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Research paper

Landslide triggered by small excavation – numerical simulations

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Abstract: The main objective of this work is to present the results of numerical simulations of the landslide triggered by small excavation. In south-eastern Poland in 2019, during excavation for a gas pipeline (relatively small – maximal depth 2.7 m), a landslide was observed. Length of the landslide was about 80 m, width about 50 m, maximal depth 6.5 m. Excavation was partially buried. Observed cracks of the terrain surface were wide, up to 0.8 m. Stability of the landslide was analyzed using the proportional reduction of the soil strength parameters (c-fi reduction) algorithm with the use of ZSoil.PC Finite Element Method (FEM) system. Stability analysis of the slope before and after excavation was performed, together with analysis of the tendency of the landslide to propagate upwards. The obtained stability loss modes were compared with the results of the field observations and a good correlation was noticed. Hypothesis that a landslide was triggered by small excavation was proved (although reasonable margin of safety was obtained for state before excavation, stability factor SF = 1.60). Use of residual soil strength parameters (instead of peak ones) and activation of cut-off (no tension) condition are advised. Presented methodology is open and can be used in engineering practice.

Keywords: landslide, Finite Element Method (FEM), numerical modeling, stability

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1. Introduction

Landslides are, according to [1], complex phenomena. The main factors, which have a significant influence on their behavior, are changes in the geometry of the slope (excavations or construction of the embankments) and changes in water conditions [2–4], especially due to heavy rainfall. More information about landslides causes are given in [5] and [6]. Due to the complexity of the problem, classic engineering methods (Fellenius, Bishop, Janbu, Morgenstern-Price) for stability assessment often fail [7]. In this situation, numerical analysis of the stability could be useful [2, 7–13] giving possibility to model landslide problems very close to the reality. Stability analysis of the landslide is usually performed with use of strength reduction (c-ϕ reduction) method (described in details in [14, 15]). Main advantage of the strength reduction method is that initial assumption of the stability loss mechanism (shape of the sliding surface, cylindrical or other) is not required – shape and location of the failure surface is a result of the simulation. Back analysis is often used to estimate soil strength parameters (cohesion and friction angle), examples are given in [16–18]. However, back analysis problems are often ill-based, so different set of parameters could results in almost this same results.

Combined, multidisciplinary (geophysical and geotechnical) approach to a landslide stability problem is often used, examples are given in [6, 8, 19].

Monitoring of the landslide also could be used to judge if a landslide is active and to identify potential stability loss mechanism. For example, terrestrial laser scanning (described in [5]) or inclinometric monitoring [17] could be used.

Influence of the excavation on landslide stability could be complicated. Two problems should be distinguished: local stability of the excavation wall and global stability of the whole slope (Fig. 1). Very common bad design practice is to protect only local stability of the excavation walls without taking into account global stability of the slope.

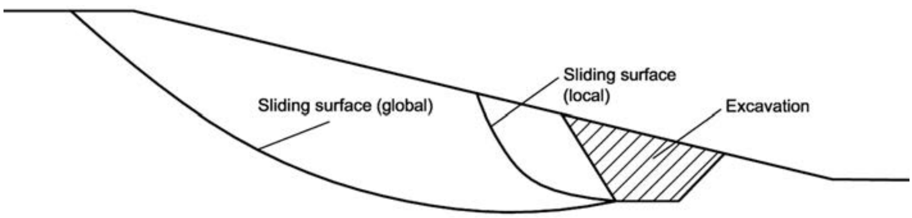

Fig. 1. Local and global stability problem

In general, excavation near the top of the slope improves global stability of the structure, but excavation in the bottom part of the slope worsen. It is obvious, because the weight of the soil in the upper part of the slope mostly produces destabilizing forces and the weight of the soil in the bottom of the slope results mostly in stabilizing forces (Fig. 2).

Example of a large landslide caused by excavation id given in [20]. Similar problem is analyzed in [21], the results of numerical simulations with use of strength reduction method are presented. Negative influence of the excavation on slope stability is clearly demonstrated. Centrifuge tests described in [22] show tendency of the excavation – induced

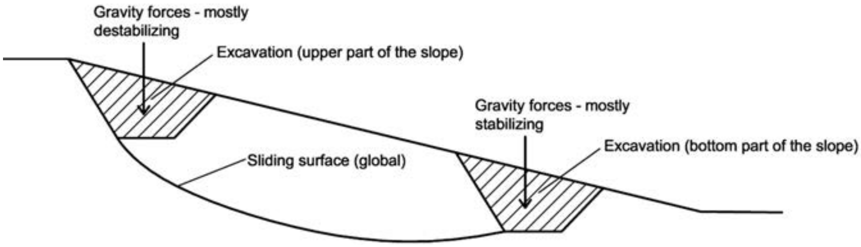

Fig. 2. Excavation in the upper and bottom part of the slope

landslide to propagate upwards. Special attention is paid to the tensile failure of the soil in the upper part of the slope.

2. History of the case

In 2019, in a mountain region of south-eastern Poland excavation for a gas pipeline was executed. Excavation was a linear one, unsupported, with a depth of about 2.7 m. Walls of the excavation were rather steep, with an inclination 1:0.64. During the earthworks stability loss of the soil mass occurred, the excavation was partially buried. Initially, the problem was identified as a local problem of the excavation itself. However, cracks of the slope surface were observed above the sliding zone (Fig. 3). Therefore it was not a

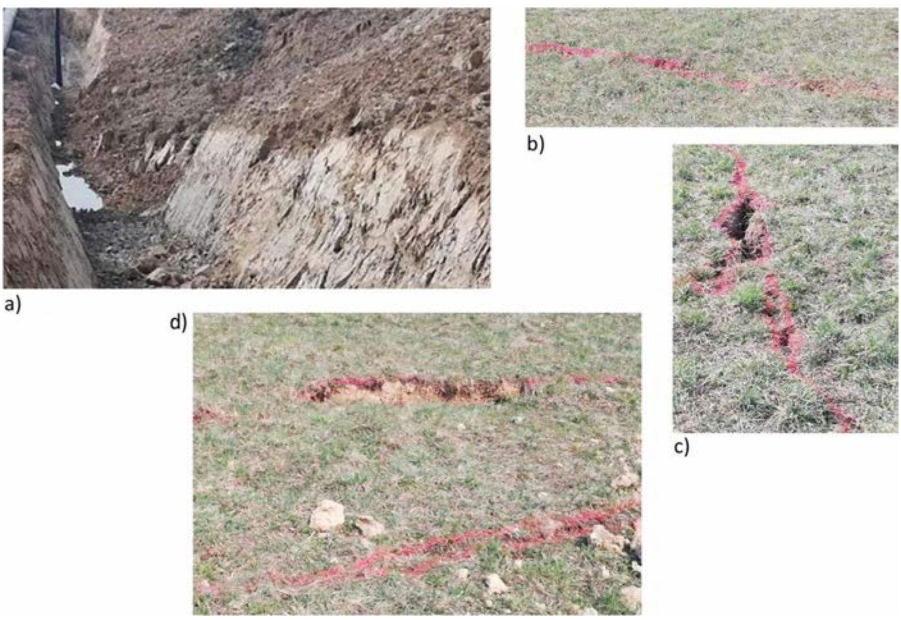

Fig. 3. Landslide photo a) partially buried excavation b), c), d) cracks of the slope surface

local (excavation) stability problem but a global (whole slope) landslide. Further field examinations showed that landslide length (alongside the excavation) was about 80 m, width about 50 m. Observed cracks of the surface had a width up to 0.8 m and a depth up to 1.9 m. An additional geotechnical drilling shows that the sliding surface could be located deeper than it was expected, at a depth of about 6.5 m, in a layer of weak clay.

To find the causes of the landslide activation and to analyze tendency of the landslide to propagate upward, numerical simulations were performed.

3. Numerical simulations

All simulations were performed with the use of ZSoil Finite Element Method (FEM) system. The strength reduction (c–ϕ reduction) method (detailed description could be found in [14, 15, 23]) was used to estimate Stability Factor SF. All simulations were performed in the plane strain conditions (2D model). Mohr-Coulomb elastic-plastic model was used for the soil – mainly because of its simplicity and usability in an ultimate state problems. Usage of cut-off condition (no tension) was tested. Peak and residual soil strength parameters were used in simulations, obtained results were compared. It's not possible to include peak and residual parameters in one simulation, so every presented simulation was run twice – first time with peak and second with residual parameters. Typical, geotechnical boundary conditions for solid phase were assumed – no vertical and horizontal displacements on bottom edge, no horizontal displacements on lateral edges and zero perpendicular to the edge stress on top edge. Numerical model (presented in Fig. 4) consisted of 224 quadrilateral elements and 2305 nodes.

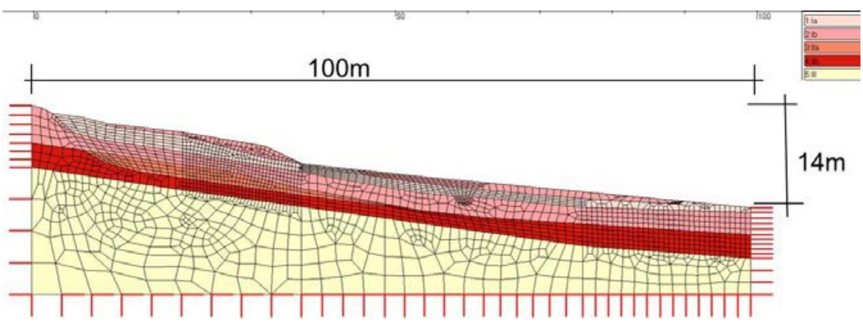

Fig. 4. Numerical model of the landslide area, before the excavation

More sophisticated models (Hardening Small Strain model for example) could be of course used, but for a pure stability problem it would not results in a significant change in obtained results.

Examples of usage of a similar approach to a landslide stability problems are given in [7, 10, 11, 16].

Soil-water composite was treated as a single-phase media. Parameters used in the simulations are given in Table 1. Values of the friction angle and cohesion were obtained from direct shear tests.

Table 1. Parameters of the soil used in the stability analysis

ID	Material	γ [kN/m^3]	ϕ [°]		c [kPa]		E [MPa]
			residual	peak	residual	peak	
1	Ia (clSi)	18.7	13.4	14.6	5	7.9	18.4
2	Ib (clSi)	19.8	22.6	25.5	18.6	20.7	23.1
3	IIa (Cl)	16.8	7.9	8.5	5.8	7.3	12.2
4	IIb (Cl)	19.7	20.6	21.5	32.8	34.8	15.4
5	III (schist – soft rock)	22	21.5	21.5	34.8	34.8	300.0

First of all, a stability analysis of the slope without excavation was performed. The obtained values of stability factor between SF = 1.60 (for residual soil parameters with cut-off condition) and SF = 1.96 (for peak soil parameters without cut-off condition) show that failure of the slope is not probable. However, signs of described before potential deep sliding surface were observed (see Fig. 5).

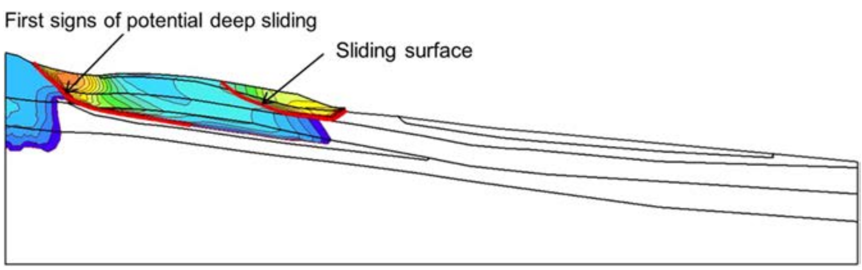

Fig. 5. Sliding surface, before the excavation

Then, analysis of the stability of the slope after excavation was performed (for the numerical model see Fig. 6).

Obtained SF = 1.0 (for residual soil parameters with cut-off condition) show that the excavation was a source of the landslide activation. For peak parameters SF = 1.59 was obtained when cut-off condition was activated and 1.96 when not. So residual parameters with cut-off condition enable to model stability loss of the landslide much closer to the reality than peak ones. Usage of peak parameters without cut-off condition results in neglecting of the influence of the excavation on slope stability, which is incompatible with observed in reality stability loss. Use of back analysis to estimate soil strength parameters was not necessary in this case. Obtained values of SF are given in Table 2.

In the further analysis residual parameters with cut-off condition were used. However, the sliding zone observed in the simulations is relatively small (Fig. 7), smaller than cracked

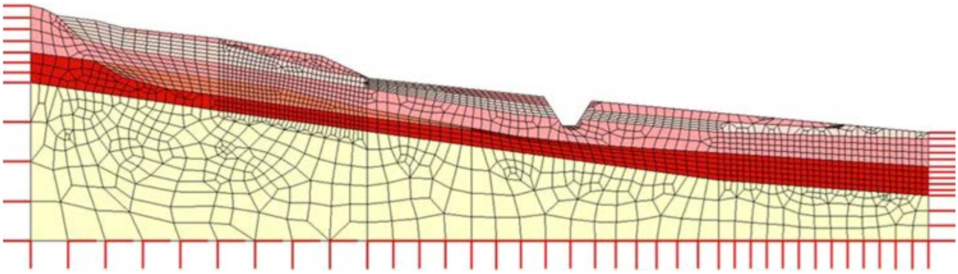

Fig. 6. Numerical model of the landslide area, after the excavation

Table 2. Stability calculations results – values of SF

	Peak c and ϕ		Residual c and ϕ	
	cut-off	no cut-off	cut-off	no cut-off
before excavation	1.95	1.96	1.60	1.71
after excavation	1.59	1.96	1.00	1.55

zone observed in the field. Therefore analysis of the tendency of the landslide to propagate upwards was analyzed. To perform such an analysis, the soil from the sliding zone was removed from the numerical model and stability analysis was performed again. This is a bit conservative approach, because soil from the sliding zone does not "disappear" in reality. It has (after landslide occur) very low strength parameters (c and ϕ), but its weight is still acting as a "support" of the downside of the slope. Such analysis was performed several times, as long as SF > 1.50 (according to [2] SF > 1.50 show that landslide failure probability is very low).

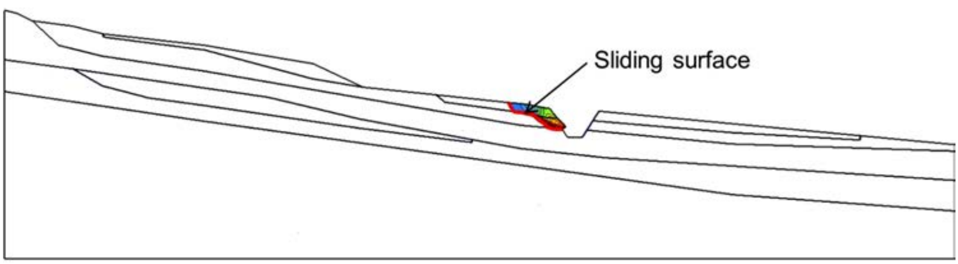

Fig. 7. Sliding surface, after the excavation, residual soil parameters

Obtained results show that the sliding surfaces of the first 8 phases of the landslide propagation are rather shallow, the sliding zones are small (width about 1–2 m, see Fig. 8, volume between 2.4 and 5 m^3/m, see Table 3). Sliding surface of the 9 phase is much deeper (depth about 6.5 m), the sliding zone width is about 35 m, volume is much bigger (141.4 m^3/m). Phases 10 and 11 are also deep, but the sliding zone width is smaller, about

10 m, volume between 30 and 41.6 m^3/m. The probability of the stability loss of phase 12 (SF = 1.65) is very low, so the range of phase 11 (about 55 m from the excavation) could be identified as a maximal range of the landslide. It coincides well with the field observations, where the last signs of the landslide were observed about 50 m from the excavation.

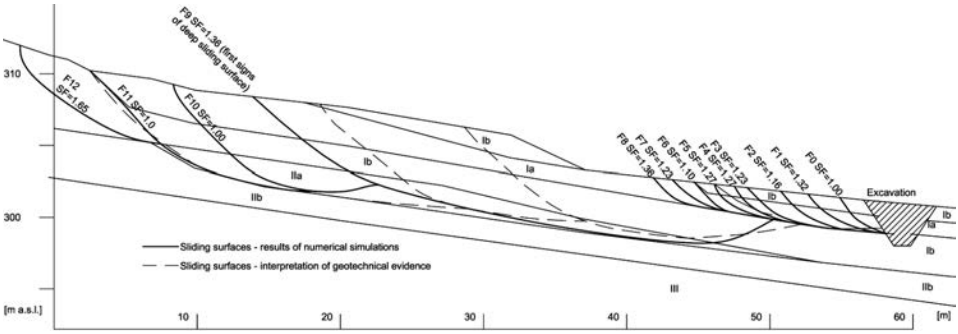

Fig. 8. Landslide propagation analysis results – sliding surfaces and stability factors

Table 3. Tendency of the landslide to further propagation analysis results

Phase	SF	Volume of sliding zone [m^3/m]
1	1.32	4.0
2	1.16	4.4
3	1.23	5.0
4	1.27	2.4
5	1.27	2.8
6	1.10	2.5
7	1.23	2.1
8	1.36	2.6
9	1.36	141.4
10	1.0	41.6
11	1.0	30.0
12	1.65	21.7

4. Conclusions

Performed numerical analysis of the landslide stability proved that the landslide was triggered by excavation. Tendency of the landslide to propagate upwards was analysed and a potential landslide range of about 55 m was obtained. This coincides well with field observations, where the last signs of landslide were observed about 50 m from the excavation. Landslide is active, the design of support structure is necessary. Presented methodology shows its efficiency in dealing with landslide stability problems. Main conclusion for geotechnical engineers is that even a small excavation in the bottom part of the slope could trigger a big landslide, with a sliding zone volume much bigger than volume of the excavated soil. Residual soil strength parameters should be used in such analysis (instead of peak ones) in order to model stability loss process close to the reality. Also cut-off condition (no tension) should be activated.

References

[1] D.H. Cornforth, *Landslides in Practice*. John Wiley & Sons, Inc., 2005.

[2] L. Wysokiński, "The methods of landslides prediction and their protection", in *XXV Scientific Conference "Building failures"*. 2011, pp. 291–320.

[3] D. Sarah and M. R. Daryono, "Engineering geological investigation of slow moving landslide in Jahiyang Village, Salawu, Tasikmalaya Regency", *Indonesian Journal of Geology*, vol. 7, no. 1, pp. 27–38, 2012.

[4] G. Tang, J. Huang, D. Sheng, and S. W. Sloan, "Stability analysis of unsaturated soil slopes under random rainfall patterns", *Engineering Geology*, vol. 245, pp. 322–332, 2018, doi: 10.1016/j.enggeo.2018.09.013.

[5] J. Kogut and E. Pilecka, "Application of the terrestrial laser scanner in the monitoring of earth structures", *Open Geosciences*, vol. 12, no. 1, pp. 503–517, 2020, doi: 10.1515/geo-2020-0033.

[6] J. Kogut, E. Pilecka, and D. Szwarkowski, "Analysis of landslide effects along a road located in the Carpathian flysch", *Open Geosciences*, vol. 10, no.1, pp. 517–531, 2018, doi: 10.1515/geo-2018-0041.

[7] A. Ozbay and F. Cabalar, "FEM and LEM stability analyses of the fatal landslides at Çöllolar open-cast lignite mine in Elbistan, Turkey", *Landslides*, vol. 12, pp. 155–163, 2015, doi: 10.1007/s10346-014-0537-2.

[8] B. Pasierb, M. Grodecki, and R. Gwóźdź, "Geophysical and geotechnical approach to a landslide stability assessment: a case study", *Acta Geophisica*, vol. 67, no. 6, pp. 1823–1834 2019, doi: 10.1007/s11600-019-00338-7.

[9] E. Pilecka, J. Zięba, and D. Szwarkowski, "Analysis of the behaviour of the high and steep slope of a road made through waste under the influence of rainfall", *Archives of Civil Engineering*, vol. 67, no. 2, pp. 293–307, 2021, doi: 10.24425/ace.2021.137169.

[10] A. Truty, A. Urbański, M. Grodecki, and K. Podleś, "Computer aided models of landslides and their protection problems", *Scientific-Technical Papers of Communication Engineers and Technicians of the Republic of Poland in Cracow*, vol. 88, pp. 395–419, 2009.

[11] Y. Zheng, X. Tang, S. Zhao, C. Deng, and W. Lei, "Strength reduction and step-loading finite element approaches in geotechnical engineering", *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 1, no. 1, pp. 21–30, 2009, doi: 10.3724/SP.J.1235.2009.00021.

[12] S.E. Cho, "Stability analysis of unsaturated soil slopes considering water-air flow caused by rainfall infiltration", *Engineering Geology*, vol. 211, pp. 184–197, 2016, doi: 10.1016/j.enggeo.2016.07.008.

[13] J-S. Xu and X-L. Yang, "Three-dimensional stability analysis of slope in unsaturated soils considering strength nonlinearity under water drawdown", *Engineering Geology*, vol. 237, pp. 102–115, 2018, doi: 10.1016/ j.enggeo.2018.02.010.

[14] D.V. Griffiths and P.A. Lane, "Slope stability analysis by finite elements", *Geotechnique*, vol. 49, no. 3, pp. 387–403, 1999, doi: 10.1680/geot.1999.49.3.387.

[15] T. Matsui and K-C. San, "Finite element slope stability analysis by shear strength reduction technique", *Soils and Foundations*, vol. 32, no. 1, pp. 59–70, 1992, doi: 10.3208/sandf1972.32.59.

[16] M. Berti, L. Bertello, A. R. Bernadi, and G. Caputo, "Back analysis of a large lanslide in a flysh rock mass", *Landslides*, vol. 14, pp. 2041–2058, 2017, doi: 10.1007/s10346-017-0852-5.

[17] A. Urbański and M. Grodecki, "Protection of a building against landslide. A case study and FEM simulations", *Bulletin of the Polish Academy of Sciences. Technical Sciences*, vol. 67, no. 3, pp. 657–664, 2019, doi: 10.24425/bpasts.2019.128545.

[18] A. Urbański and M. Grodecki, "Piles system securing road against landslide. 2D/3D method of numerical modeling and design problems", *Bulletin of the Polish Academy of Sciences. Technical Sciences*, vol. 68, no. 6, pp. 1433–1442, 2020, doi: 10.24425/bpasts.2020.135378.

[19] Z. Bestyński, E. Sieinski, and P. Śliwiński, "Geophysical investigation and the use of their results in the evaluation of the stability of slopes of artificial water reservoirs in the flysch Carpathians", *Archives of Civil Engineering*, vol. 68, no. 3, pp. 71–85, 2022, doi: 10.24425/ace.2022.141874.

[20] J.B. Peng, Z. Fan, D. Wu, Q.B. Huang, Q.Y. Wang, J. Q. Zhuang, and W.Y. Che, "Landslides triggered by excavation in the loess plateau of China: A case study of Middle Pleistocene loess slopes", *Journal of Asian Earth Sciences*, vol. 171, pp. 246–258, 2019, doi: 10.1016/j.jseaes.2018.11.014.

[21] J.J. Wang, Y. Liang, H.P. Zhang, Y. Wu, and X. Lin, "A loess landslide induced by excavation and rainfall", *Landslides*, vol. 11, pp. 141–152, 2014, doi: 10.1007/s10346-013-0418-0.

[22] Z.J. Fan, P.H.S. W. Kulatilake, J.B. Peng, W.Y. Che, Y.Z. Li, and Z.J. Meng, "In-flight excavation of a loess slope in a centrifuge model test", *Geotechnical and Geological Engineering*, vol. 34, no. 5, pp. 1577–1591, 2016, doi: 10.1007/s10706-016-0067-x.

[23] S. Commend, S. KIvell, R.F. Obrzud, K. Podleś, A. Truty, and T. Zimmermann, *Computational geomechanics & applications with ZSOIL.PC*. Lauzanne, Switzerland: Rosolis Editions & Zace Services, 2022.

Osuwisko spowodowane małym wykopem – symulacje numeryczne

Słowa kluczowe: Metoda Elementów Skończonych (MES), modelowanie numeryczne, osuwisko, stateczność

Streszczenie:

Artykuł przedstawia wyniki symulacji numerycznych osuwiska wywołanego przez mały wykop. W południowo-wschodniej Polsce w 2019 r. w czasie wykopów związanych z wykonywaniem gazociągu (niewielkich, o maksymalnej głębokości 2.7 m) doszło do powstania osuwiska. Długość osuwiska wynosiła około 80 m, szerokość około 50 m, maksymalna głębokość 6.5 m. Wykop został częściowo zasypany przez osuwający się grunt. Zaobserwowano szerokie pęknięcia powierzchni terenu, o szerokości do 80 cm. Stateczność osuwiska analizowano z wykorzystaniem metody proporcjonalnej redukcji parametrów wytrzymałościowych gruntu ($c - \phi$ redukcji). Obliczenia wykonano za pomocą systemu Metody Elementów Skończonych (MES) ZSoil.PC. Analizowano stateczność zbocza przed i po wykonaniu wykopu oraz tendencję osuwiska do dalszej propagacji w górę stoku. Uzyskane mechanizmy utraty stateczności porównano z wynikami obserwacji terenowych i stwierdzono dobrą zgodność. Hipoteza że osuwisko zostało spowodowane przez mały wykop została potwierdzona (mimo że w stanie przed wykonaniem wykopu zbocze posiadało wysoki współczynnik stateczności wynoszący 1.60). Zaleca się wykorzystywanie w obliczeniach stateczności rezydualnych wartości parametrów wytrzymałościowych gruntu oraz wykorzystanie warunku cut-off (oznaczającego brak wytrzymałości gruntu na rozciąganie). Prezentowana metodologia może być wykorzystana w praktyce inżynierskiej.

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