due to the barrage effect through the dense arrangement of piles can lead to uneven settlement and the buildings roll of residential buildings in the direction of high-rise buildings.

The comfort of staying in a building with a close location of transport routes depends on the parameters of the damping of the type of soil, its physical condition and the structural design of the foundations. The calculation showed when the free supporting the piles on the caps occurs less impact for a modern high-rise buildings.

Today, legislation regulates zoning of settlements only on the surface (horizontal). The widespread intervention into the underground space (on the territory of Kiev of the 1970-ies has built more than 1000 high-rise buildings with an underground depth from 25 to 80 m).

The influence of the underground part of a new or reconstructed engineering object should not interfere with the deepening zone of other existing building. Therefore, the development of standards for deep (vertical) zoning become relevant, that should be done depending on the geological features of the built-up area and surrounding buildings.

The functional zones of the city should be developed taking into account not only the social and economic-planning factors, but also to compare it with the engineering-geological conditions, the geodynamic features of the territory (tectonic disturbances, changes in the lithological composition of the soils, etc.), anthropogenic load of the territory (building, etc.), that is connected with the safety of people.

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