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A comparative analysis of the results of terrestrial laser scanning and numerical modelling for assessing the stability of a road embankment on the active landslide on the Just mountain at Tęgoborze at Just – Tęgoborze

Analiza porównawcza wyników naziemnego skanowania laserowego i modelowania numerycznego dla oceny stateczności nasypu drogowego na aktywnym osuwisku Just – Tęgoborze

Abstract

This article presents a method for the quick assessment of the safety of the road on an active landslide on the Just mountain at Tęgoborze using the landslide hazard ratio of landslide movements. The hazard indicator for landslide traffic has been defined as the quotient of the largest displacements obtained from measurements using a terrestrial laser scanner to the largest displacement obtained from a numerical model of the worst geotechnical conditions and an unstable landslide. The application of this indicator was presented on the example of national road No. 75 along the section of the road in km from 51 + 900 to 52 + 700 at the location of the Just mountain at Tęgoborze in the south of Poland. The road is located on an active landslide and has a lot of traffic. The measurements were conducted with the RIEGL. VZ400 terrestrial laser scanner from 2012 to 2016. As a result of the measurements performed with a terrestrial laser scanner, a cloud of 3D points was obtained. Differential models of subsequent measurements were constructed and compared to the first base measurements. The results of 3D differential models obtained from terrestrial laser scanner measurements were compared with results obtained from 3D numerical modelling. Numerical calculations were conducted assuming the worst geotechnical conditions. The model of the landslide was fully saturated. A numerical simulation computed using the finite element method (FEM) in the MIDAS GTS program was applied. A result of the safety factor F = 0.8 (i.e. an unstable landslide) was obtained. In order to estimate the hazard, the values of the landslide hazard indicator were determined for each date using the measurements conducted with the laser scanner.

Keywords: landslides, terrestrial laser scanner, numerical modelling, FEM

Streszczenie

W artykule przedstawiono metodę szybkiej oceny bezpieczeństwa drogi na osuwisku za pomocą wskaźnika zagrożenia ruchem osuwiskowym. Zdefiniowano wskaźnik zagrożenia ruchem osuwiskowym jako iloraz największych przemieszczeń wyznaczonego z pomiarów naziemnym skanerem laserowym do największego przemieszczenia wyznaczonego z modelu numerycznego dla najgorszych warunków geotechnicznych i niestatecznego osuwiska. Przedstawiono zastosowanie tego wskaźnika na przykładzie odcinka drogi krajowej nr 75 wzdłuż odcinka drogi w km od 51 + 900 do 52 + 700 w miejscowości Just-Tęgoborze na południu Polski. Droga położona jest na czynnym osuwisku i ma duże natężenie ruchu. Pomiary przeprowadzono naziemnym skanerem laserowym RIEGL. VZ400 w okresie od 2012 do 2016 roku. W wyniku pomiarów naziemnym skanerem laserowym otrzymano chmurę punktów 3D. Wykonano modele różnicowe kolejnych pomiarów w porównaniu do pierwszego bazowego pomiaru. Porównano wyniki modeli różnicowych 3D otrzymanych z pomiarów naziemnym skanerem laserowym z wynikami otrzymanymi z modelowania numerycznego 3D. Obliczenia numeryczne przeprowadzono dla najgorszych warunków geotechnicznych czyli całkowitego nasycenia osuwiska metodą elementów skończonych (MES) w programie MIDAS GTS. Otrzymano wynik współczynnika stateczności F = 0,8 czyli osuwisko niestateczne. W celu oszacowania zagrożenia wyznaczono wartości wskaźnika zagrożenia osuwiskiem dla każdej daty wynikającej z przeprowadzonych pomiarów skanerem laserowym.

Słowa kluczowe: osuwisko, naziemny skaner laserowy, modelowanie numeryczne, MES

1. Introduction

Landslides are a very dangerous phenomenon for road infrastructure. They cause large material losses and disrupt transport [11, 20]. of quick risk assessment for roads located on active landslides are still being sought. This article proposes a method for the quick assessment of road safety on a landslide with the aid of the landslide hazard indicator. The hazard indicator for landslide traffic has been defined as the quotient of the largest displacements obtained from a terrestrial laser scanner to the largest displacement obtained from a numerical model for the worst geotechnical conditions and an unstable landslide.

In Poland, the largest landslide threat to roads occurs in the Carpathian mountains in the south of the country south of the Carpathians (Fig. 1). It results from the geological structure of the Carpathian flysch, which largely consists of sandstones and shales [13, 18]. Sandstones and shales are arranged alternately, which causes the formation of slip planes in layers of clay shales, which easily become soggy. A feature of the geological structure of the Carpathian flysch is also the existence of a weathered zone under the soil layer, which is characterised by a large extent of rock material. Such a layer of weathered zone laid on a bedrock has a great susceptibility to landslide because a slip zone is formed between the weathered zone and the bedrock. Slip planes may be a useful non-invasive method of seismic interferometry [19]. Many scientists have assessed the threat to the infrastructure of landslides including [1, 4, 6, 10, 21].

Over 95% of all landslides in Poland are registered in the Carpathians. Zabuski et al. [23] reported that 625 road sections (statistically, one landslide on every 5 km of public roads) and 86 sections of railway tracks (statistically, one landslide on every 10 km of railway line) were in the Karpaty region threatened by a landslide. Currently, the situation is more serious as it is related to climate change and the development of infrastructure, where it is not possible to avoid landslides. Landslides threaten buildings and infrastructure. The damage caused by landslides results in huge material losses and constitute a real threat to human life (Fig. 2). Figure 3 presents a summary of the number of landslides occurring on individual national roads within the Krakow Branch of the General Directorate of National Roads and Motorways

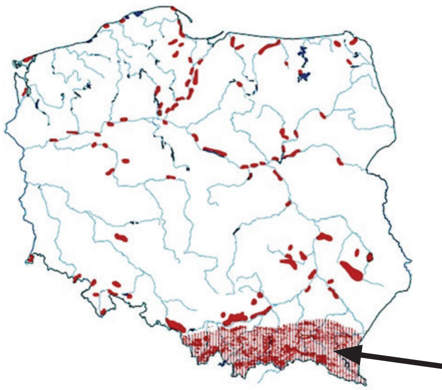

Fig. 1. The landslide threat in Poland [24]

Fig. 2. Landslide on national road No. 87, 28 June 2009 [26]

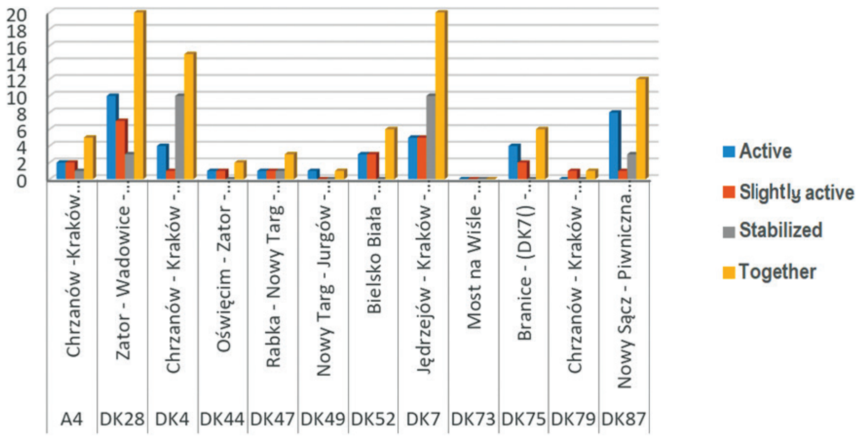

Fig. 3. List of the number of landslides occurring on individual national roads within the Krakow Branch of GDDKiA [16, 24]

(GDDKiA). It can be seen that the most active landslides are on the DK28 Zator–Wadowice national road and on the DK87 Nowy Sącz–Piwniczna route.

The main natural factor for activating landslide movements is water. The saturation of the soil with water results in an increase in its weight as the water displaces the air from the space between the soil particles. Rainfall plays a major role here. Experience shows that long-term rainfall is the most dangerous kind. The additional water contributes to an increase in the water content, the amount of pore water pressure, plasticity or soil compactness and alters rock formations. When the rocks are filled with water, their properties change significantly. Terzaghi [22] has already drawn attention to this problem. Research in this direction on the specific example of landslides was conducted by Ali, et al. [2]. Changing the properties of soils under the influence of water content has a significant effect on their behaviour in relation to pressure. This is of great importance in the formation of landslides. Lowering the cohesion of deeper deposits may lead to larger soil masses. The results of the numerical calculations presented in this article refer to the total losses resulting from landslides, which means the worst geotechnical design variant for the safety factor.

2. Monitoring landslides with a terrestrial laser scanner

For monitoring, surface geodetic methods are used as well as depth monitoring**.** Traditional geodetic methods are not suitable for analysing the vast areas of landslides. Imaging methods are very expensive and labour-intensive. The opportunity for a quick examination of the terrain threatened by a landslide lies in terrestrial laser scanning. This method has been in development all over the world for several years. The laser scanning method applied to road landslides was presented extensively at the Second World Landslide Forum conference in Rome in 2011. In the world literature, many examples of using a terrestrial laser scanner to monitor landslides in close proximity to roads have been shown in publications [5, 7, 9].

Laser scanning is possible in inaccessible places. Kasperski et al. [12] demonstrated the possibilities of using laser scanning to monitor the active Séchilienne landslide in the French Alps. This landslide is a threat to people and to the road RD1091. Similar results of the use of laser scanning were presented by Chinese scientists who determined the risk of a landslide using the example of a landslide in Jingyang, Shaanxi province [15]. The methodology of scanning landslides using a terrestrial laser has been widely developed in many countries, including Italy, the Netherlands, USA and Japan, which has a lot of active landslides as a result of earthquakes. In Poland, measurement technology based on the measurements of terrestrial laser scanners has been in development for several years and has been applied in many areas. It is used in the creation of three-dimensional models of terrain, buildings. Devices are used to detect defects and faults. The first landslide measurements were made at the Polish Geological Institute – the Research Institute [14]. Based on the examples of performed displacement measurements, it may be stated that the use of a terrestrial laser scanner enables the determination of the displacement value with millimetre accuracy. At the same time, the measurement time is shortened, the composition of the qualified measuring team is reduced to one person and the values of the occurring displacements are immediately obtained.

Terrestrial laser scanning is a technology in which the time of the return of a laser beam reflected from the tested surface to the measuring device is measured [3]. Knowing the speed of the electromagnetic wave and the time, the device calculates the distance from which there is a coherent point in space. The emission angle of the laser beam (vertical and horizontal) is also recorded. As a result, after completing the necessary number of measurements (scanners have the ability to process about 200,000 points per second [17], a point cloud is obtained (a set of coordinates of points X, Y, Z) in relation to the position of the scanner. As a result of this, knowing the exact position of the device in space, after recalculation (occurring automatically), the actual coordinates of the measured points are obtained, which produces

Fig. 4. Measurements with a laser scanner on the Just – Tęgoborze landslide [16]

a three-dimensional model of the terrain after further processing. The treatment is necessary to remove irrelevant elements (e.g., plants). It is also important to take measurements from many places (scanner located in different positions) not only does this make the obtained results are more reliable, it also enables the obtaining of data that may be impossible to obtain from another measurement point (part of the area may be obscured by terrain obstacles, rocks, trees, etc.).

In the case of landslide movements, having the results of several measurements performed at certain time intervals by overlapping individual models it is possible to determine the range and size of displacements. As a result of this, the identification of a potential landslide is possible. On the basis of this model, differential analyses and other measurements and calculations are made for the object being scanned. The accuracy of the scan results is approx. 1–5 mm. The RIEGL VZ-400 terrestrial laser scanner was used for the measurements (Fig. 4).

3. Results of measurements with a terrestrial laser scanner

The measurements were performed on a road embankment located on the Just – Tęgoborze landslide. These measurements were conducted cyclically, twice a year; in the spring, after the snow subsided, and then a second measurement, usually in the autumn. The measuring points were located in such a manner as to monitor places of possible moves of road embankment and escarpments on the landslide. National road No. 75 passes through the landslide (Fig. 5).

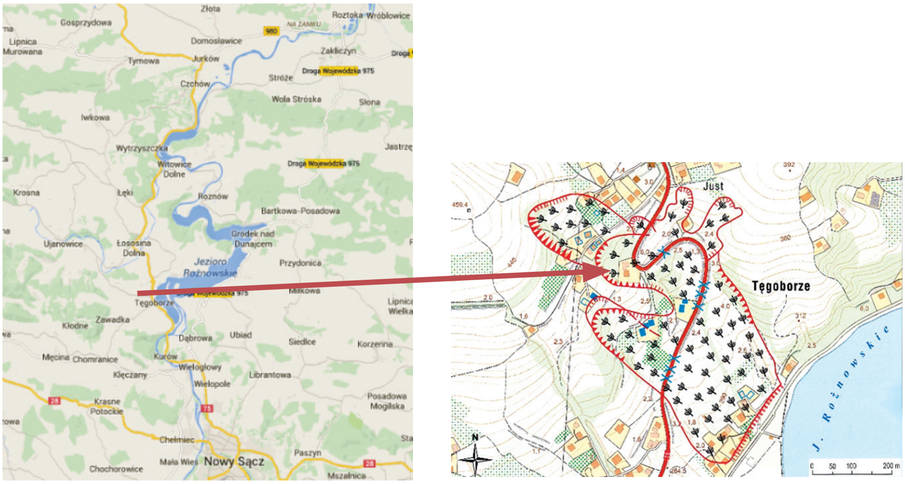

Fig. 5. Location of the Just – Tęgoborze landslide [25]

The terrestrial laser scanner was always located in the same position as determined by GPS coordinates. The processing of data obtained in the scanning process was performed using specialised RiSCAN PRO software. The first measurement was conducted on 10 November 2012. On the basis of these measurements, a three-dimensional landslide model was generated which included the path located on it (Fig. 6).

Fig. 6. Three-dimensional terrain model DK 75 on the Just-Tęgoborze landslide [16]

A further five series of measurements were performed (27.04.2013, 22.10.2013, 04.04.2014; 14.08.2014; 11.06.2016) on the basis of which, displacements occurring in the investigated area of the Just landslide were analysed. Different models were made at different time intervals. Recently, drainage works have been executed in the Just landslide and this has resulted in a change in the morphology of the area. For this reason, the analysis was performed on archival data. Differential models show vertical displacements occurring at given time intervals. The reference point in time was the so-called zero measurement. In this way, variations in displacement changes in the area of interest may be tracked. However, it should be noted that on the monitored area of the landslide, there were constant movements of the colluvium, and therefore in a given place, there may be a negative displacement at a given time, i.e. a ground loss or positive soil movement due to the ground shifting from the top of the slope. Sometimes, at a given moment in time, there may even be a zero displacement, i.e. the ground mass may have moved, therefore, in comparison with the zero measurement in the differential model, it would have zeroed out. The results of the differential numerical models are shown in Figs. 7; 8; 9; 10 and 11. The analysis was conducted in the area of greatest deformation obtained in the numerical model (the area indicated by the rectangle).

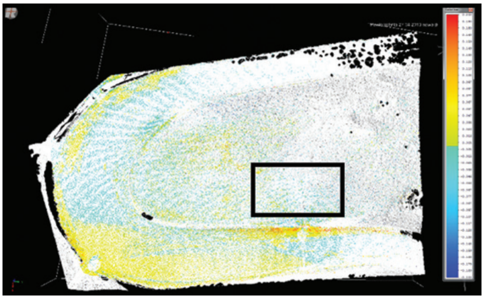

Fig. 7. The differential model between the zero measurement on 10.11.2012 and the control measurement on 27.04.2013

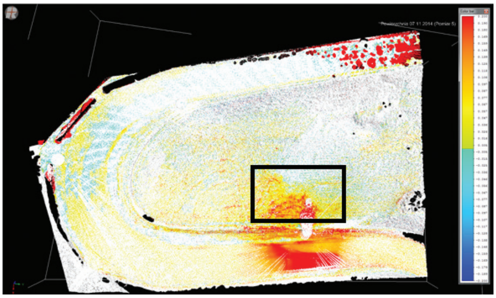

Fig. 8. Differential model between the zero measurement on 10.11.2012 and the control measurement on 04.04.2014

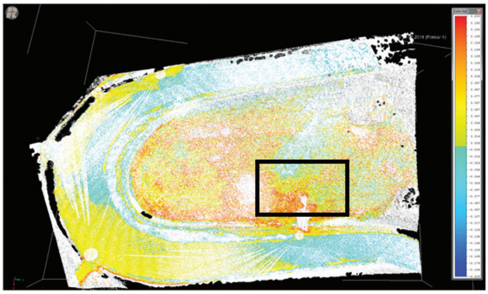

Fig. 9. Differential model between the zero measurement on 10/11/2012 and the control measurement on 14/08/2014

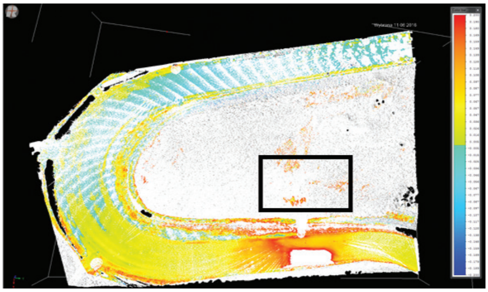

Fig. 10. Differential model between the zero measurement on 10/11/2012 and the control measurement on 11.06.2016

Figure 12 shows the maximum displacements in the test area based on the results obtained in Figs. 7 to 11.

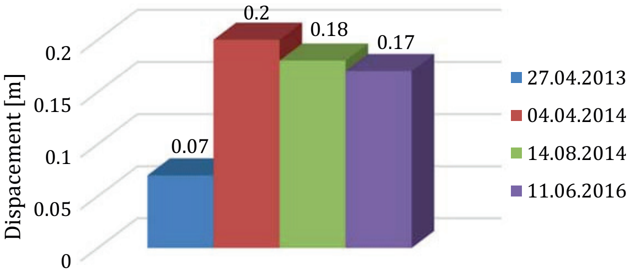

Fig. 11. Maximum displacements read for the tested section

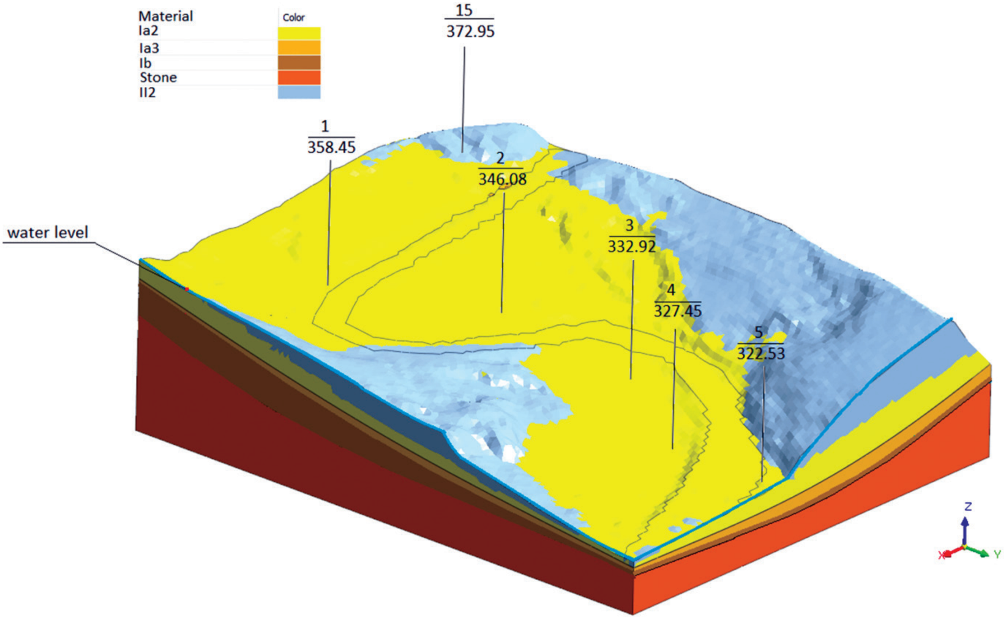

Fig. 12. Geotechnical model of the landslide area in the region of Just – Tęgoborze

4. Results of the numerical stability analysis

The numerical analysis was performed on the 3D spatial model. The model was constructed on the basis of data from six holes [8]. The location of the holes is shown in Fig. 13. The lithological limits have also been confirmed by seismic interferometry studies [19]. The most unfavourable level of the landslide fault were marked. This is a theoretical case of full landslide irrigation. Such a case may take place as a result of, for example, heavy rainfall over a long period of time.

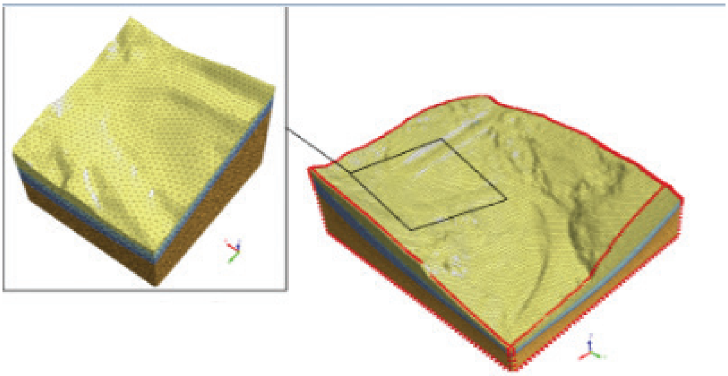

Fig. 13. Model for numerical calculations using MIDAS GTS NX software

The calculations include the values of the physical and mechanical parameters of individual layers (Table 1).

Table 1. Physical and mechanical parameter values of individual layers

Symbol	Density ϱ[g/cm^3]	Poisson ratio *v* [-]	Angle of internal friction φ [o]	Cohesion *c* [kPa]	Deformationmodulus E_0 [MPa]
Asphalt	2.05	0.30	-	-	9,000
Ia2**	1.9	0.30	10*(12)	15*(18)	14
Ia3**	1.9	0.30	10*(15)	15*(25)	17
Ib**	2.18	0.30	15	23	33
Stone	2.5	0.20	–	–	,2000
II2**	2.15	0.30	21	30	27

* introducing the angle of internal friction and cohesion, taking into account flooded area ($I_L > 0.75$)
** Geotechnical layers were adopted on the basis of geotechnical documentation [8] Ia2,Ia3-refers to clay colluviums: saciSi, saclSiOr, Co,clsiOr, saSi, siSa, Ib refers to soft rock, IIa refers toclay delluvium (sasiCl, Cl)

The numerical analysis was performed in the spatial state of stress and strain. The linear elastic-perfectly plastic behaviour of the considered ground was taken into account. The soil model was based on the Coulomb-Mohr hypothesis. A simplified course of geotechnical layers was established, and determined on the basis of geological – engineering documentation (Fig. 14) [8]. The discretisation of the area was made on the basis of quadrilateral elements. Figure 12 shows the area that was then analysed in the context of vertical displacements for the total level of failure. The area is the same as for the 3D scans analysed above. A numerical analysis was conducted over a larger area to avoid the influence of boundary conditions on the results.

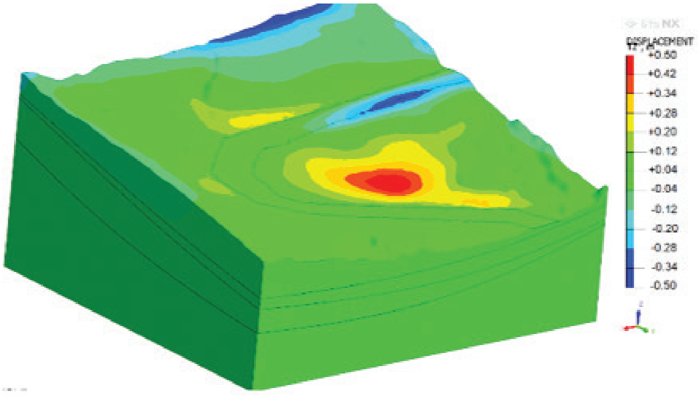

Fig. 14. Results of vertical displacements calculated using the FEM in the MIDAS GTS NX software

As a result of numerical analysis for the conditions of complete failure, a model was obtained that proved to be unstable (safety factor lower than 1) $F = 0.8$. The indicator determined by shear strength reduction method. It is important that reduction of effective stress affecting the reduction of shear strength. In these conditions, vertical displacements illustrate the displacements for boundary conditions (Fig. 15) and may be compared with the vertical displacements obtained by an experimental method from terrestrial laser scanner measurements. From numerical modelling for the conditions of total maximum windfall and slope loss stability, the vertical displacement is 0.5 m. In order to assess the hazard, the landslide hazard indicator R_0 was defined using the following relationship [16]:

$$R_o = \frac{d_{\max}}{D_{\max}} \cdot 100\% \qquad (1)$$

where:

- $d_{\max}$ – the maximum displacement obtained from the differential model obtained from measurements using a laser scanner,
- $D_{\max}$ – the maximum displacement obtained from the numerical model for a given level of ground failures.

The results are summarised in Table 2.

The maximum displacement was considered in order to always assess the most unfavourable situation from the point of view of landslide movement. As seen in Table 2, the threat of landslide movement has different values depending on the displacement measured with the ground laser scanner. Different values of measured displacements at different times result from the movement of the colluvium along the slope and testify to the uneven progress of landslide movements.

Table 2. Hazard indicators for various time periods

	Date	Number of days from zero measurement	Maximum displacement [m]	Hazard indicator
1	2013-04-27	168	0.07	14%
2	2014-04-04	510	0.20	40%
3	2014-08-14	642	0.18	36%
4	2016-06-11	1309	0.17	34%

The following limit values for the landslide hazard indicator have been proposed: $R_0 \geq 50\%$ – increase in the risk of landslide movement, $R_0 \geq 70\%$ – large threat of landslide movement, $R_0 \geq 90\%$ – very large threat of landslide traffic.

5. Summary

The article has presented a methodology for assessing the safety of roads located on natural landslides based on a landslide hazard indicator. The indicator has been defined on the basis of the numerical modelling of landslides and surface monitoring by the RIEGL VZ-400 terrestrial laser scanner. The tests were performed on a section of the road passing through an active landslide. Measurements were conducted from 2012 on national road No. 75 along the section of the road in km from 51 + 900 to 52 + 700 in the town of Tęgoborze – Just. The research was performed on a well-known geologically active landslide. An appropriate level of geological-engineering recognition guarantees the reliability of the obtained results. The presented method of assessing the level of landslide hazard could be used to quickly assess the safety of a road on a landslide.

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