Landslides
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Landslide protection of the historical heritage in Odessa (Ukraine)

Abstract This study focuses on the specifics of modern geological conditions and deformations of landslide-affected slopes within the historical center of the city of Odessa. Landslide protection was developed in the 19th century and during 1960s on adjacent coastal areas, according to urban planning and landslide protection plans. The historical center was formed around the Odessa port and includes several unique architectural monuments such as the 142-m-long Potemkin Stairs, Primorsky Boulevard, and the Odessa Opera Theater. Architectural and urban planning designs in the city include landslide protection and preventive measures. Results of landslide studies show that landslide development along the Odessa coast is influenced primarily by tectonic movements and the heterogeneity of the geological substrata. All historical and contemporary protective and preventive landslide measures maintain their engineering geological integrity and effectiveness despite the differences in time of their construction and design.

Keywords Landslide protection · Slope deformation · Odessa · Ukraine

Introduction

The city of Odessa is located on the northwestern coast of the Black Sea (Fig. 1), which experiences widespread landslides and thus has become an area of continuous engineering geological investigations. The city of Odessa was founded in 1795, shortly after the first survey was conducted by Russian General Suvorov to establish the Port of Odessa in September 1794. Since 1794, Odessa became a key economic, political, and cultural center on the Black Sea. It's Byzantine and baroque architecture is still preserved and attracts numerous tourists from all over the world. The Potemkin Stairs were built in 1834–1841 and later, were commemorated by Sergei Eisenshtein in his classic film "Battleship Potemkin." The Odessa Opera Theater was built in 1887 by architects F. Felner and G. Gelmer and at that time it was considered the second most beautiful theater in Europe after the Vienna Theater.

Geology and landslide environment

From the beginning of the city's development, landslides have posed tremendous difficulties for engineers and architects to stabilize the slopes and keep architectural monuments intact. Landslide development is influenced primarily by the geological structure of the coast, hydrogeology, and geomorphology. Earlier investigations (Zelinsky et al. 1993a) show that the landslide activity extends from the upper parts of the slopes (40–50 m above msl) to 60–70 m below the surface.

The stratigraphy and lithology of the landslide-affected slope includes Meotian, Pontian, Middle–Upper Pliocene, and Pleistocene formations (Fig. 2). These formations gently dip in a southerly direction that is approximately perpendicular to the coastal slope orientation. Meotian clays are exposed along Odessa Bight above the high sea level mark; these clays are overlain by Pontic limestones, sandy and clay deposits of Upper Pliocene and Pleistocene loesses (Zelinsky et al. 1993a). The prevailing type of deposits is clay; less distributed are sandy and cemented carbonate deposits. All deposits are characterized by heterogeneous composition, lithology, and spatial distribution of their physical and mechanical properties. For the period from 1797 to 1964, the coast of Odessa experienced more than 250 different landslides of various types (Zelinsky et al. 1993a). By 1964, Odessa started the implementation of new landslide preventive and protective measures that included slope grading, drainage system, and reinforcement of the lower parts of the landslide-prone coastal areas by artificial beaches that provided necessary loading mass to prevent rotational landslides.

The variety of landslide types along the Odessa coast is the result of the structural geology of the slopes, mechanical properties of the soils, intensity of the coastal erosion, and other geological processes such as groundwater drainage and surface erosion. Along the Odessa coast, there are four types of landslides: (1) Landslide flows in Quaternary loess deposits caused by oversaturation; (2) Landslide blocks movements of loess deposits over Upper Pliocene clay surfaces that can also transform into flows; (3) Landslide blocks movements of the whole Neogen–Quaternary formation above sea level (i.e., translational type); and (4) Landslide blocks movements causing deformations of Meotian clays and developing a sliding surface below sea level, termed rotational landslides (Zelinsky et al. 1993a).

Analysis of collected data shows that the main factors influencing the landslide distribution and development are the following:

- Structural geological characteristics of the coastal deposits, such as limestone layer, weakened zones of Meotian clays based on their lithological and genetical characteristics (Zelinsky et al. 1993a), and weakened tectonic zones (Cherkez 1996);
- Erosional coastal processes that cause an increase in slope gradient and also redistribution of stresses within the landslide slope (Gorokhovich 1988b);
- Groundwater effect on stress distribution and physical–mechanical properties of the landslide slope; there are three different aquifers within landslide-affected areas on the Odessa coast: (1) in Quaternary loess deposits, (2) Pontian limestones (underlying Meotian clays, which serve as an aquitard), and (3) Sarmatian aquifer, which is below Meotian clays;
- Urbanization and economic development (Gorokhovich 1988a); these include dredging activities by seaports and increase of the water discharge in Quaternary loess deposits due to water leakages from the infrastructure in urban areas and excessive irrigation in agricultural areas on the coast.

Fig. 1 Black Sea map and location of Odessa

The present study will consider the details of the contemporary conditions and deformations of the landslide slopes within the historical center of the city of Odessa and the vicinity where landslide protective and preventive measures were implemented in the 19th and 20th centuries. Data and conclusions in this study are based on geodetic surveys of fixed benchmarks established on the landslide-affected coastal areas. These data were also compared with geophysical methods (Cherkez et al. 1991; Budkin et al. 1998) based on electromagnetic frequencies measured in the field as proxies for the stress conditions of the bedrock.

Landslide protection and preventive measures

Architectural and planning designs in Odessa targeted slope stability as the main factor that provides safety to structures. In relation to the geological structure of the Odessa coast, three main measures were used in each design: reinforcement of slope by piles or embankments, slope grading, and drainage of the groundwater. Implementation of these engineering measures in each design project ensured stability and safety of architecture and infrastructure in Odessa.

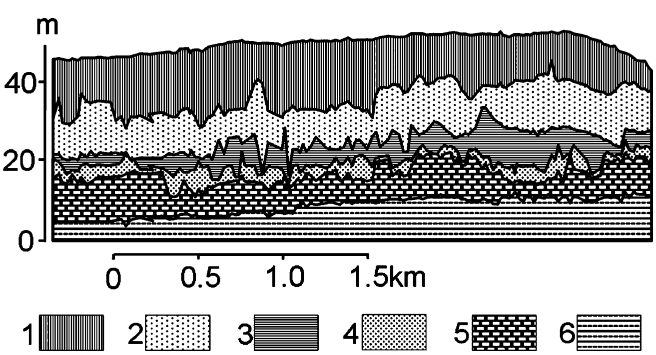

Fig. 2 Geological cross-section (south–north) along the drainage gallery of the first stage of the landslide protection in Odessa (for the location of the landslide protection complex, see Fig. 3). *1* Pleistocene loess, *2* Pleistocene loess-like loam, *3* Upper Pliocene red clay, *4* Alluvial sediments on Pontian limestone, *5* Pontian limestone, *6* Meotian clay

The first landslide protective measures were implemented in the vicinity of the Odessa sea port immediately after the city of Odessa was founded (Fig. 3). The first reinforcement structures in the port itself were built in 1815. They consisted of piles armored by stone, installed along a 100- to 159-m stretch. The construction of the embankment started in 1825–1835. The construction material for this project was taken from the lower part of the slope, which subsequently caused landslide activity. Later, in 1841, the development of the Primorsky Boulevard included the construction of the Potemkin Stairs. The Potemkin Stairs connected the embankment and the boulevard across the slope, stabilized it, and therefore fulfilled the role of a landslide protection measure.

The foundation of the Potemkin Stairs included 400 pilings that reinforced the loose material of the landslide head and upper boundary of Meotian clays. The retaining wall was located below the stabilized landslide deposits on both sides of the stairs. Several retaining walls were also built in the upper part of the slope between the Potemkin Stairs and the palace of the Odessa Mayor Voronzov (Voronzov Palace) to prevent the Primorsky Boulevard from deformation and destruction. A drainage system with surface and subsurface storm drains was also built.

During the construction of the Odessa sea port, a 100-m-long jetty was built near the low level of the Potemkin stairs to provide transportation access to the cargo and passenger ships. Its height measured 6 m and total loading (i.e., overburden stress) was approximately 300–350 m^3/1 m of the shore. The base of the jetty covered eight lower steps of the Potemkin Stairs. Wave breaking structures, retaining walls, and terraces were also built.

The realization of other landslide measures along the Odessa coast occurred during 1883. At this time the drainage tunnel was

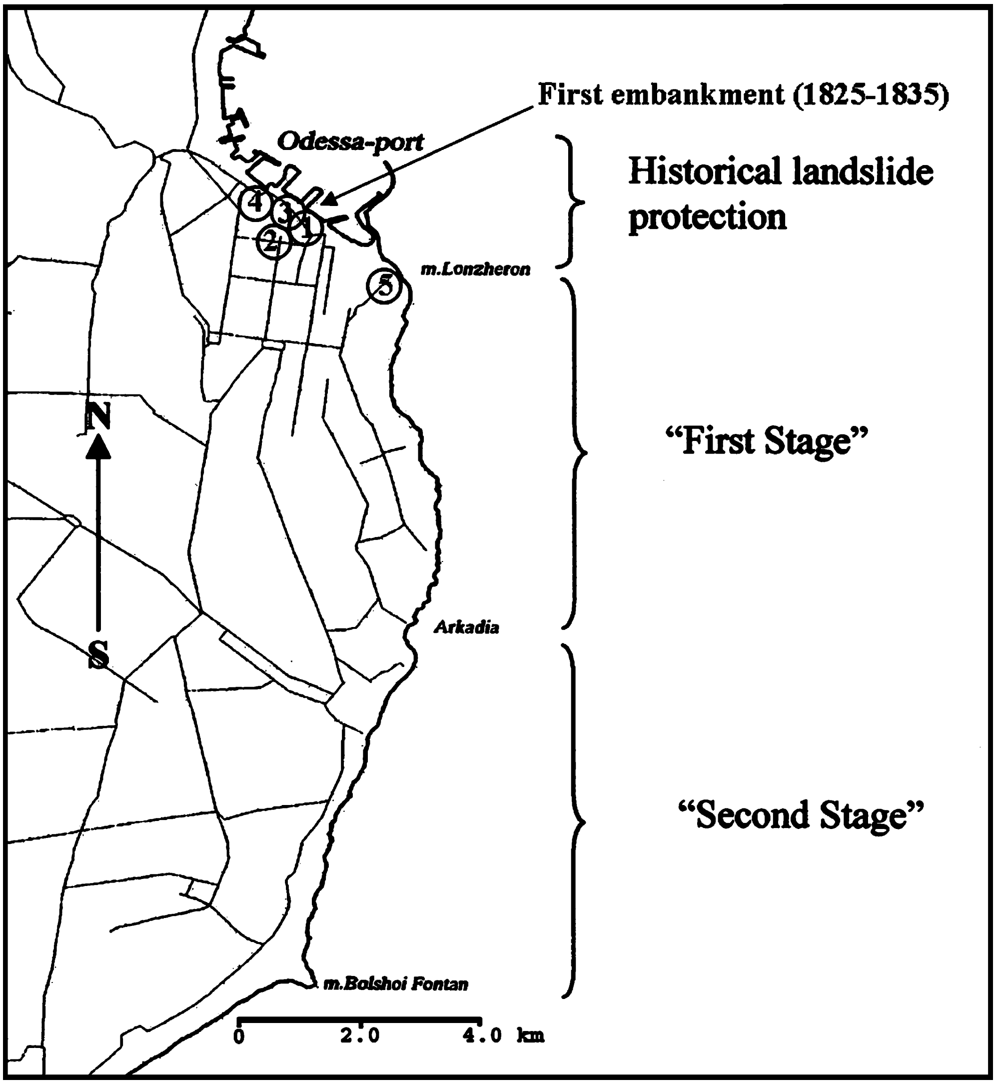

Fig. 3 Landslide protection zone along the coast from Odessa Port to Bolshoi Fontan and the various temporal stages. *1* Primorsky Boulevard, *2* Odessa Opera Theater, *3* Potemkin Stairs, *4* Boulevard of Arts, *5*–Suvorov Alley

built near Bolshoi Fountain Cape to divert groundwater flow from the Pontian limestone aquifer. However, this and similar efforts in other coastal areas did not prove to be efficient. The drains were removed later because they did not stop the landslide activity. This experiment showed that the drainage of Pontian aquifer itself was not an effective measure to prevent landslides. In addition, the jetties built along the coast were deformed right after their construction and therefore, also proved to be ineffective as the sole landslide preventive measure. However, the central historical part of Odessa and associated port territory, including embankment, the Potemkin Stairs, and Primorsky Boulevard, proved to be stable.

The new stage of the landslide protection in Odessa started in 1964 between the Lonzheron and Arkadia capes (first stage) and later (second stage) in 1970s between Arkadia and Bolshoi Fontan (Fig. 3). The design of this protective measure took into account specific geological characteristics of the Odessa coast and consisted of the following elements (Fig. 4):

- Artificial beaches and structures (jetties and wave breakers) that were designed to keep beach material intact and to prevent further wave erosion;
- Grading landslide-prone slopes to reduce their gradient and tangential stresses in rocks and embankments;
- Drainage of groundwater from the Quaternary aquifer using vertical drains; drainage of the Pontian aquifer using horizontal galleries and passages;
- Constructing surface storm drain system and planting vegetation.

These measures were aimed to reduce and mitigate all possible factors contributing to the landslide activity and to provide stability of the landslide-prone slopes. The detailed design characteristics of the first stage are depicted on Fig. 5.

Characteristics of landslide deformations on Primorsky Boulevard

For more than 150 years, landslide protection structures provided stability to the territory of the sea port in Odessa and protected it from rotational landslides. Despite this protection, other landslide-prone slopes within the historical center of Odessa, such as Primorsky Boulevard, the Boulevard of Arts, and Suvorov Alley (Fig. 3) experienced deformations during the past several decades. These deformations manifested themselves in surface fractures, deformations of retaining walls, failure of the city escalator, and other evidences.

Fig. 4 View of the segment of the landslide protection from the second stage (1970s)

During the last 40–50 years, tectonic factors triggered an increase in landslide activity within the area of Primorsky Boulevard and other areas within the territory of Odessa. These factors include increase of static loadings, surface water intrusions in upper parts of the landslide slope and landslide debris, failure of part of the drainage system built in 19th century, lack of maintenance of retaining walls, etc.

To understand the cause of deformations within Primorsky Boulevard (Fig. 6), monthly data from geodetic surveys were used for the period from 1975 to 1997. These surveys recorded vertical and horizontal movements of 57 benchmarks located across the study area. However, current analysis did not include all of them due to the lack of proper documentation and quality control for some data points. The movements of each benchmark were recorded in relation to the position of a stable benchmark located outside the deformation zone on Primorsky Boulevard. However, this benchmark cannot be considered absolutely stable due to the microtectonics deformations. Therefore, the recorded vertical measurements cannot be considered absolute and in fact are relative to the position of the benchmark. This is quite a common approach in landslide surveying techniques. Then recorded movements and benchmark locations were used to create a contour line map showing vertical deformations for selected time intervals (Budkin et al. 1998).

The analysis yields the following conclusions:

1. General azimuth of the vertical deformations did not coincide with the azimuth of the landslide slope. This means that deformations depend on some other factors, not only gravitational processes.
2. Deformation clusters appear to break into several independent "blocks" with widths up to 60 m. They have different vertical movements and in some years certain blocks experienced uplift.
3. Contour lines of vertical deformations coincided with orthogonal grid of established geodynamic zones. This grid consists of tectonic segments ranging from 40 to 60 m (Fig. 6).

Obtained results agree with geophysical surveys of Prichernomorskaya Prospecting and Surveying Agency, conducted in 1988 on the same territory. These surveys are based on the earth

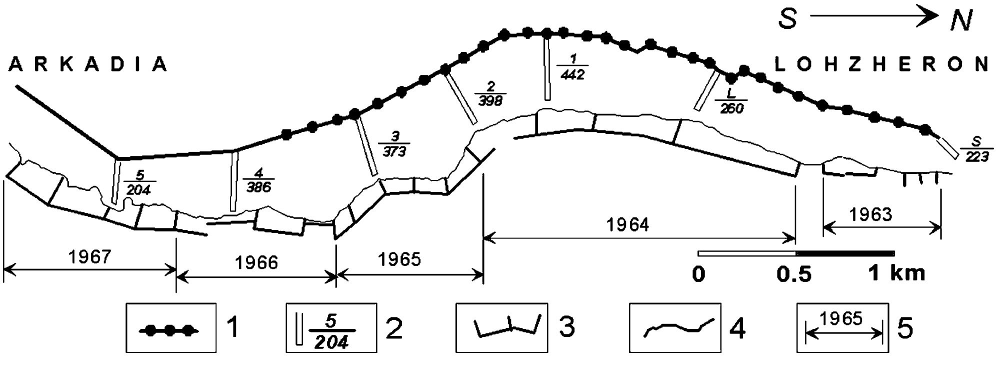

Fig. 5 The diagram of the first stage of the landslide protection system in Odessa. *1* Drainage galleries, *2* drainage tunnels, id *number (3)* or code (*L*)/ length (meters), *3* wave breakers and jetties, *4* shoreline, *5* date of the final stage of the construction

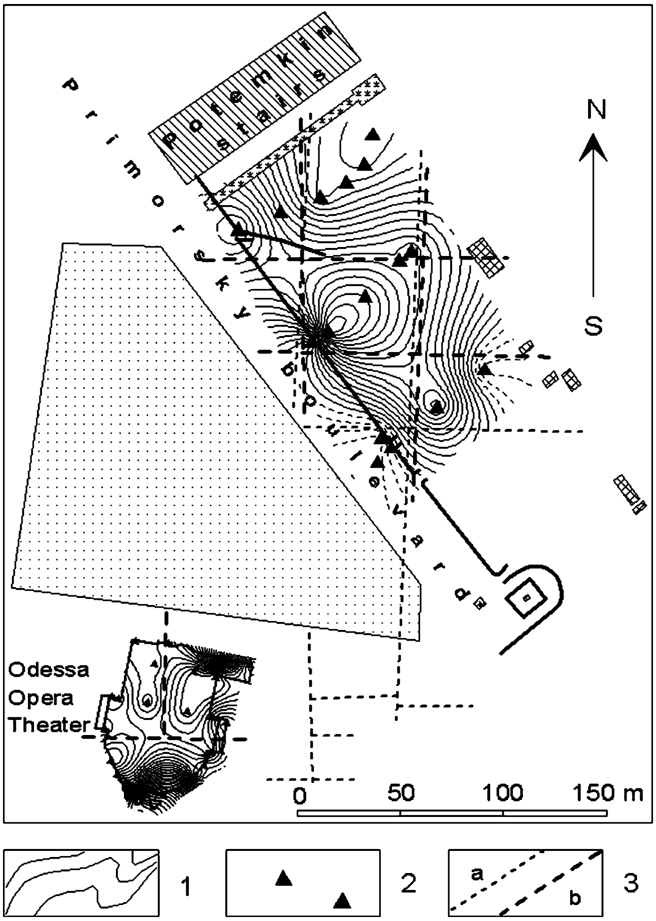

Fig. 6 Tectonical microsegmentation and geodynamic zones in Odessa near Primorsky Boulevard. *1* Contour lines of vertical deformations, *2* geodetic benchmarks, *3 a* geodynamic zones defined by geophysical methods, *3 b* geodynamic zones defined by geodetic methods

electromagnetic field method, which measures electromagnetic oscillations (frequencies) from the medium under the stress. In this case the medium is the bedrock and stress is caused by tectonic deformations. Electromagnetic frequencies are proxies of stress measured across a regularly spaced network and consequently interpolated to create a surface of relative intensity of the stress conditions in soils and bedrock. It is a qualitative method that allows comparing various areas regarding their stress conditions. Surveys revealed an existence of two systems of geodynamic anomalies according to the stress distribution. The first one is diagonal with north–west and north–east orientations. The second one is orthogonal (Cherkez et al. 1991). The orthogonal system coincided with a similar system produced by the geodetic survey of benchmarks.

It is important to mention that differentiated vertical movements can also manifest themselves in vertical deformations of buildings and other structures. Figure 6 shows an example of vertical deformations for the period from October 1996 to March 1997, measured using benchmarks installed on the building of Odessa Opera Theater. The graph shows differential movements of orthogonal orientation. Analysis of data from other time intervals shows that these movements also follow the diagonal system (Zelinsky et al. 1997, 1998) of weakened zones due to the microtectonic deformations.

Thus, the assumption can be made that within the territory, in Fig. 6, there is a system of microblocks with characteristic movements up to a few tens of meters. All microblocks move differently within various time periods that range from weeks to years. This means that within the proximity of the Odessa sea port, deformations can be caused by both gravitational and tectonic movements.

Geodetic observations in the underground drainage structures of the landslide protection system

Large volumes of data were recently summarized with hydrological, hydrogeological, and geodetic observations that were collected during the monitoring of the landslide protection system implemented in Odessa in 1964. Data analysis has evaluated the effectiveness of the landslide protection measures and has produced new information about structural and tectonic characteristics of the landslide slope rock composition and the effects of modern tectonic movements on long-term slope stability (Budkin and Cherkez 2000; Cherkez et al. 1997; Cherkez 1996).

The most important criteria for monitoring the effectiveness of the landslide protection system are recorded rock deformations and movements on the landslide slopes obtained by geodetic measurements. It is important to notice that geodetic surveys in underground structures are more precise than surveys on the surface. This is due to the fact that temperature is stable in underground galleries and passages; the underground pathways are straight; benchmarks are rarely vandalized or damaged, plus there are also no problems with transportation or traffic.

The underground network of benchmarks was established using the elements of structural reinforcements in 350- to 400-m-long drainage passages. These passages were constructed in landslide deposits and continued horizontally inside the bedrock of the slope that was not affected by landslide deformations for 150–250 m. Inside the bedrock these passages were connected with a drainage gallery located on the contact zone of Meotian clays with Pontian limestone (Fig. 7). The passages were located 1 km apart along the coastline. Measured deformations in each of them indicated the stability of the specific area. The passage is a flexible quasihorizontal structure that promptly reacts on any deformation that occurs within the rocks. These deformations were calculated by measuring horizontal and vertical displacements of the benchmarks. During 1964–1992, 18–20 sets of measurements were conducted.

Geodetic observations showed that all benchmarks, including those that were located far from the landslide slope, experienced displacements. Because of this, each set of measurements recorded absolute changes of benchmarks in relation to the most distant benchmark located in a stable area inside the bedrock. This produced an estimation of the deformations that occurred within the passage by the time new measurement period started. Data showed that some of benchmarks experienced uplifts and some

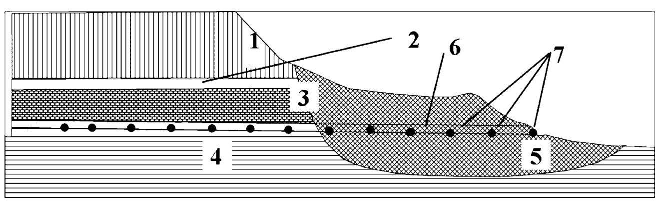

Fig. 7 Geological cross-section along the drainage *tunnel 3* (for location, see Fig. 5). *1* Pleistocene loess, *2* Upper Pliocene red clay, *3* Pontian limestone, *4* Meotian clay, *5* landslide deposits, *6* drainage *tunnel 3*, *7* benchmarks

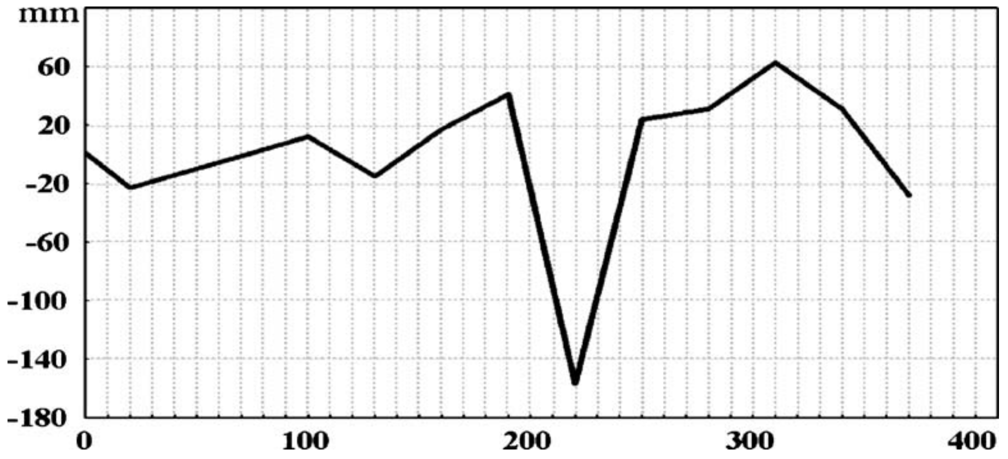

Fig. 8 Distribution of vertical deformations along the drainage gallery 3 for the period April 1966 to September 1992

experienced subsiding. Therefore, the passage could be divided into separate blocks, each experiencing its own oscillation. The analysis of deformations showed that they can be visualized as a wave spread along the passage with a wavelength of about 60 to 120 m (Fig. 8).

For the lifetime span of structures, the range of vertical displacements was recorded as 20–80 mm in the bedrock. It increased up to 100–200 mm in landslide deposits. The analysis of the horizontal deformations distributed along passages showed that slopes expanded and the most considerable increase in distance between benchmarks occurred in the contact area between the landslide and the slope. These expansion zones were identified in subsiding areas of passages. The average distance between these expanding zones was 60–120 m within the slope bedrock. The longitudinal deformations and vertical displacements of the benchmarks within the main body of the landslide occurred simultaneously with deformations of the bedrock. However, they were two to four times larger.

The rate of longitudinal displacements of the benchmarks during the steady creeping stage was 5–7 mm/year in the bedrock. It was 15–20 mm/year in the landslide itself. The total increase in the length of passages for the whole period of observations was 300–1,500 mm (Budkin and Cherkez 2000; Zelinsky et al. 1993a).

It has to be noticed that the geological structure of the landslide slopes in different areas of the Odessa coast includes various bulges and depressions within Meotian clays. These deformations occur with regular intervals (50–70 to 100–120 m) and elevation difference between depressions and bulges ranges from 10 to 20 m. This "wavy" pattern of the surface of Meotian clays is a result of plastic deformations that occur before the landslide (due to the microtectonic deformations) and also during the landslide motion (due to the deformations caused by separate landslide blocks). These wavy patterns have wavelengths similar to those measured in the drainage system passages. It is suggested that tectonic movements of separate blocks form zones of the local plastic deformations and therefore maintain a structural geological basis for the landslides and other related processes in an active state.

Conclusions

Considering the various scientific data on the landslide processes and factors that cause them, the analysis of geodetic measurements along Odessa coast during different periods of construction and implementation of the landslide protection measures shows that:

1. The stability and characteristics of the developed deformations on the landslide slopes of Odessa coast depend on various factors. The main factors are the heterogeneity of the geological structure, structural and tectonic characteristics of the bedrock, and modern (latest) movements of tectonic fractures and blocks.
2. Systems of the landslide protection located in the Odessa historical center and in adjacent coastal areas were built in different times. However, they preserve the conceptual basis and are effective as a whole.
3. Geodetic measurements along the coast where landslide protection was built in different times show that modern slope deformations have a common nature that includes the following factors:
   3.1 Differentiated vertical displacements and inclinations of the orthogonal network of tectonic microblocks;
   3.2 Periodic horizontal shrinking and expansion of the geodynamic zones;
   3.3 Surface processes caused by gravitational forces; and
   3.4 Rheological properties of deformed rocks (Fig. 8).
4. Differential tectonic movements of fractures and blocks as well as intermingled zones of shrinking and expansion reduce slope stability by increasing stress conditions in bedrock and pore water pressure. This causes continuous landslide movements and slow creeping of Meotian clays within the bedrock and landslide slope itself.

Relative displacements of landslide blocks result in the form of the wavy profile on the surface of Meotian clays. This feature occurs on both the landslide slope (Zelinsky et al. 1993b) and within the bedrock.

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