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Soil failures during construction on the slopes in Kyiv

Pannes de sol lors de la construction sur les pentes de Kiev

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ABSTRACT: The report authors as the main developers of the Ukrainian building codes for landslide protection structures may note that many questions regarding the various factor's consideration in the calculation of landslides and landslide pressure on landslide protection structures remain unanswered and need clarification. This led and continues to lead to ground failures. The theoretical and methodological problems of landslide protection structures calculation can be reduced to two main problems. The first problem is the safety criteria correct definition for the surrounding development when assessing the landslide risks for the pit walls under the new building on the slope. The second problem is the determination of the shearing pressure critical level, at which the landslide protection structure load level will correspond to the structure work beyond the elastic limit. Unfortunately, any single procedure for solving these two problems is not legalized at the building standards level in Ukraine today. Therefore, the main purpose of the report is a detailed critical analysis of two ground failures of new retaining walls during the construction of (1) a multifunctional complex on the landslide hazard slope of Staronavodnytska Ravine in Kyiv and (2) the enclosures of the pit for the construction of an office center with underground parking on Strutynskoho St. in Kyiv.

RÉSUMÉ : Les auteurs du rapport, en tant que principaux développeurs des codes du bâtiment ukrainiens pour les structures de protection contre les glissements de terrain, peuvent noter que de nombreuses questions concernant la prise en compte des différents facteurs dans le calcul des glissements de terrain et des structures de protection contre les glissements de terrain restent sans réponse et nécessitent des éclaircissements. Cela a conduit et continue d'entraîner des défaillances au sol. Les problèmes théoriques et méthodologiques du calcul des ouvrages de protection contre les glissements de terrain peuvent être réduits à deux problèmes principaux. Le premier problème est la définition correcte des critères de sécurité pour le développement environnant lors de l'évaluation des risques de glissement de terrain pour les parois de la fosse sous le nouveau bâtiment sur la pente. Le deuxième problème est la détermination du niveau critique de pression de cisaillement, auquel le niveau de charge de la structure de protection contre les glissements de terrain correspondra au travail de la structure au-delà de la limite élastique. Malheureusement, aucune procédure unique pour résoudre ces deux problèmes n'est aujourd'hui légalisée au niveau des normes de construction en Ukraine. Par conséquent, le principal objectif du rapport est une analyse critique détaillée de deux ruptures au sol de nouveaux murs de soutènement lors de la construction (1) d'un complexe multifonctionnel sur la pente de risque de glissement de terrain du ravin Staronavodnytska à Kiev et (2) des enclos de la fosse pour la construction d'un centre de bureaux avec parking souterrain sur la rue Strutynskoho à Kiev.

KEYWORDS: Ground failure, landslide hazard slope, shearing pressure, calculation, landslide protection structure.

1 INTRODUCTION.

Over the last decade, from 2000 to 2009, natural disasters damaged and destroyed about one million objects, directly affecting nearly 2.5 billion people worldwide (Lacasse 2013). Every year about 20 major landslides occur in Europe, which is much more than the number of floods, earthquakes, and hurricanes. The problems of life security and limited resources economical use are the main priorities for every family, country, and especially for the countries with economies in transition, which also defend their independence as, for instance, Ukraine resisting Putin's Russian military aggression. The correct consideration of shear loads during the new landslide protection structures construction or existing ones reconstruction will allow Ukraine to successfully overcome the above problems in the context of global warming, natural and man-made disasters intensification, and limited economic resources available. The paper authors as the main developers of the Ukrainian building codes, including DBN A.2.1-1-2008 (BN A.2.1-1-2008) "Surveying, designing and territorial activities. Surveys.

Engineering surveys for construction"; DBN V.2.1-10-2009 "Bases and foundations of buildings. Basic design provisions", DSTU-N B V.2.1-32: 2014 "Guidelines for the pits design for the foundations and embedded structures arrangement", DSTU-N B V.2.1-31: 2014 "Guidelines for the retaining walls design", DBN V.2.1-10: 2018 "Bases and foundations of buildings and structures. Basic provisions" (replacing DBN V.2.1-10-2009), DBN V.1.1-12: 2013 "Construction in seismic areas of Ukraine" and others. It should be noted that many questions regarding the various factors consideration in the calculations of landslides and shearing pressure on landslide structures remained unanswered in the mentioned documents, which caused and continues to cause various ground failures and damages in Ukraine. So, such problems need clarification and further researches. The issues of prevention and counteraction to landslide accidents and disasters were considered in many works of such domestic and foreign researchers as Barla et al. 2014; Bobrowsky, Highland 2008; Casagli, et al. 2010, 2018; Fareniuk et al. 2018; Ishchenko et al. 2009, 2015; Kaliukh et al. 2018, 2020; Kryvosheiev et al. 2017;

Lacasse 2013; Lollino et al. 2006; Lugli et al. 2016; Matveev et al. 2009; Picarelli et al. 2019; Siedin et al. 2017; Slyusarenko et al. 2013, 2015; Shokarev et al. 2017; Take, Bowman 2018; Tytarenko et al. 2017; Trofymchuk et al. 2018, 2019; Ulitsky et al. 2017; Urciuoli et al. 2019; Vlasyuk et al. 2015, 2019; Zhukovskaya et al. 2015, 2019; Zhukovskyy et al. 2019. According to their researches, the theoretical and methodological problems of the landslide protection structure calculation can be reduced to two main problems. The first problem is to correctly define the safety criteria for the surrounding buildings when assessing the landslide hazard of the pit walls under the new building on the slope. The second problem is to determine the shearing pressure critical level, at which the level of load on the landslide protection structure will correspond to the structure work beyond the elastic limit. Unfortunately, today in Ukraine there is no single legalized procedure for solving these two problems at the construction standards level. Therefore, the report is aiming at a detailed critical analysis of the ground failures with the new retaining walls during the multifunctional complex construction on the landslide hazard slope of the Staronavodnytska Ravine in Kyiv and the pit enclosures construction for the office center with underground parking on Strutynskoho St. in Kyiv in order to contribute to the Ukrainian building codes improvement in their new versions.

2 CASE STUDY 1. GROUND FAILURE IN THE COURSE OF THE MULTI-STOREY GARAGE CONSTRUCTION ON THE LANDSLIDE HAZARD SLOPE OF THE STARONAVODNYTSKA RAVINE

The multi-storey garage at Staronavodnytska Street, 2-20 in Kyiv includes the buildings and structures complex for cars parking, repair and movement; the administrative and auxiliary purposes buildings; the engineering structures in the form of retaining walls. Geomorphologically, the construction site is located on a stabilized landslide hazard area. The absolute elevations on the ravine slope vary within 140.50 ... 178.60 m. The height difference reaches 38.1 m. According to engineering and geological surveys, the geological structure up to the explored depth of 30.0 m is composed of a complex of Quaternary and Neogene deposits represented by sands, sandy loams, loams and clays, covered from the surface with a filled soils layer. During surveys, the groundwaters are found in some boreholes mainly at depths of 1.7 m to 9.6 m, depending on the terrain and geological structure. The gray-brown clays serve as a waterproof layer for groundwaters. The groundwaters unevenness in depth and in plan is associated with the terrain complexity, geological structure, and drainage system operation. The "perched water" type groundwaters on the surveyed area are found in boreholes at the depths of 5.0 and 4.5 m from the day surface (absolute elevations of 152.71 and 162.51 m, respectively). The perched waters movement on the surveyed area is directed down along the ravine slope, and their flow is gradually dissipated (free groundwater table is not recorded). The groundwaters recharge on the ravine slope is due to atmospheric water infiltration, industrial waters leakage from the municipal water supply systems and drainage system malfunction. The site belongs to the flood hazard areas by its potential underflooding degree. The complex of landslide protection and retaining structures includes the Ø 620 mm CFA piles with a 700-mm spacing in axes and variable lengths from 13.3 m to 14.85 depending on the terrain, made to the absolute elevation of 150.9 m and combined with each other in a single ground beam; the Ø 620 mm CFA piles with a 700 mm spacing in axes and a length of 14.2 m, made to the absolute elevation of 151.1 m and combined into a single ground beam; the Ø 620 mm CFA piles with a 800 mm spacing in axes and variable lengths from 13.3 m to 14.85 m depending on the terrain, made to the

absolute elevation of 150.9 m and combined with each other into a single ground beam etc. In some axes the piles are arranged in a checker-board order and combined with each other into ground beams along axes; the piles have lengths of 14.2 m and the pile toes absolute elevations are 151.1 m.

The intensive soil development lasted from 18.11.2003 to 01.12.2003, and after soil excavation from the pit in the Y... H/1 ... 39 axes to the absolute elevation of 155.95 m the landslide protection structures could not withstand shearing pressure and began to displace in the pit direction, which has led to a ground failure and an emergency situation in the civil structures of landslide protection structures (Figure 1). When the landslide protection structures deformations increased almost twice and their walls horizontal displacements reached 835 mm, the soil excavation from the pit was stopped. But the landslide protection structures horizontal deformations continued to increase and on 12.12.2003 the displacement amount reached 1093 mm. That meant that a shear body had formed on that portion of the slope. It was clearly indicated by the crack of stabbing, which appeared higher on the slope and increased in time, plan, and depth. Detailed photographs of the stabbing crack above the landslide protection structures on the slope beyond the Y" axis as of 28.11.2003, 14.12.2003 and 21.12.2003 are shown in Figure 1.

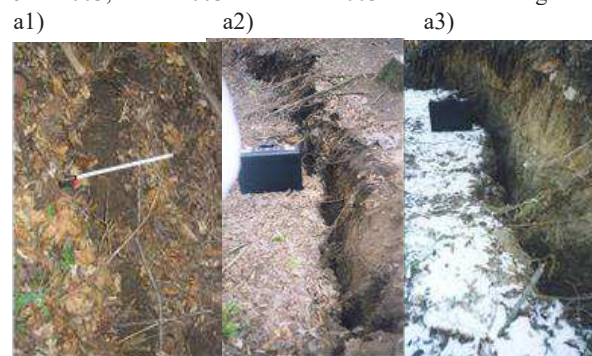


Figure 1. Stabbing crack above the landslide protection structures along the slope as of: a1) 28.11.2003; a2) 14.12.2003; a3) 21.12.2003.

The left and right wings of the upper tier retaining wall received the significant horizontal displacements (1000-1200 mm and more), which caused the reinforced concrete ground beam destruction by vertical cracks with the widths of up to 50 mm due to retaining walls continuous horizontal displacements along the Y... Y" axes in the 1... 12 axes and the emergency situation initiation. The deformations ("bending" under the shearing pressure action) of the garage complex enclosure piles ground beam along the Y axis in the 31 ... 39 axes are shown in Figure 2. (A-B). The further soil deformations could lead to a larger ground failure and deformations of building structures located above the buildings of a multi-storey urban development. To save and correct the situation, as well as to perform the project documentation comprehensive analysis and audit, existing structures visual inspection and mathematical modeling of the stress-strain state of the garage complex slopes and building structures, the concept and principles of landslide protection structures construction in restrained urban development were used. It was decided to improve the general concept of the multi-storey garage structural solution. According to the revised design version, the load-bearing structures of the multi-storey garage retaining walls had to be located in a cascade on the slope; be interconnected by underground elements and held by the load-bearing elements of the buildings frames, forming a single rigid spatial system. Based on this concept, the appropriate mathematical models of the complex buildings were developed and calculated, taking into account both traditional loads and

influences from retaining walls, which already had significant horizontal displacements at that time.



A). State as of 28.11.2003 B). State as of 17.02.2004 B). State as of 13.10.2004

Figure 2. Ground failure: the deformations (bending under the shearing pressure action) of the garage ground beam piles

To determine the slope stability taking into account its undercut for the construction, the mathematical modeling of the soil mass together with the pit enclosure structures was performed; the slope stability was assessed using the Morgenstern and Price, Bishop, Janbu and finite element methods with the assumption that sliding surfaces had a circular cylindrical shape or were assigned in the form of broken lines.

The following conclusions are made:

1. The building load-bearing system includes columns and stiffening diaphragms integrated into a spatial system by the floors disks resting on the foundations system composed of the piled ground beam. The stiffening diaphragms, in addition to taking up the vertical loads, ensure the building rigidity in the shearing pressure direction and transfer the load from the slope soils to the foundations and the underlying base soils. In the calculations, B30 grade concrete is taken for superstructures and B25 grade concrete is taken for the structures of foundations. The building loads include the building dead weight, payload, as well as snow and shear loads. The shear loads are obtained by means of the analysis of slope stability calculations results.

2. A complex three-dimensional computer model of the building is developed. It consists of two substructures operating in a unified automatic mode and combined at the level of contact with the base. Based on the slope calculations results with an allowance for the existing retaining landslide protection structures along the Y' and Y axes in the 1 ... 12 axes, it is found that the obtained slope stability number (0.954 ... 1.111) is less than its normative value.

3. As the slope continuously displaces with retaining structures and the already erected landslide protection structures are insufficient for the slope stabilization, a need arises for additional measures to stabilize the slope deformed state.

4. The carried out numerical studies show that the arrangement of ground anchors with 60 t working tension along the Y axis at the top of pile row ensures the slope stability with the coefficient of 1.351 ... 1.354. When the tension force is 20 t, it will be in the range of 1.092 ... 1.212, and if the soil backfill arrangement in the Y ... H1/7... 10 axes is taken into account, it will belong to the range of 1.138 ... 1.340].

To stabilize the structures retaining the slope along the Y ... Y'' axes in the 1 ... 12 axes, the following works were performed: the retaining wall strengthening along the Y'' axis by installing the inclined ground anchors via a multi-span metal spreading beam; the retaining walls pile rows inclusion into the joint operation along the axes Y' and Y'' by their integration by connecting elements at the ground beam level; the walls rigidity increasing in the axes Y ... Y'' by installing the tie-spreaders in the form of reinforced concrete beams and thus creating a spatial retaining structure, the stability of which will increase at the subsequent

construction stages; the soil backfilling in the Y ... H1/7... 10 axes; the slope cutting beyond the Y'' axis in the 5... 12 axes.

As a result of the performed works, shear deformations at all construction sites of the multi-storey garage were stabilized and stopped, which was confirmed by later geodetic surveys. It was decided to improve the general concept of the multi-storey garage structural scheme. According to it, the load-bearing structures of the retaining walls of a multi-storey garage had to be arranged in a cascade on the slope; be interconnected by underground elements; be held by the load-bearing elements of the buildings frame to form a single rigid spatial system.

3 CASE STUDY 2. PIT WALLS GROUND FAILURE IN THE COURSE OF THE CONSTRUCTION ON THE STRUTYNSKOHO STREET IN THE RESTRAINED URBAN DEVELOPMENT CONDITIONS

Geomorphologically, the construction site is located within the right slope of the Staronavodnytska Ravine in Kiev, complicated by various runoff hollows and man-made factors (soils filling and undercutting, or housing development). The day surface absolute elevations vary within 138.500 ... 160.000 m. The site geological structure includes a deluvial deposits stratum with a thickness of 15.0 to 24.0 m, which corresponds to the absolute elevations of 121.500 ... 124.000 m. Based on the engineering and geological surveys, and field and laboratory studies of soils physical and mechanical properties, 15 engineering-geologic elements (EGE) were identified. The site hydrogeological conditions are characterized by two aquifers presence. The both aquifers move down the slope towards Druzhby Narodiv Boulevard and further towards the Dnipro River. The construction site belongs to the II (medium) category of the engineering and geological conditions complexity. The pit for construction has a closed and complicated configuration in plan and height. It is surrounded by 7 buildings that fall into the pit influence zone. The pit and surrounding buildings layout plan is shown in Figure 3, where:

D1 is a one-storey brick non-residential building (shop). The minimum distance from the building to the pit enclosure outer perimeter is approximately 9.5 m;



Figure 3. – The layout of the construction site and surrounding development buildings and structures

D2 is a two-storey brick residential building. The distance from the building to the pit enclosure outer perimeter is approximately 13.0 m (design section H) and 18.0 m (design section I);

D3 is a two-storey brick residential building. The distance from the building to the pit enclosure outer perimeter is 5.5 m;

D4 is a one-storey brick residential building. The distance from the building to the pit enclosure outer perimeter is 30.0 m; D5 is a two-storey brick residential building. The distance from the building to the pit enclosure outer perimeter is 23.0 m; D6 is a residential brick building. The distance from the building to the pit enclosure outer perimeter is approximately 12.0 m; D7 is a two-storey non-residential building (gas station building). The distance from the building to the pit enclosure outer perimeter is 9.0 m.

The construction complexity is caused by the presence of two niches in the slope upper and lower parts and the difference in its heights. Under the horizontal loads action, the upper niche becomes a weak part in the enclosure. The structural scheme of the pit sheet piling is represented by a system of secant bored piles of $\varnothing 1020$ mm and variable lengths of 11.0; 12.0; 28.0; 33.0 and 37.0 m with 750 mm spacing in the axes, which are combined by a reinforced concrete ground beam. There are four buttresses in the highest part of the enclosure wall. The upper niche is built up from top to bottom with the arrangement of the floor discs in thrust with the enclosure piles. These structures provide a thrust in the weak enclosure part and are arranged before the pit soil excavation. The next piles but one are reinforced. The absolute elevation is 112.000 m for the reinforced piles points and 123.800 m for the unreinforced piles points. The base for the pit enclosure reinforced piles is composed of EGE-13 soils (clay layer is covered with light, silty, stiff, or hard loam). The absolute elevation of the pit bottom is 128.000 m. The free height of the pit enclosure wall varies from 10.0 to 21.0 m, depending on the location on the slope. The preliminary calculations were performed similarly to the planar problem, which did not consider the stratification nature of the soil environment surrounding the pit enclosure structure, as well as its spatial closed circuit. That is why the calculations results were overestimated. Thus, when a borehole for an anchor was drilled, in the house at Michurina St., 15 (south wing) the new cracks arose, and, in addition, new cracks were noticed in the structures located on the adjacent territory (Figure 4).



Figure 4. – Cracks within the building at Michurina St., 15 (the south wing)

Until 05.02.2011, the new cracks occurrence or existing ones opening were not noticed, but the cracks development was fast progressing after that date. The anchors arrangement for shoring the pit walls (Figure 3) caused the buildings subsidence around the pit and their destruction beginning (Figure 4). To ensure the

stability of the pit enclosure wall, inclined ground anchors with pre-tensioning are designed. The anchors are arranged in tiers via non-reinforced piles with the use of distribution metal beams at 10° , 15° and 17.5° angles to the horizon. According to the free height of the pit enclosure wall, 2 to 8 tiers are designed; the anchors length is from 15.0 to 38.5 m (including the root length of 5.0 and 8.0 m). The total number of anchors is 664 pcs. The value of the anchors pre-tension is from 200.0 to 851.0 kN. To calculate the pit enclosure wall, a spatial plate and rod based finite element model is developed, the general view of which is presented in Figure 5.

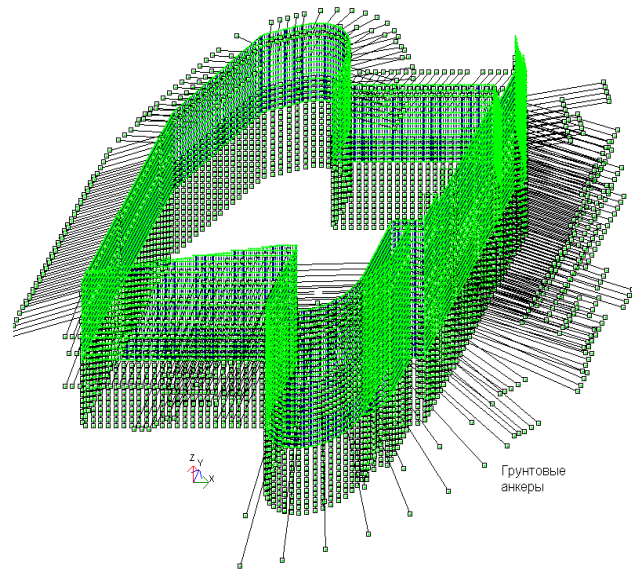


Figure 5. The pit enclosure calculation model. General view: грунтовые анкеры - ground anchors.

The reinforced piles work is modeled along the entire heights of their shafts by rod elements. The rigidity characteristics of each of the rod elements are assigned as for the material of bored piles with a cross section of $\varnothing 1020$ mm made of B30 grade concrete. To model the structure interaction with the soil base in the horizontal direction, such soils characteristics around the piles as the index of liquidity IL and the void ratio e are used. The retaining wall is designed with an allowance for the soil properties in accordance with the current Ukrainian standards. To model the soil base rigidity in the horizontal direction (along the OX and OY axes), in the nodes of laying out the working pile shafts the finite elements with one-directional rigidity in the horizontal directions are installed starting from the pit excavation depth level to the pile tips level (elevation of 128.000 m). Such rigidities values specified for the finite elements are determined depending on the piles calculated portions embedment and the soils characteristics in accordance with the current Ukrainian standards. Besides, the features of the soils lithological structure around the piles are taken into account in accordance with the results of engineering and geological surveys at the construction site. To model the non-reinforced piles operation, the plate finite elements, which are connected by ties with rod finite elements simulating the working piles operation, are used. The rigidity characteristics of these elements are specified based on the structures material elasticity modulus and geometric parameters. The pile ground beam work is modeled by rod finite elements with the following characteristics: the elasticity modulus value is specified as for a material of B30 grade concrete and the geometrical characteristics are accepted according to the pit enclosure working drawings, namely, cross-sectional width of

ground beam elements is 1200 mm and cross-sectional height is 800 mm. The pit enclosure wall was calculated for the situation with the pit excavation to the 128.000 m elevation and the installation of all anchors envisaged by the project, in plan and by height of the pit enclosure structure. The calculation results are shown in figures 6 and 7.

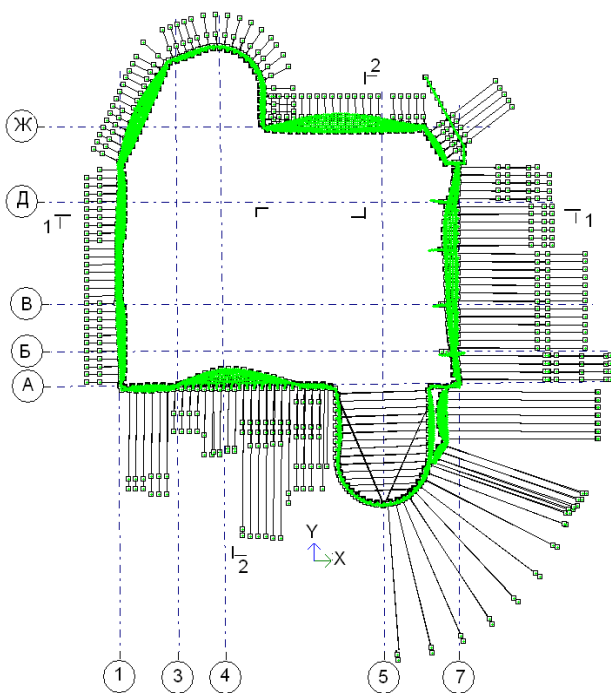


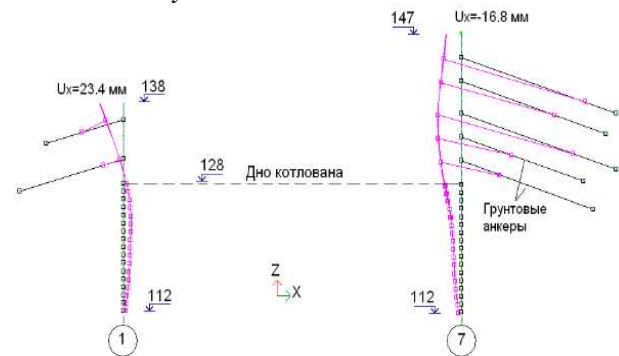
Figure 6. General view of the pit enclosure deformed state

In Figure 6 it is seen that the enclosure deformations differ in the various wall parts. The maximum displacement value in the ground beam level is 16.8 mm in the first case and 33.3 mm in the second case (see Figure 7). The horizontal displacements of the calculation model nodes along the piles entire lengths are directed inside the pit. At the elevation level of 130.000 m the wall displacement amount is 25.1 mm along the 7 axis and 26.1 mm along the A axis. On the areas along the 1 and Ж axes, the pit enclosure wall upper part deviates on the area above the pit bottom towards the soil mass by 23.4 mm in the first case and by 8.3 mm in the second case. The piles are bent into the inside of the pit in their embedded parts. The obtained behavior of piles deformations is explained by the following factors: the pit enclosure wall areas along the 7 and A axes are located in a higher part of the slope and are subject to a high soil pressure with the free length of piles being 15... 21 m along the 7 axis and 10... 17 m along the A axis. However, the obtained values of the pit enclosure horizontal displacements are not such that could cause the deformations of the area adjacent to the pit. By applying a certain scheme of the pit excavation and installation of retaining structures such as the foundation slab inside the pit in accordance with the soil excavation progress, it is possible to reduce the structures deformations. The piles free length on the wall areas along the 1 and W axes is about 9 m.

The number of anchors and their tension forces turned out to be sufficient to take up the soil pressure on the pit enclosing structures. The presented calculation results reflect the outcome - the pit excavation up to the 128.000 m elevation. The structures deformations are influenced by the very process of performing works on the pit excavation and installing anchors, since these works are mutually linked, and, in fact, mutually opposite. On

the one hand, the soil excavation in the pit weakens the soil layer retaining power, but, on the other hand, the anchors number and their tension degree determine the soil retaining power.

Cross section by 1-1



Cross section by 2-2

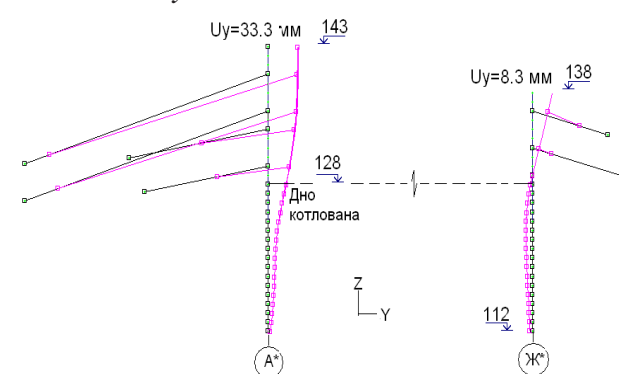


Figure 7. Schemes of the piles and ground anchors deformation s at individual segments of the pit enclosure wall: cross section by 1-1; cross section by 2-2; дно котлована – pit bottom; грунтовые анкеры – ground anchors

4 CONCLUSIONS

1. The report presents the detailed critical analysis of two ground failures of the new retaining walls during the construction of the multifunctional complex on the landslide hazard slope of Staronavodnytska Ravine in Kyiv and pit enclosures for the office center with underground parking on Strutynskoho St. in Kyiv. Both objects are erected on the landslide hazard slopes. In the first and second cases, due to the systematic disregard for the landslide hazardous factors, a critical synergistic effect of the landslides activation was achieved, which in both cases caused the ground failures.
2. For both cases, the practical measures that made it possible to stabilize and completely stop landslide activity near the construction sites and allowed the pits soil excavation up to the design elevations and the complexes construction completion are described.

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