Monitoring of soil structure

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Abstract. Based on data from the Central Office of Construction Supervision, there were 5455 construction disasters in Poland between 2008 and 2019. Four thousand twenty-three disasters were caused by random events, of which 110 were caused by landslides. Most of these events took place in 2010, when there were up to 94 disaster-related landslides. Landslides have been occurring with different intensity, significantly influencing the current structure of the Earth surface. In natural conditions, without human intrusion, these phenomena have a character of long-term processes that activate depending on the changes of natural external conditions such as ground saturation with water, area deforestation, high degradation or slopes erosion. Everyone who had contact with landslides knows that it is not a sudden phenomenon, but a process - chain of events occurring one after another and developing with time. This phenomenon forces constant necessity of getting more detailed knowledge of the processes mechanism and character and phenomena occurring inside the slopes. That is why slope monitoring plays such an important role in understanding the mechanism of landslides. In Poland, most structures of this type belong to the second or third geotechnical category in accordance with the Regulation of the Minister of Transport, Construction and Maritime Economy (2012). The law obliges the owner of the land on which this type of structure is located to perform inspections and monitoring of its condition. The monitoring of the slope protecting the liquid waste landfill facility located at the food processing plant was analysed in the article. In 1997, the slope was subject to a construction disaster in consequence of washout by the Oder River and too high irrigation of the ground structure. Following the disaster, the slope with the waste reservoirs slid into the river polluting it. Since the reconstruction, the slope is subject to constant monitoring of the external geometry and checking the condition of the ground building the dam. The paper discusses the applied monitoring methods and shows the methodology of conducting the measurements. The results of slope settlement were analysed and compared with model calculations. In conclusion, modern monitoring techniques were shown, which could be applied to this type of structures.

1. Introduction

The law of our country was harmonized with European law after Poland joined the European Union. One of the new standards that were introduced was Eurocode 7 - the standard concerning geotechnical design. Previously used standards as well as the new ones imposed an obligation on the owner of an engineering structure, which is undoubtedly an earth slope, to perform monitoring of the construction. Monitoring means that the structure is to be regularly (systematically) examined. The survey consists in collecting and analysis of qualitative and quantitative information obtained from measurements and observations of phenomena. These studies are carried out for a predetermined period in a cyclic or continuous and long-term manner. [1]
The basic method of monitoring geotechnical structures is the observation method. For many years this method has been improved and modified. This methodology has been formed by Nicolson et al. as a result of which it is accepted as one of the monitoring methods approved according to Eurocode 7 [1], [2], [3]. Currently, the regulations of the Construction Law [4] and the ordinances issued by the relevant ministers [5] and [6] impose the determination of the construction monitoring method at the design stage. As part of the geotechnical design, a civil engineer or a geotechnical engineer with appropriate qualifications are obliged to determine what method the construction object will be monitored by and what deviations from the occurring data will be allowed.

Between 2008 and 2019, there were 5455 construction disasters in Poland. Four thousand twenty-three disasters were caused by random events, of which 110 were caused by landslides. The highest number of such events occurred in 2010, when as many as 94 landslide-related disasters occurred. [7] In natural conditions, without human intrusion, these phenomena have a character of long-term processes that activate depending on the changes of natural external conditions such as ground saturation with water, area deforestation, high degradation or slopes erosion. Everyone who had contact with landslides knows that it is not a sudden phenomenon, but a process - chain of events occurring one after another and developing with time. This phenomenon forces constant necessity of getting more detailed knowledge of the processes mechanism and character and phenomena occurring inside the slopes. That is why such important role for understanding the mechanism of landslides plays the monitoring.

2. Research subject
The research work carried out between 1997 and 2015 by the Department of Geotechnics and Geodesy at the Opole University of Technology included geodetic and geotechnical monitoring of the slope which is a structural element of the liquid waste landfill area. This structure described in this article is an earthen structure used as the earth dam for the bleaching water reservoir (plant wastes) and as the flood control dike. It is located in the area of the industrial unit in Brzeg, Poland, on the right bank of the Oder River (Figure 1). [8]

![Figure 1. Location of the slope by the Oder River](image)
In 1997, the slope was subject to a construction disaster in consequence of underwashing by the Oder River and too high irrigation of the ground structure. Following the disaster, the slope with the waste reservoirs slid into the river polluting it. Since the reconstruction, the slope is subject to constant monitoring of the external geometry and checking the condition of the ground building the dam [10]. The monitoring is conducted on the basis of the observation of the fixed spots established in two sections on the slope declivity and surcharge, and at the base of the slope according to the figure 2.

![Figure 2. Placement of the measuring points on the slope][11]

3. Geodetic Monitoring of the Slope

Any theoretical considerations need to be confirmed and extended by the model studies or studies conducted on the real object. To verify the calculations, measurements of the earth slope geometric levelling (precise) estimated as the most accessible and accurate for this type of structure were conducted. The geodetic technologies are used when inventorying the changes in the geometry of the structures like: earth dam, embankment of the industrial settling reservoirs, flood control dikes, railway embankments [12], [13]. The above-mentioned structures are characterised by heterogeneity of the material from which they are built and by their large scale. The above conditions influence the way of conducting the geodetic measurements [14], [15].

To verify calculations made in the doctoral dissertation [11], measurements of a soil slope were made using the geometrical levelling method (precise), which was evaluated as the most available and accurate for this type of structures. The height measurements were made using the geometric levelling method with increased precision. The error of a typical observation was ± 0.15 mm. The measurements were made with a high-precision digital level NA 3003 made by Leica, using precise Leica Invar patches. Before the measurements, the levelling instrument was checked and rectified in accordance with PN-ISO 17123-2:2005 Optics and optical instruments - Field test procedures for surveying and measuring instruments - Part 2: Levels [16].
In the calculations and results, the heights of the tested points in the Kroonstad reference system are indicated. In addition to levelling, a GPS type HiPer Pro was used to determine the geometry of the slope. Based on these measurements, the model shown in Figure 3 was created.

![The slope model basing on the GPS measurements](image)

Figure 3. The slope model basing on the GPS measurements [11].

The measurements of the points on the slope have been conducted every year since 1997. Basing on the measurements of the behaviour of the measuring points it was established that there are areas that also comprise a danger to the slope stability and in these areas, in 2005, additional measuring points were established. The most unstable section was the section II, including points from 13 to 18 and point 9. This section also indicated the occurrence of local landslide of small range that has stabilized after some time. Location of the benchmarks on the slope side is shown on the figure 4. The measurements were made for previously installed surveying points. The arrangement of geodesic points was determined individually for the examined structure and is connected with the operation of the object and its construction (points from 1 to 8), points located in the cross-section of the slope, numbered from 9 to 13 - their arrangement resulted from the local slip zone occurring in this place.

![Location of the measuring points on the slope in section II (own photo)](image)

Figure 4. Location of the measuring points on the slope in section II (own photo).

Next points up to number 28 are connected with observation of the slope as a whole. The results of the measurements properly processed were presented in a numerical (graphic) form. The measurements made in 2015 were the fourteenth in succession, including the initial session in 1997, for the slopes and
the seventh for the settlements. Twenty-four points on the slope and five points on the surface of the settling ponds were measured. [17]

4. Measurement results
The results of surveys indicate that vertical displacements of all the benchmarks since 1997 range from -19.5 mm (point 6) to -60.8 mm (point 7) for points established in 1997. For points installed in 2005 the results of measurement differences range from -21.5 mm (for point 22) to -83.5 mm (for point 18). In 2012 several points numbered 13, 20, 21 and 30 were added because they were damaged as a result of reservoir reclamation works. No large vertical displacements were recorded at these points. The highest settlement during many years of surveying was measured for point 7 and the lowest for point 6 [17].

The slope measurements were summarized on a column graph presented in Figure 5 [17].

![Figure 5](image1.png)

**Figure 5.** Displacements of points of the surcharge and base of the slope and the zone of local slip [17]

![Figure 6](image2.png)

**Figure 6.** Displacements of additional points installed on the slope in the year 2005 [17]
5. Calibration of the Computational Model

The soil calculation model was calibrated using the above measurements made in 1997-2010. The above calibration was conducted as follows

- In Z_SOIL environment [18], the shape of the slope with its geological location was modelled (figure 7). Individual layers are marked as the macro elements and divided to the finite elements within them in such a way that the continuity of the grid was preserved. The system automatically models the set bank conditions. The side supports were set as articulated – slidable and the lower ones as articulated – unslidable. The basic computational model with the limit conditions are shown in the figure 7 [19].

![Figure 7. Model of the macro-analysed slope with determined geological layers: 1 – clay (Cl), 2 - sandy clay (saCl), 3 – medium sand (MSa), 4 – mineral embankment of clayey sand (Mg[siclSa]) [11].](image)

- In the doctoral dissertation [11], an analysis of the slope model shown in the figure 2 and 4 for the calibration of the Coulomb - Mohr model with non-associated flow rule was conducted. The calculations were conducted for the model subjected to gradual load q [kPa] of the values: 15, 30, 60, 120, 180, 240, 300, 360, 420, 480, 520, 600, and 660 kPa. The material constants obtained during the geotechnical tests were inserted into the program as the material data, except for the additional parameter of the relative dilation angle. This angle depends on the value of the effective internal friction angle. Within the calibration of the model, calculations were conducted with the set load for the value of the dilation angle of: 0.2ϕ', 0.4ϕ', 0.6ϕ', 0.8ϕ'. The calculations were also conducted for the associated flow rule that is with the dilation angle equal to the internal friction angle.

- The representative measuring point was selected on the surcharge of the embankment. At this point, the vertical shift with the load increased incrementally was calculated. The analysis was illustrated by the graph shown in the figure 8. The colour indicates the individual values of the ratio of the dilation angle to the internal friction angle. The above graph shows the vertical shift of the representative point. As can be seen, not for every value of the dilation angle, full curves "load – settling" were achieved. The procedure turned out to be divergent, generally the sooner the closer to zero or one was the ratio of the dilation angle to the internal friction angle obtained. The longest curves were obtained for the relative dilation angle of 0.4ϕ’ and 0.6ϕ’.
The calibration criterion was the compatibility of the theoretical settlement curve of the representative point with the results of the geodetic measurement. During the measuring works, recultivation of the bleaching water reservoirs situated over the slope was carried out. During this time, on the slope there stood the trucks with trailers loaded with the chemical agent for the land recultivation. This fact was used to determine the shift responding to the increase of the load using the geodetic method. The increase was 7.3 mm. The start shift at this point from the start load of

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**Figure 8.** Graph of the vertical shift of the point 13 located at the surcharge with incrementally increasing load of the surcharge [11]

**Figure 9.** Comparison of the calculated vertical shift of the point located on the slope surcharge and the shift obtained in the monitoring [11]
15 kPa was -3.4 mm. The load during the works was 42 kPa. The above results of the monitoring were compared with the calculations with the changing value of the dilation angle. The results of the comparison are shown in the figure 9.

- For better recognition of the ratio of the dilation angle to the internal friction angle, additional calculations for the values of the load matching the load during the works were carried out. The results of the measurements are shown by the red dotted line. It was concluded basing on the comparison of the curves that the best compliance of the theoretical estimations to the measurements is achieved for the dilation angle of 0.2$\phi'$. To make sure, additional calculations of the point shift for the ratio of the dilation angle to the internal friction angle: 0.1, 0.15, 0.3, and 0.35 were carried out. In all cases, the deviations are higher.

6. Results

The results of measurements were compared with the results of calculations performed in Z_Soil program. Maps of the development of plastic zones for the assumed $\Psi=0.2\phi'$ were prepared in it. For the slope model shown in Figure 7, a plot of the development of plasticization zones under loads of 15, 240 and 355kPa was made. These values were the limits considered for the Coulomb - Mohr model with non-associated flow law. The results are shown in Figure 10. As can be seen on the cross-section, a zone is locally formed on the slope, the stability of which may be disturbed (Figure 10a - pink zone on the slope inclination). This zone develops slowly with subsequent loading. The development of this zone is consistent with the local landslide observed in reality, which later stabilized. The slope has never been subjected to boundary loading in its history.

![Figure 10](image)

Figure 10. Distribution of the plasticization zones in the slope – a) load of 15 kPa, b) load of 240 kPa, c) load of 355 kPa [11]

7. Conclusions

Monitoring of soil structures is nowadays a very complex and extensive form of various activities. Such monitoring includes not only geodetic measurements, but also strength tests of the soil that builds up the slope and in-depth tests locating slip zones. In recent years, the research methods used in monitoring have developed considerably.
First of all, the possibility of remote data transmission, described in works [13], [20] and [21], should be mentioned here. Laser scanning is used to accurately monitor the surface of earth structures, as described in more detail in [22] and [23]. Inclinometers, fibre optics or displacement sensors are used in monitoring systems of soil structures.

In this resource of different methods, the geodetic method of measuring the displacement of fixed points is probably the most popular and most commonly used mainly due to cost. Geodetic methods can be used not only to observe displacements of soil structures but also to calibrate mathematical models used for calculations and checking slope stability.

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