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Research paper

The landslide in the slope and side of the Warta River valley in the village of Wronki – process analysis, exploratory research, preventive measures, monitoring

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Abstract: The landslide is located in Wronki. It covers the southern side on the bank of the Warta River and occupy an area of 500 m in length. The landslide was once again activated on August 22-23, 2018, causing numerous failures. The Warta River slope in the area of mass movements is built by non-construction embankments, under which the Poznań Miocene–Pliocene of quasi-layered structure lie. There are horizontal interlayers of sandy silts in these clays. The Warta drains water from a large area, and the runoff takes place mainly on the roof of clays. The slide surface of the landslide was precisely the roof of the Poznań clays. Bearing in mind the properties of the Poznań clays, such as relaxation, block disintegration, expansiveness features, the following were considered the direct causes of the failure: heavy rainfall that occurred after a drought, loading of the slope with indiscriminate cubature buildings, construction of a linear sewage system and periodically repeated vibrations caused by the implementation of neighboring investments. In order to identify the area, test boreholes were made, samples were taken for laboratory tests, and geodetic measurements were taken. Based on the obtained results, slope stability calculations were made and a measurement network was developed for systematic monitoring of geodetic displacements of control points. It was recommended to perform drainage to drain the slope and side of the Warta River, plant bushes, and make changes to the land development plan in order to prohibit further development of the area in the endangered zone.

Keywords: anthropopressure, clays of the Poznań series, landslide, monitoring, prevention

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1. Introduction

In the area of the Polish Lowlands, mass movements in the construction ground occupy a much smaller area than in the mountain and highland areas. Since these processes are rare, or even incidental, the possibility of their occurrence is often underestimated, even if there are clear reasons for it. The basic mistake made by land owners, investors, and even officials deciding on the method of land development is that despite the earlier symptoms indicating the activation of mass movements, potentially endangered areas are not excluded from development in time and properly secured. As a result of the lack of funds or savings, steps that would fully secure the area at risk of mass movements are not taken. Often these steps are limited to the so-called half-measures, or leaving the matter to run its course. Such a situation took place in the town of Wronki, in the Greater Poland Voivodeship, where the landslide became active on the left bank of the Warta River, in the built-up area, and the long history of development and drainage of the study site and adjacent areas proves the decision-making and investment mistakes.

In accordance with the Instruction for the Development of the Map of Landslides and Areas at Risk of Mass Movements in the scale of 1:10,000 from 2008 [2], the landslide in Wronki in the documentation card prepared in 2018 [18] was classified as an active earth slide, non-consistent, with a rotational movement.

2. Purpose and methodology of research

The aim of the research was to identify the causes of the landslide in Wronki, on the slope of the Warta River. In addition to determining the causes of the failure, a very important part was to take countermeasures to stop the unfavorable phenomena and define repair recommendations.

To achieve the intended goal, the following were used: archival and literature data on the history of development of the Warta bank, the results of exploratory drilling (43 boreholes with a depth of 3.5 m to 15.0 m and 3 additional boreholes with a depth of 6.0 m to 7.0 m), CPT static soundings (4 CPT soundings with a depth of 10.0 m to 12.0 m) and numerous laboratory tests of collected soil samples (determination of natural moisture content – 340 samples, particle size composition – 20 samples and organic substance content – 22 samples).

In addition, the geological-engineering cross-sections, the determination of water conditions, as well as observations of the consequences of the failure, that were made as part of this work, contributed to the interpretation of the sequence of events.

3. Failure description

The described landslide is located in the town of Wronki, Szamotuły County, Greater Poland Voivodeship. The town is located approximately 60 km north-west of Poznań.

The landslide covers the southern slope on the left side of the Warta River. The range of landslide processes that took place in 2018 can be estimated at approx. 500 m (Fig. 1).

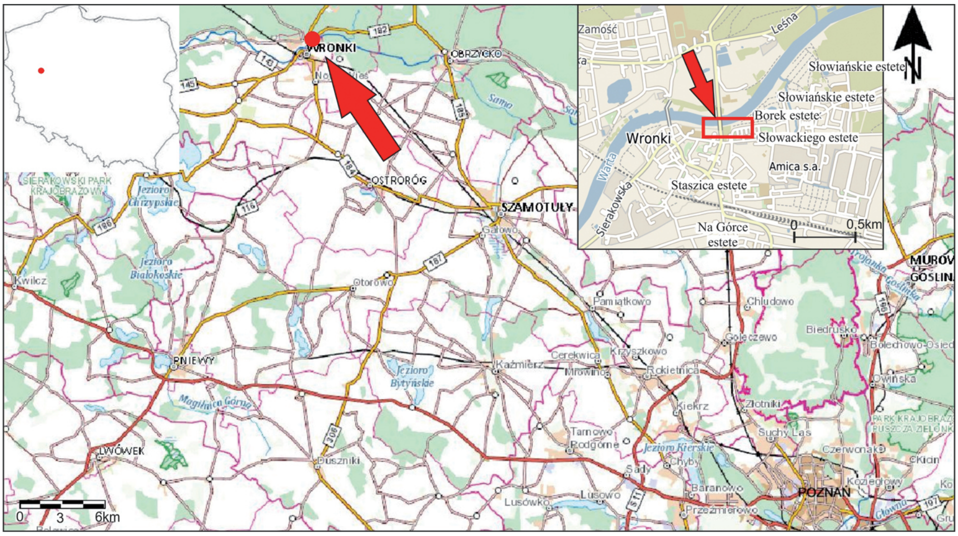


Fig. 1. Location of the landslide in the slope and side of the Warta River in Wronki (www.geoporatal.gov.pl)

The last observed landslide process of a dynamic nature and catastrophic consequences was activated on August 22, 2018 and August 23, 2018 in the section from the monastery of Franciscan friars towards the east, transversely to the bridge over the Warta River, along the voivodeship road No. 182, through the closed wastewater treatment station of the Correctional Facility, the Municipal Sewage Pumping Station to the end of the allotment gardens.

Earlier mass movements of the earth in this area were observed in the 1970s, when symptoms of the landslide activity in the area of the wastewater treatment station of the Correctional Facility in Wronki were observed. On the other hand, since the 1950s, during the construction of residential buildings at Mickiewicz Street and in Słowacki housing estate, there were problems related to the subsoil, and later cracks in the resulting buildings. Even earlier, the movement of earth masses within the Franciscan monastery was observed. For the area in question, in November 2018, a landslide documentation was prepared along with an opinion, in which the landslide was inventoried as still active [7, 18]

During the site inspection, in the autumn of 2018, an inventarization of deformations in the subsoil was made. They arose after mass movements in the slope and side in the area of the road bridge in Wronki. Fig. 2 shows the research area with the, marked in pink, cracks in the surface caused by landslides. As can be seen on the map, the greatest amount of ground deformation developed in the area to the east of the bridge, i.e. in the area of the closed wastewater treatment station of the Correctional Facility, the sewage pumping station of the Municipal Enterprise in Wronki and allotment gardens.

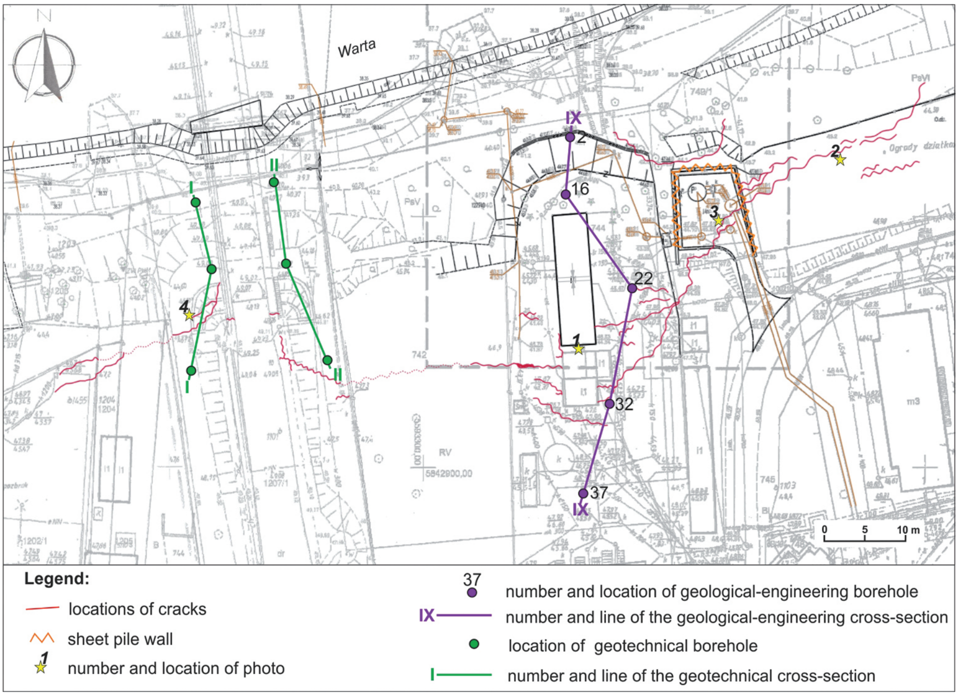


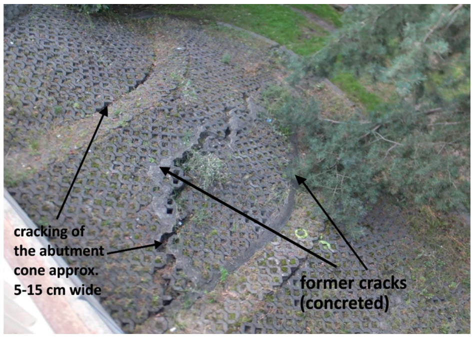
Fig. 2. Map of the distribution of deformations in the subsoil of the Warta side in Wronki [12]

During the field inventorization, numerous photographic documentation of the damages and deformations of the ground was also made. Selected damages that occurred in the discussed area in August 2018 are shown in the photos below (Fig. 3).

Visible inclination of the building by about 25 cm towards the river in the closed wastewater treatment station of the Correctional Facility in Wronki

Cracks in the ground, approx. 50 cm wide, in the allotment gardens in Wronki

Damages visible at the sewage pumping station of the Municipal Enterprise in Wronki



Cracks of the cone of the road bridge abutment in Wronki

Fig. 3. The discussed area in Wronki [9]

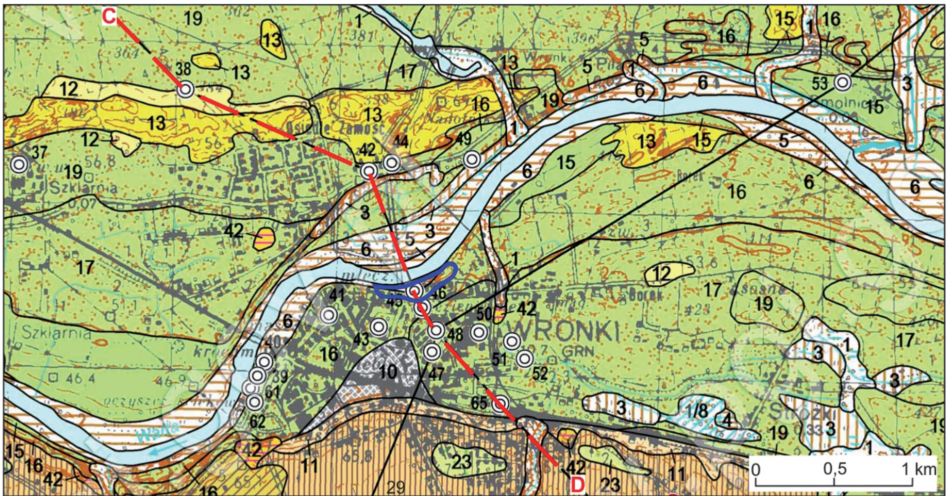
4. Geological structure and geological-engineering conditions

In order to determine the causes of the landslide, the geological structure of the study area was analyzed in detail. The detailed geological map of Poland (Wronki sheet) shows the presence of mainly non-cohesive soils in the subsurface zone, i.e. river-periglacial sand and gravel of the alluvial terraces of the Warta river and sand and silty sand of floodplains of the Warta river (Fig. 4) [5].

In turn, the sediments that appear below are illustrated by the geological cross-section included in the explanations to the above-mentioned map [6]. The mentioned sands (marked with number 6 and 17) lie on cohesive soils formed as Neogene clays of the Poznań series (marked with number 41), and locally on the boulder tills of the Middle Polish glaciations (marked with number 36). The Warta river bed is eroded in Neogene sediments, on which a layer of sand with a small thickness lie (Fig. 5).

In the period from November 2018 to February 2019, in order to determine the causes of the landslide, extensive soil tests were carried out, which included performing 43 testing boreholes with varying depths from 3.5 m to 15.0 m and 4 static CPT soundings of depth from 10.0 m to 12.0 m. Additionally, in April 2022, complementary research were carried out to supplement the exploration of the subsoil by another 3 testing boreholes with a depth of 6.0 m to 7.0 m. The following laboratory tests were performed: determination of natural soil moisture (340 samples in total), particle size distribution (20 sieve analyzes) and organic substance content (22 samples) [16].

Successively, after completion of field work, numerous geotechnical and geological-engineering cross-sections were made perpendicular and parallel to the Warta River. An exemplary geological-engineering cross-section, just like the geological cross-section (Fig. 5), runs from north to south and shows the contemporary structure of the subsoil in the slope and side of the Warta River in the place where the greatest damage occurred in August



Key: Holocene: 1 – humic sand and sandy alluvium of valley bottoms and periodically flowing depressions, 3 – alluvium and peaty alluvium, 5 – sand and silt (fen soil) of floodplains 1-2 m a.s.l. of the Warta river as well as oxbow lakes alluvium and peat, 6 – sand and silty sand (fen soil) of floodplains 2-4,5 m a.s.l. of the Warta river, 10 – diluvial and colluvial sand and tills, 11 – colluvial clays and tills, 13 – aeolian sand in the dunes, 15 – sand and sand with gravel on the alluvial terraces 6-8 m a.s.l. of the Warta river; Pleistocene (North Polish glaciation): 16 – river-periglacial sand and gravel of the alluvial terraces 9-11 m a.s.l. of the Warta river, 17 – river-periglacial sand, sand with gravel and gravel of the alluvial terraces 12-16 m a.s.l. of the Warta river, 23 – fluvioglacial sand and gravel (outwash plain), 29 – boulder till; Pleistocene (MiddlePolish glaciation): 36 – boulder till; Neogene (Miocene): 41 – Poznań Formation, 42 – silt, sand, clay, brown coal
— — — line of geological cross-section from Fig. 4 —— the area of works and research

Fig. 4. Location of the research area against the background of a fragment of the detailed geological map of Poland, sheet 392 – Wronki, scale 1:50 000 [5]
(source: http://bazadata.pgi.gov.pl/data/smgp/arkusze_skany/smgp0392.jpg)

2018 (Fig. 6). The yellow color in the cross-section shows a package of Neogene sediments created mainly in the form of clays, silty clays and clayey silty tills with variable value of liquidity index. This package is locally layered with silts, silty tills and silty sands marked in blue. In the zone of the steepest slope of the roof of the Neogene formations, there is a small thickness layer of fluvial- and fluvioglacial accumulation sediments of the North Polish glaciation, formed as silty sand, fine-grained sand, medium-grained sand and sand/gravel mix, in moderate dense state (marked in green) and partially watered. The watered sediment layer is discontinuous with a unconfined and confined nature of the groundwater table (Fig. 6). Fluctuations in the groundwater table in the annual cycle may range from +1.0 m to –1.0 m depending on the intensity of precipitation and fluctuations in the level of the Warta River in this area.

The geological-engineering cross-section illustrates the characteristic geological structure within the range of the analyzed landslide and shows a significant transformation of the slope's subsurface zone, what is confirmed by all the testing boreholes made, in which non-construction and construction embankments with variable thickness of up to 5.7 m were drilled in the subsurface zone. Below these embankments, cohesive soils are generally deposited (Fig. 6).

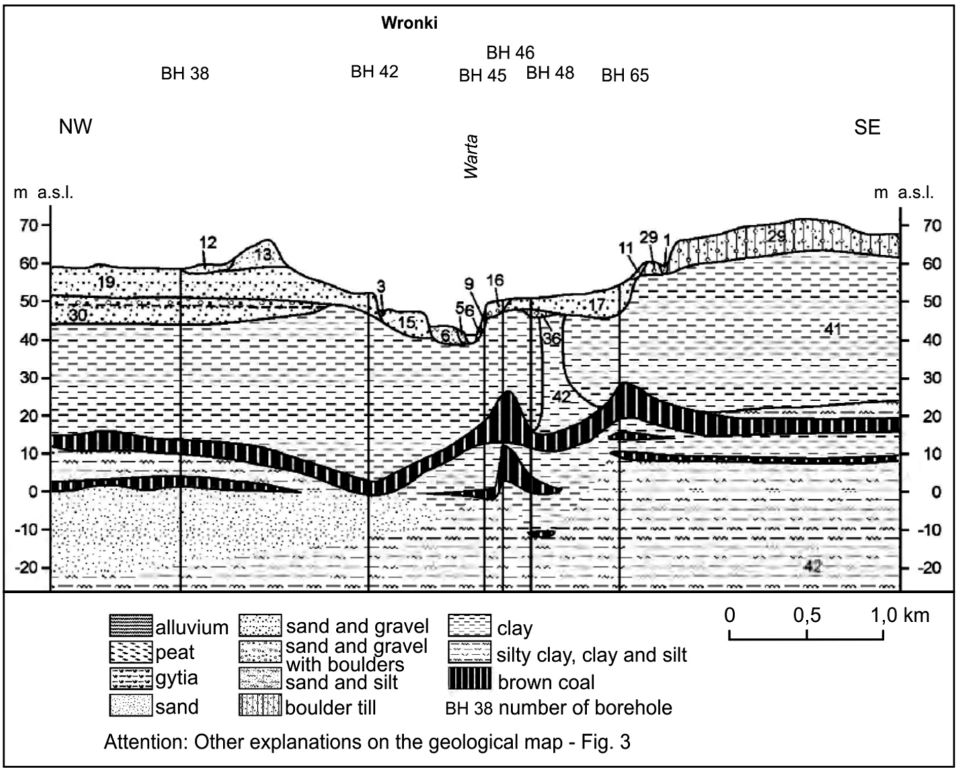


Fig. 5. The fragment of the C–D geological cross-section [6]

Mio-pliocene clays from Wronki were the subject of research by Jeż [3], for which he determined strength parameters. The tested soil consisted of silty clay and silty clay on the border of clay. The determined mean value of the angle of internal friction and cohesion determined in the direct shear apparatus were: $\phi = 10{-}11.5^\circ$ and $c = 10{-}80$ kPa.

Calculations of slope and side stability in the area of landslide activity were made in the area directly adjacent to the road bridge along the provincial road No. 182, based on the geological-engineering structure in two sections I–I and II–II (Fig. 2). The calculations were carried out using standard procedures: the Fellenius method, the simplified Bishop method and the Morgenstern-Price method. These methods determine the stability on a cylindrical plane, and additionally for the Morgenstern-Price method, the probable slide surface was set in accordance with the inclination of the roof of cohesive soils. The values of strength parameters were adopted as expert parameters according to Eurocode 7 [9]. The results of stability on the given slide surface for section I–I were $R_d/E_d = 0.53$, and for section II–II $R_d/E_d = 0.867$ at the required value of min. = 1, where R_d is the calculated value of the resistance to impact and E_d is the calculated value of the effects of the impact. This means that non-construction embankments placed on the roof of natural cohesive soils may slip due to heavy rainfall. Detailed calculations of the slope stability were included

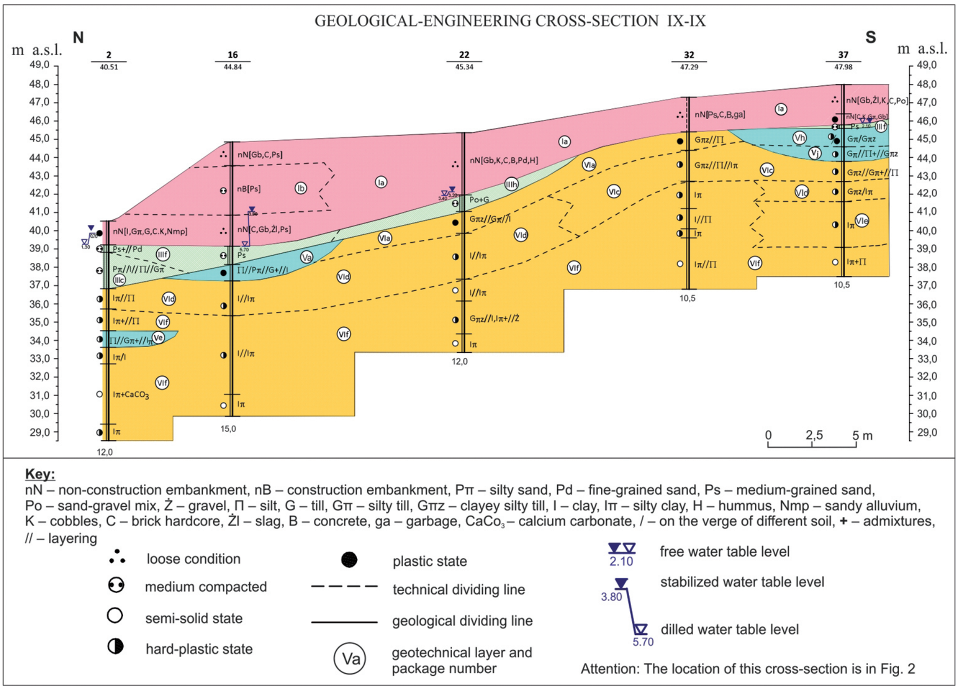


Fig. 6. The fragment of the geological engineering cross section IX–IX (modified) [16]

in the geotechnical expertise [9]. For forecasting the stability of slopes and escarpments, modeling programs are more and more often used, which enable the use of at least several variables (e.g. the ZSoil program) [4]. In addition, geophysical surveys are increasingly used in assessing slope stability. The development of an appropriate methodology for these studies enables to determine the geometry of the existing landslides (the course of the slip surface and the horizontal extent), which provides the necessary information to carry out a computational analysis of the slope stability [1].

5. Discussion and interpretation of research results

The area in question is a geodynamically active zone due to its geological structure and sensitivity to exogenous factors. This zone was developed successively. The development process has intensified especially since the 1960s and 1970s of the last century, which resulted in systematic loading of the slope and changes in geological-engineering and hydrogeological conditions in the slope area [12].

In addition, the area in question is located on the outer curve of the meandering Warta River, where the intensity of the slope undercutting is the highest in the area, as the river current is located very close to the southern shore. This is where the most intense mass movements took place in 2018 [12].

The inclined towards the Warta River roof of the Poznań clays, on which rainwater flows, infiltrating through embankments and native non-cohesive soils, can undoubtedly be classified as an aspect conducive to the phenomena of mass movements. The more that the river is draining in this section – it collects water from the moraine plateau. The conditions of surface and deep water outflow changed significantly with each construction investment, including the expansion of underground infrastructure, which also entailed a change in the state of cohesive soils through their plasticization and the condition of non-cohesive soils through the activation of suffosion and quicksand phenomena. In the summer season of 2018, long-term and intense precipitation occurred, which was one of the important factors in the development of the landslide. In the last 20 years, in the area of the closed wastewater treatment station of the Correctional Facility and the municipal pumping station, numerous linear excavations have been made. They directed the flow of groundwater perpendicular to the Warta River. These waters, as it was visible in the geological-engineering cross-section, run down the roof of the Poznań clay, which was the slide surface. Bearing in mind the properties of the clays of the Poznań series, such as relaxation (formation of the slickenside surfaces), block disintegration, expansiveness features (swelling and shrinkage), the following were considered the direct causes of the failure: heavy rainfall that occurred after a long-term drought, long-term loading of the slope with indiscriminate cubature buildings, construction of a linear sewage system within the slope and periodically repeated vibrations caused by the implementation of neighboring investments (e.g. driving piles or micro-explosions when breaking ice on the river). In addition, cracks were formed on the terrain surface, which facilitated the penetration of rainwater, which further reduced the strength parameters of cohesive soils in the subgrade [10, 12, 16, 17].

Moreover, at the same time, the construction of a pedestrian and bicycle path at the foot of the escarpment along the Warta River was carried out in the discussed area. Intensive transformation of the slope zone during construction, loading with embankment soil and vibrations from construction equipment superimposed on increased soil moisture after intense rainfall, including the roof of Poznań clays, which are expansive soils (susceptible to swelling and shrinkage phenomena when their humidity changes), as a consequence, triggered the launch of landslide processes in this area, which occurred in August 2018.

6. Remedial recommendations

The analysis of the archival materials and their reference to the obtained results of the geotechnical investigations allowed for the formulation of the following guidelines for the repair and protection of the slope and the side zone [9, 10, 16]:

– the construction of drainage to dewater the slope and the side (the slope stability analysis showed the need for applying drainage to dry the slope and the side zone along the entire length from the bridge to the end of the allotment gardens); Performing only a fragment of the drainage will not dry the landslide zone, therefore the entire project will be ineffective;

- securing the road bridge along the voivodeship road No. 182. The works related to securing the road bridge have already been completed and consisted mainly in strengthening and stabilizing the slope and cones of the abutments from the side of Wronki, on the construction of a drainage at the abutment and the demolition of the existing transition slab and construction of a new transition slab behind the abutment from the side of Wronki;
- after the period of drying of the side zone and the slope, it is possible to start designing the retaining structure of the slope (after about two years of the failure). Among the many possibilities, a gabion structure supported on reinforced concrete piles drilled into the ground was suggested. Such a structure should ensure permanent drainage of the slope.

After performing the drainage system to dewater the slope and the side, the following proposals were made:

- cutting out only a few selected trees (tall ones, which cause dilatation of the subsoil during strong winds), especially at the edge of the escarpment, also on the “park” plot – between the closed wastewater treatment station and the bridge;
- planting bushes that have a high water demand and, at the same time, are resistant to its lack, e.g. wicker, in the area of allotment gardens, in several rows;
- continuation of geodetic monitoring until the completion of repair work;
- making changes to the land development plan in order to prohibit the further development of the area in the danger zone.

7. Monitoring of the landslide

The measurement network is arranged so that it is possible to analyze all the critical points of interest, thus it covers the area of active landslide and allows to determine the displacement of surface points in the X, Y, Z direction. The presented map shows the distribution of geodetic control points in the zone where the greatest landslide movements occurred in 2018 (Fig. 7). Measurements are carried out from December 4, 2018. 13 control points marked with the letter U are located in the area belonging to the Wronki City Hall (currently measurements are carried out for points U1–U9) and 6 control points marked with the letter P are located on the premises belonging to the Company Municipal in Wronki. Points marked with the letter Z are located on the premises of the Correctional Facility in Wronki, where currently measurements are no longer carried out (completed in December 2018) [13–15].

In the Documentation of the subsoil research in March 2019, it was recommended to extend the monitoring by additional checkpoints in the area at Mickiewicz Street and a housing estate [10]. From October 28, 2019, measurements are carried out in the area belonging to Słowacki housing estate in Wronki using 8 control points marked with the letter B (Fig. 7).

The existing measurement network for the control of the landslide process in the subsoil is the result of a compromise between the financial possibilities of the City Hall and the Municipal Enterprise in Wronki and the needs of technical analysis of mass movements.

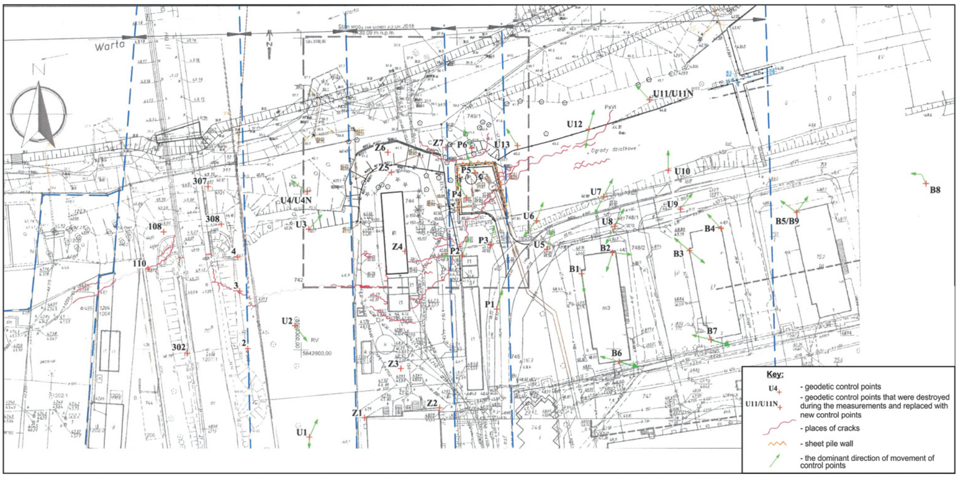
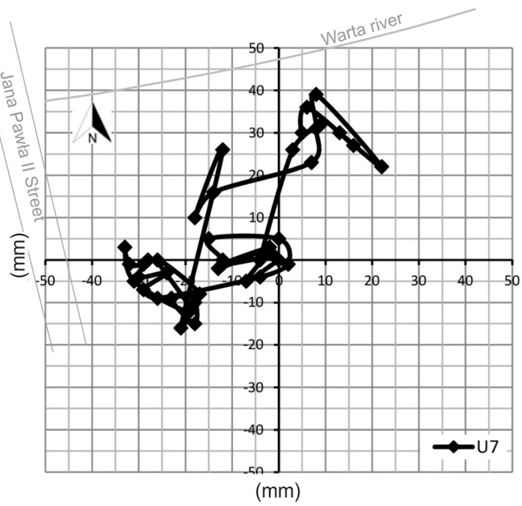


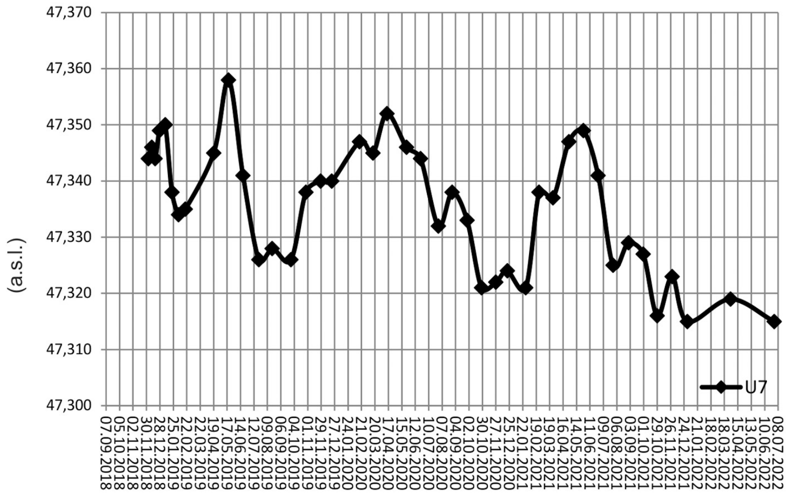
Fig. 7. Distribution of geodetic control points [13–15]

For all benchmarks, a tabular summary of the results of geodetic measurements of displacements as well as graphs of horizontal displacements and vertical displacements in time is prepared. The results of the measurements were presented for 2 selected geodetic control points, i.e. for the U7 point located in the area of allotment gardens (Fig. 8) and the P4 point located in the municipal sewage pumping station (Fig. 9).

The graphs show the chaotic movement of control points. All points in the landslide zone have a very similar nature of displacements, i.e. they are ambiguous, unequal displacements, and therefore very difficult to interpret. Harmonic displacements of control points once to



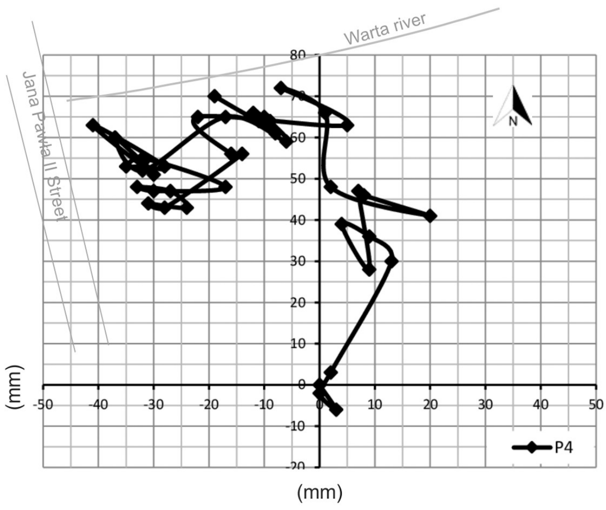
(a)



(b)

Fig. 8. Diagrams of horizontal (a) – measurements made in the period from December 2018 to February 2019, every 1–2 weeks; from March 2019 to December 2021, every 1 month; from January 2022 to June 2022, every 3 months and vertical displacements (b) for the control point U7

the left, once to the right, once up and once down can be explained by the fact that the mass movement takes place in very specific geological-engineering conditions, i.e. within the slope and on the side, on the surface of intensely irrigated and plasticized expansive soils with considerable potential for changes in volume with changes in humidity. The high



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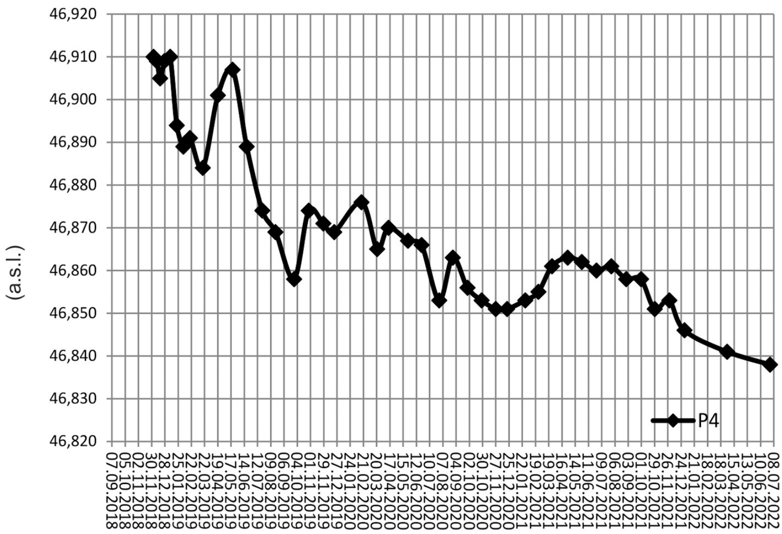

(b)

Fig. 9. Plots of horizontal (a) – measurements made in the period from December 2018 to February 2019, every 1–2 weeks; from March 2019 to December 2021, every 1 month; from January 2022 to June 2022, every 3 months and vertical displacements (b) for the control point P4

degree of expansiveness of Pliocene clays is related to the presence of a large amount of smectite minerals in their mineralogical composition. The average content of each group of clay minerals in the entire series of Pliocene clays is as follows: smectite – 46%, illite – 28% and kaolinite – 26% [8]. Smectite minerals absorbing water can increase their volume at least 4 times. This is undoubtedly one of the most important, cause of vertical movements of the studied benchmarks [11, 13–15].

The results of the movement of measuring points are partially related to the processes causing clay swelling, to the slope landslide movement, but they can also be associated with measurement errors resulting, for example, from relatively free access of outside people or construction equipment to the measuring points. The disadvantage of the currently functioning network is the inability to observe mass movements at certain depths below the ground surface.

8. Drainage of the landslide zone

In order to dewater and dry the landslide zone in the area of the communal road No. 250120P (Słowacki housing estate in Wronki), the deep drainage of the landslide area was designed to drain waters away to the Warta River. The purpose of the drainage is to intercept rainwater and meltwater infiltrating into the subsoil on the landslide area, and the groundwater flowing along the impenetrable layer (clay, till) from the valley slope towards the river. The depth of the constructed drainage depends on the level of the roof of natural cohesive soils or the depth of the stabilized groundwater table [16].

In order to drain the landslide zone in the area of the communal road No. 250120P in Wronki, three drainage lines ("A", "B" and "C") were designed with concrete drainage outlets to the Warta river (WD-1, WD-2, WD-3) [8], which is shown on Fig. 10.

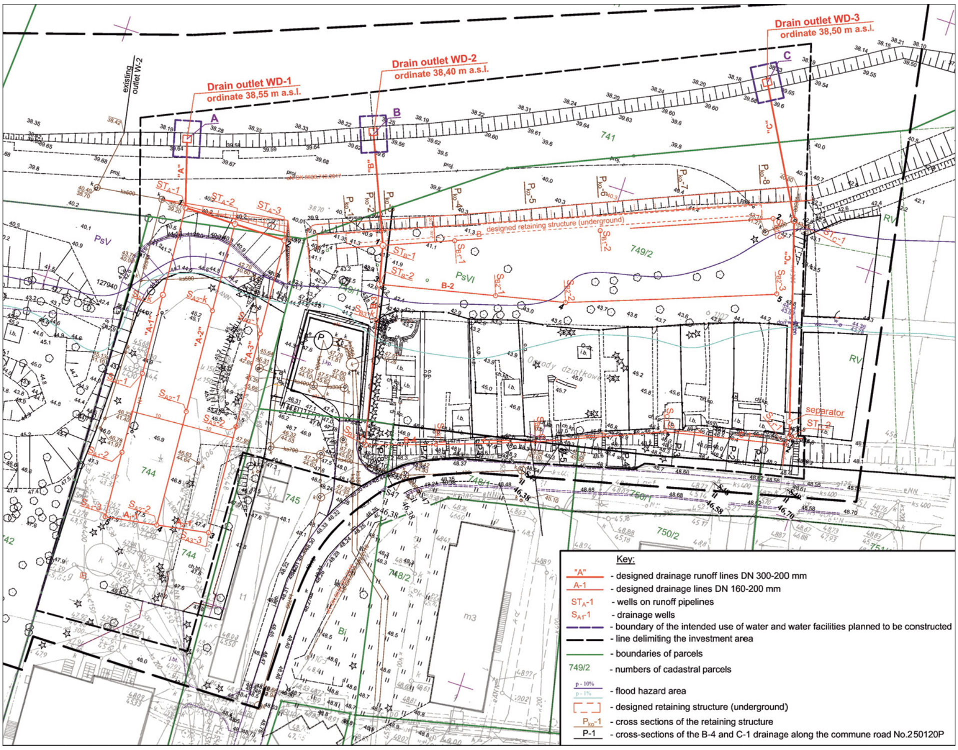

Fig. 10. The plan of the designed drainage system of the landslide zone in the area of the communal road (modified) [16]

Additionally, in the place of the visible landslide phenomenon (splitting of the slope), a retaining structure with a total length of approx. 80.0 m was designed. It should be made of mesh-stone gabions and covered with mineral soil. The gabion structure laid in a stepped arrangement on a concrete base, supported by reinforced concrete pressed piles, 3.0 m long, spaced every 3.0 m. Behind the retaining structure, the B-1 drainage pipeline in the filtration gravel pack was designed. The entire retaining structure will be covered with mineral soil (gravel, sand/gravel mix, coarse- and medium-grained sand), mixed with hummus and sown with a mixture of grasses [16].

In addition, separately in the area of the plot, where the sewage pumping station of the Municipal Enterprise in Wronki is located, drying drainage was designed and strengthening the site after works, which is currently under construction.

9. Conclusions

Many factors are responsible for the process of the formation and activation of the landslide, it is not possible to clearly state which of them was the key for the landslide to be in its present state. The complex geological structure is an undeniable factor significantly influencing the instability of the slope. In the area predisposed to the development of mass movements, over the years there has been free development, without any concept of securing the slope and side, and without thoughtful drainage, which would be absolutely necessary in this type of investment. Despite the fact that after the activation of the landslide, which resulted in a number of material losses, protective measures were taken, due to the lack of sufficient financial resources, they were insufficient and were based on the use of half-measures (e.g. surface monitoring).

From the moment of starting the kinematic process of mass movements, the present prediction of its further development is difficult. Therefore, all the preventive measures we propose, as well as in-depth monitoring of displacements, are necessary to observe and maintain the stability of the slope and side in order to maintain the safety of the city's inhabitants and its infrastructure.

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Osuwisko w skarpie i zboczu Warty w miejscowości Wronki – analiza procesu, badania rozpoznawcze, działania zapobiegawcze, monitoring

Słowa kluczowe: antropopresja, iły serii poznańskiej, monitoring, osuwisko, zapobieganie

Streszczenie:

Opisywane osuwisko znajduje się w miejscowości Wronki, powiecie szamotulskim, województwie wielkopolskim. Obejmuje ono zbocze południowe, po lewej stronie rzeki Warty i zajmuje teren o rozciągłości ok. 500 m. Osuwisko po raz kolejny uaktywniło się w dniach 22–23 sierpnia 2018 r. powodując liczne awarie i zniszczenia.

Skarpę Warty w obszarze występujących ruchów masowych budują nasypy niekontrolowane (o zróżnicowanym składzie), pod którymi zalegają mioceńsko-plioceńskie iły serii poznańskiej o quasi-warstwowej budowie – w iłach występują horyzontalne wkładki pyłów piaszczystych. Rzeka Warta drenuje wody z dużego obszaru, a spływ wód odbywa się głównie po stropie iłów. Strefę poślizgu stanowił właśnie strop iłów serii poznańskiej. Mając na uwadze właściwości iłów serii poznańskiej takie jak odprężenie (powstanie powierzchni zlustrzeń), dezintegracja blokowa, cechy ekspansywności (pęcznienie i skurcz), za bezpośrednią przyczynę awarii uznano: obfite opady, które wystąpiły po długotrwałej suszy, wieloletnie dociążanie skarpy nieprzemyślaną zabudową kubaturową, budowę liniowej instalacji kanalizacyjnej w obrębie skarpy oraz okresowo powtarzające się drgania spowodowane realizacją sąsiednich inwestycji (m.in. wbijanie pali czy mikrowybuchy).

W celu rozpoznania terenu wykonano liczne otwory badawcze, pobrano próbki do badań laboratoryjnych, wykonano pomiary geodezyjne. Na podstawie uzyskanych wyników, dokonano obliczeń stateczności skarpy i opracowano sieć pomiarową do systematycznego monitoringu przemieszczeń geodezyjnych punków kontrolnych. Zalecono wykonanie drenażu w celu odwodnienia skarpy i zbocza Warty, posadzenie krzewów, dokonanie zmian w planie zagospodarowania przestrzennego w celu wprowadzenia zakazu dalszej zabudowy terenu w strefie zagrożonej.

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