Scientific Journal of Silesian University of Technology. Series Transport
Zeszyty Naukowe Politechniki Śląskiej. Seria Transport

Volume 118 **2023**

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: https://doi.org/10.20858/sjsutst.2023.118.17

Journal homepage: http://sjsutst.polsl.pl

Article citation information:
Zabuski, L. Stability analysis of the slope subjected to the dynamic loading. *Scientific Journal of Silesian University of Technology. Series Transport*. 2023, **118**, 243-255.
ISSN: 0209-3324. DOI: https://doi.org/10.20858/sjsutst.2023.118.17.

Lesław ZABUSKI[1]

STABILITY ANALYSIS OF THE SLOPE SUBJECTED TO THE DYNAMIC LOADING

Summary. This paper presents the results of a stability analysis of a slope located in the immediate vicinity of a railway line. The plans for the extension of this railway track include the construction of another line, which would run parallel to the existing one, within a few metres distance. It is expected that intensive goods train traffic will generate both static and dynamic forces in the underlying subsoil. Consequently, seismic vibrations will be generated in the subsoil, propagating mainly not only in the horizontal direction but also in the vertical direction. The method of seismic coefficient of the earthquake intensity determined by a pseudo-static method and horizontal component of acceleration is appropriate and recommended because it is simple, and the safety factor of the slope is calculated in the same way as in conventional stability calculations.
Keywords: slope stability, landslide, pseudo-static analysis stability

1. INTRODUCTION

This paper presents the results of a stability analysis of a slope located in the immediate vicinity of a railway line. Loading of the slope results from existing forces which are generated by trains and seismic waves that are mostly horizontal and transmitted into the slope space.

[1] Institute of Hydro-Engineering Polish Academy of Sciences, Kościerska 7, 80-328 Gdańsk, Poland. Email: lechu@ibwpan.gda.pl. ORCID: https://orcid.org/0000-0003-0270-4477

Dynamic load (for example, earthquake) can be also simulated by an "equivalent" static acceleration acting on the mass of the landslide in a limit equilibrium analysis (Figure 1). Static load exerted by the moving train in the analysed case equals 260 kN.

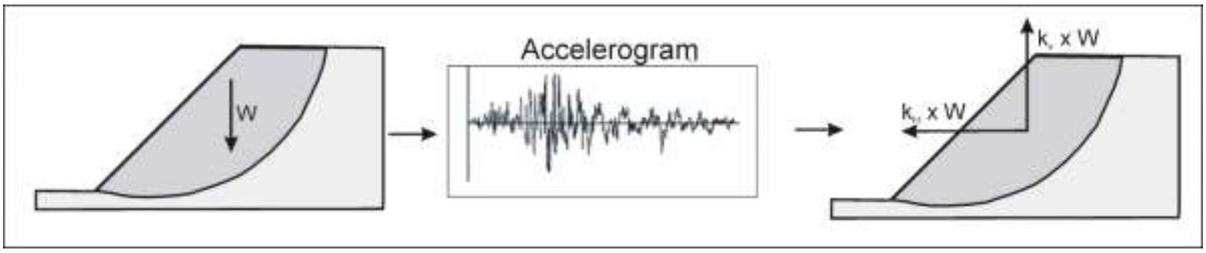

Fig. 1. Principles of the pseudo-static method [20]

The simplest approach to the dynamic slope stability calculation consists of pseudo-static analysis, where the dynamic load is simulated in a limit equilibrium analysis by an "equivalent" static acceleration acting on the landslide mass (Figure 1). The pseudo-static approach is one of the most commonly used in current practice [4-6, 8, 17, 21] alternative procedure is known as Newmark or cumulative displacement analysis [3, 11, 14, 18, 22, 26, 32].

Researchers have developed several calculation methods that affect seismic effects in slope stability problems. Nevertheless, the conventional pseudo-static method is still the most commonly used in engineering design; perhaps because of its simplicity [2, 12, 19, 20, 25, 27-29, 33]. The method of “seismic coefficient”, which is the fraction of the Earth’s acceleration, is proper (as it is simple), and the factor of safety of the slope can be calculated in the same way as in the conventional stability solution. In that, no advanced analysis is necessary.

The important horizontal acceleration k_h is *de facto* unknown so it is necessary to assume its magnitude. Different authors determined k_h in a rather arbitrary way, considering mainly experience and studied *case histories* [27]. The acceleration generally depends upon the local seismic activity, the importance of the infrastructure and the geological properties of the medium. According to Bragato and Slejko [2], strong earthquakes in the Italian Alps caused horizontal seismic waves equal to 0.28 g (where g is Earth acceleration equal to g = 9.81 m/s^2). For “catastrophic” earthquakes, horizontal acceleration equal to 0.5 g could be assumed [20]. Officially approved horizontal acceleration differs depending on the country. In the USA, for example, k_h = 0.05÷0.15 g, while in Japan k_h = 0.12÷0.25 g. Based on Chinese recommendations, Yang Xin Guang et al. [33] assumed k_h = 0.1÷0.4 g, depending on the earthquake intensity. Seed [27] proposed k_h = 0.1 for terrains in the neighbourhood of faults generating earthquakes of magnitude 6.5 (Richter scale) and for earthquakes with magnitude 8.5, k_h = 0.15. These authors determined horizontal acceleration as the product of this acceleration and the above coefficient.

The publications described above concern mainly earthquakes. However, the effect of seismic waves presented in the analysis is identical, although on a much smaller scale. According to the presented considerations, both transversal and longitudinal seismic waves dispersed in all directions from the vibrating source, including horizontal direction, significantly load the surrounding slope and negatively influence their stability.

The influence of seismic tremors is worth mentioning for the sandstone quarry in Lipowica near Dukla in the Low Beskid [1]. Blasting works during sandstone exploitation, and thus, seismic vibrations probably caused the development of a very extensive landslide. This means that most landslides can be related to human activity.

Furthermore, earthquakes with magnitudes ranging from 2 to even 6 on the Richter scale have been recorded in Poland. The greatest number of earthquakes were recorded in mining areas – in Silesia and the Copper Belt (Lubin region in Lower Silesia). However, there is no mention of damage caused by landslides, even though landslide processes, mainly in the Carpathian Flysch, are very intensive. It can be thought that landslides caused by seismicity were either not.

2. CHARACTERISATION OF THE REGION

The area of interest is situated in the region of the province Polish-Central Lowland, sub-province South-Baltic Lakeland, East-Pomeranian and South-Pomeranian macro-regions and the Kashubian Lakeland mesoregion [16, 30]. The land formed in the period of the North-Polish (Vistula) glaciation by the accumulative activity of the continental glacier and melting water. This region constitutes a part of a morainic uplift with extensive outflow fans. The relief of the terrain is diversified and hummocky, and its maximum altitude is 328 m a.s.l. (Wieżyca Mount). The outflow areas are plain and, in some areas, form depressions. Glacial throughs, where lakes have developed, for example, Dąbrowskie, Patulskie and Ostrzyckie (Figure 2), are characterized by steep ridges.

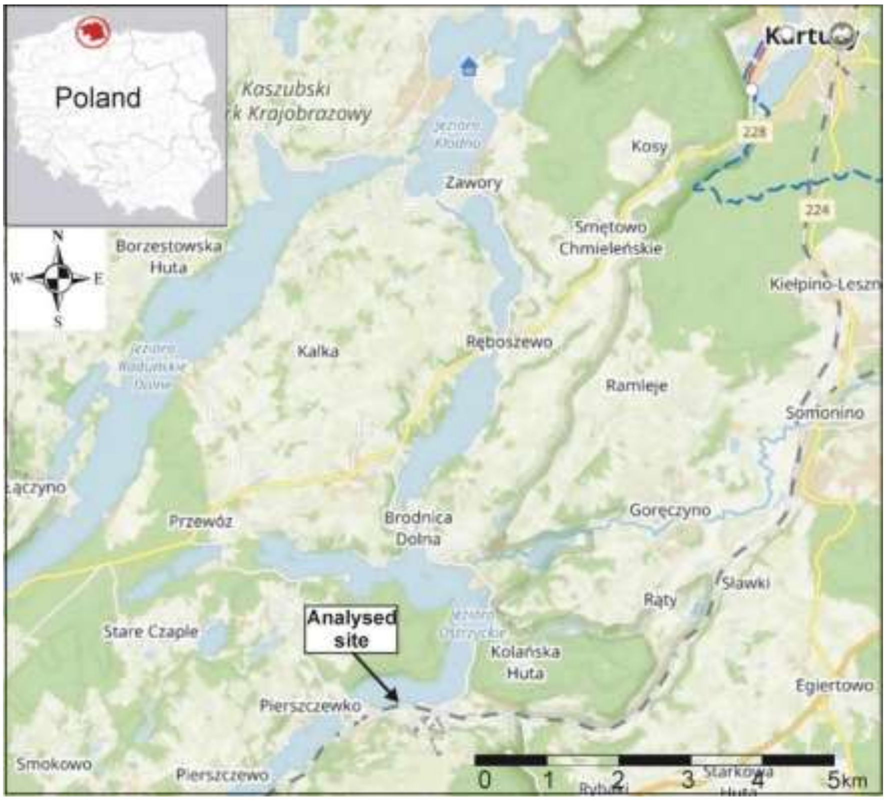

Fig. 2. Location of the test site

No landslides have been recently recorded in the neighbourhood of the tested site, despite this region being considered likely to generate such movements. It is mostly formed as steep scarps of lake shores and larger depressions. These types of terrains can also come in the forms of outwash plains and rivers or slopes of glacier uplifts or denudations.

The foundation soils have diverse properties and include non-cohesive, such as sand and gravel, and cohesive (loam, clay) and organic (peat, silt) soils. The soils take various forms – ranging from firm to soft-plastic.

Hydrogeological conditions are generally favourable. The depth of underground water ranges from 1 m to over a dozen metres. The water table is usually suspended and exceptionally has the character of ground superficial water, which is in hydraulic contact with deeper underground water levels.

3. NUMERICAL MODELS AND PROCEDURE OF ANALYSIS

Numerical analysis of slope stability was performed by applying the two-dimensional explicit Finite Difference (FD) method and using the FLAC2D software [13]. This method is a powerful, accurate and versatile approach to the analysis, both of the stability and displacement of slopes. Its additional advantage is that it makes no assumptions about the failure mechanism. In contrast to the traditional "limit equilibrium" analysis, the FD method provides a full solution to the coupled stress/displacement, equilibrium and constitutive equations [24, 34]

Most of the calculations in the analysis were based on the "strength reduction technique" [9]. The geotechnical reconnaissance showed that the slope is dry and there is no groundwater level. The subsoil is mainly composed of fine and medium sand. Table 1 in the calculation model presents the parameters of soil layers.

The analysis of slope stability was performed for two cross-sections of the slope (Figure 3). Cross-section I-I is drawn approximately in the centre of the building below the slope base and is limited to its immediate surroundings, including the retaining wall supporting this section (Figure 4a). Cross-section II-II starts at the level of the railway line and finishes up to the lake (Figure 4b).

Fig. 3. Location of cross-sections

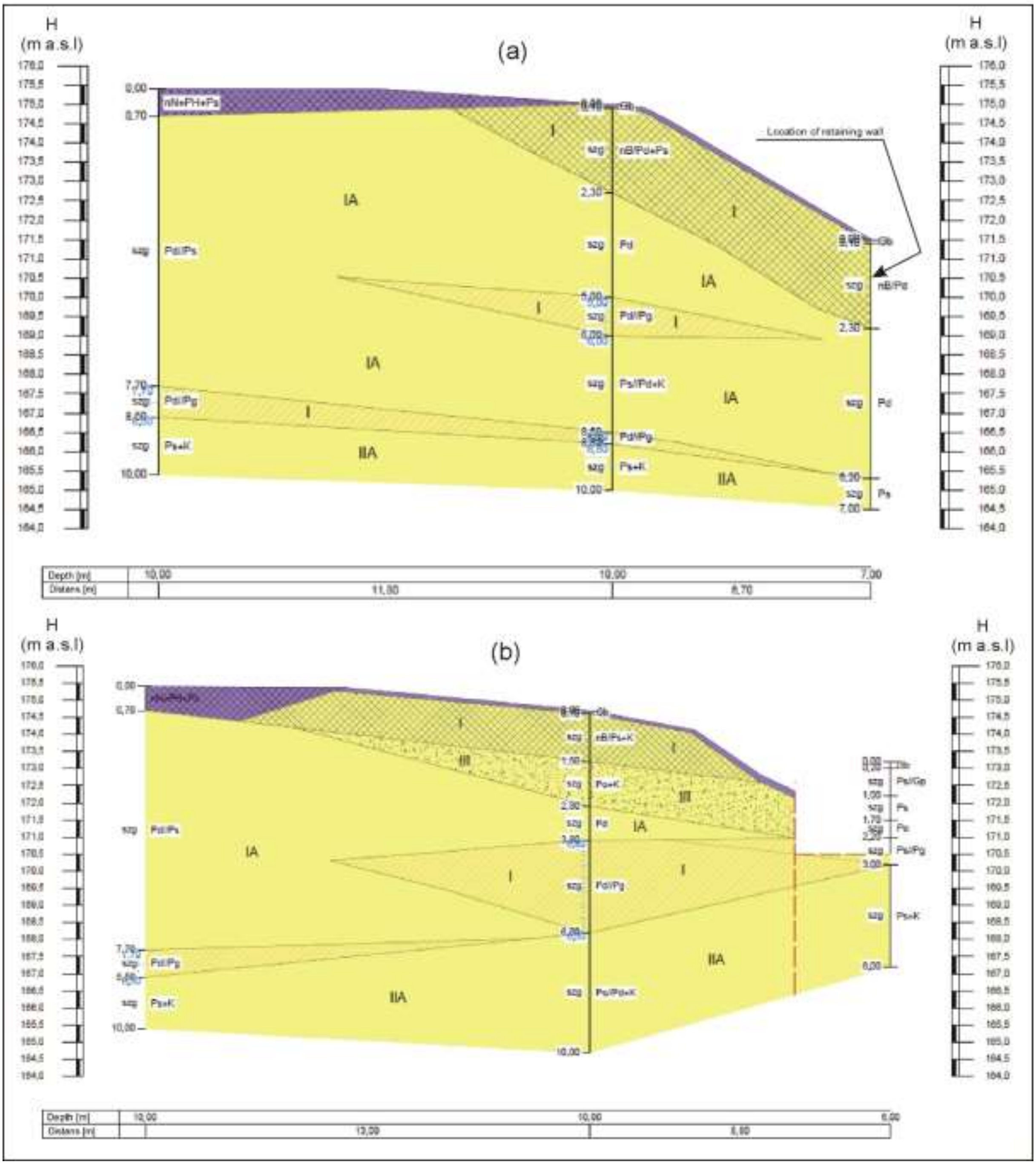

Fig. 4. Analysed cross-sections: a) I-I; b) II-II

Both geomechanical and numerical models are built considering the slope geometry and geotechnical properties of the soil. The model of each cross-section is divided into specific “elements”, that is, finite different zones (FDZ), and the numerical program calculates stress and displacement and determines the state zone (elastic, failed), mode of failure (shear, tension), etc., in each FD zone or nodal point of the mesh.

Figures 5a and b show the division of the slope model into specific geotechnical layers for I-I and II-II, respectively. It was assumed that the lowest zone of the II-II cross-section is built of the IIA layer.

Given the unknown magnitude of the seismic wave, four variants of the α_i, inclination of the acceleration vector were analysed (Figure 6). Angles of the inclination from the vertical, ranging between 5% and 20% (equivalent of seismic wave α_i realised in a pseudo-static way), were considered.

Tab. 1

Geotechnical parameters of soils

No. layer	Soil	Volumetric unit weight γ [kN/m³]	Shear modulus G [kPa]	Bulk modulus K [kPa]	Cohe-sion c [kPa]	Friction angle ϕ [°]
I	Fine sand, “undefined” (uncontrolled) soil	15.95	21154	45833	0	28.13
IA	Fine sand, medium-compacted	15.61	23846	51667	0	28.80
II	Undefined soil, sand medium-loose,	16.31	23846	51667	0	28.80
IIA	Medium-grained sand, medium-compacted	18.62	91667	42308	0	32.40
III	Gravel, medium-compacted	16.91	120833	55769	0	34.20

4. PRESENTATION AND DISCUSSION OF RESULTS

Results of calculations are presented in the form of diagrams of horizontal displacements and zones for the considered variants of deviation of acceleration vector from the vertical. The horizontal displacement fields generated for cross-sections I-I and II-II are presented in Figures 7 and 8, respectively. The concentration of displacement zones in the two railway lines concerns the designed tracks.

Figures 9 and 10 show the distributions of the slide concentration zones and the values of safety factors for cross-sections I-I and II-II, respectively. The safety factors without horizontal acceleration (that is, $\alpha_a = 0^o$) are slightly above 1.0, while in the other cases $\alpha_a < 1.0$; this means that the slope is unstable.

Figure 11 presents the relationship between the slope safety factor for both cross-sections and the deviation angle of the seismic acceleration between the vertical in the general direction of the slope. The diagram indicates that the slope is only stable when acceleration is vertical (that is, $g = 9.81$ m/s^2 without any exceptions and deviations) and when the α_i angles differ only slightly from the vertical; in such cases, the safety margin of the slope is very small. The horizontal line in the diagram illustrates the limit equilibrium state, where safety factor F equals $F = 1.0$. The intersection of this line with the above curves determines the limiting angles of acceleration inclination to the vertical. These angles equal 4.1^o and 2.8^o for the cross-section I-I and II-II, respectively. It corresponds to the acceleration of 0.7 m/s^2 and 0.47 m/s^2, respectively, and after multiplying by the mass of the medium (in mass unit, that is, kg), the horizontal force exerted on the slope is obtained, influencing its stability. Moreover, additional calculations showed that vertical acceleration has an almost negligible influence on the factor of safety of analysed slopes.

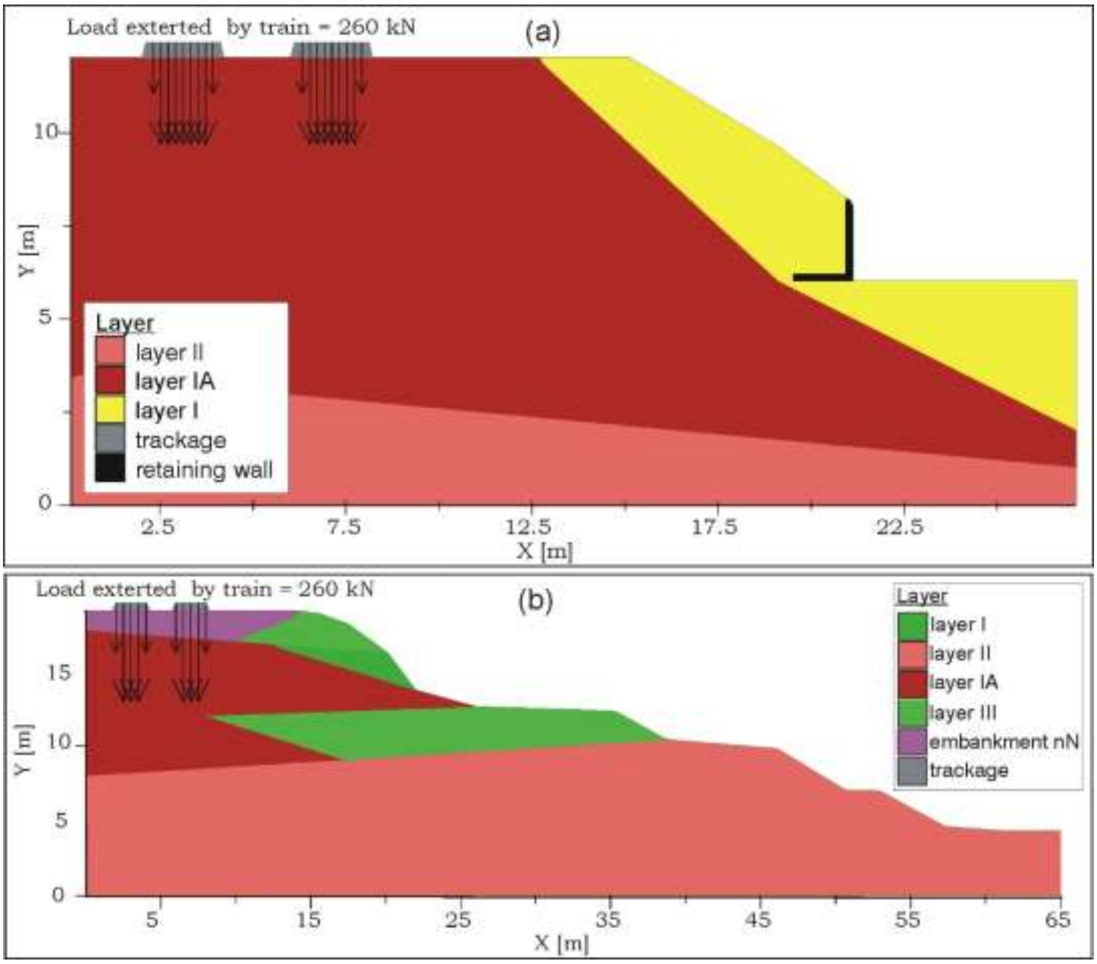

Fig. 5. Division of the model into layers: a) cross-section I-I; b) cross-section II-II

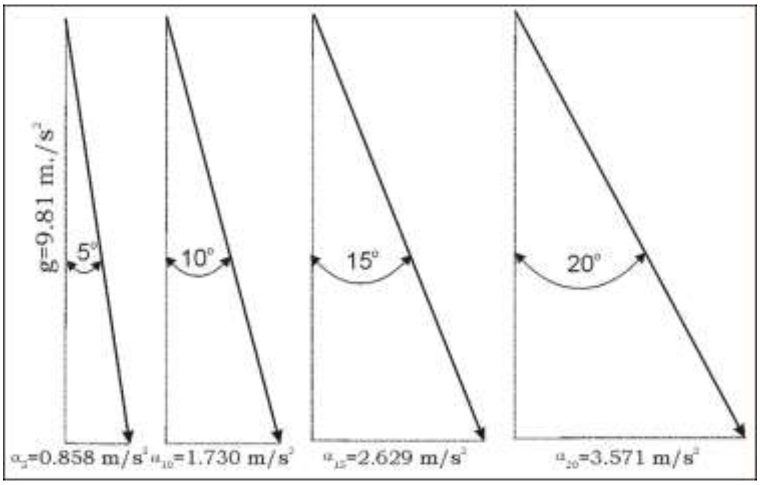

Fig. 6. Different angles of the inclination of vector acceleration from the vertical (equivalent of seismic wave α_i realised in a pseudo-static way)

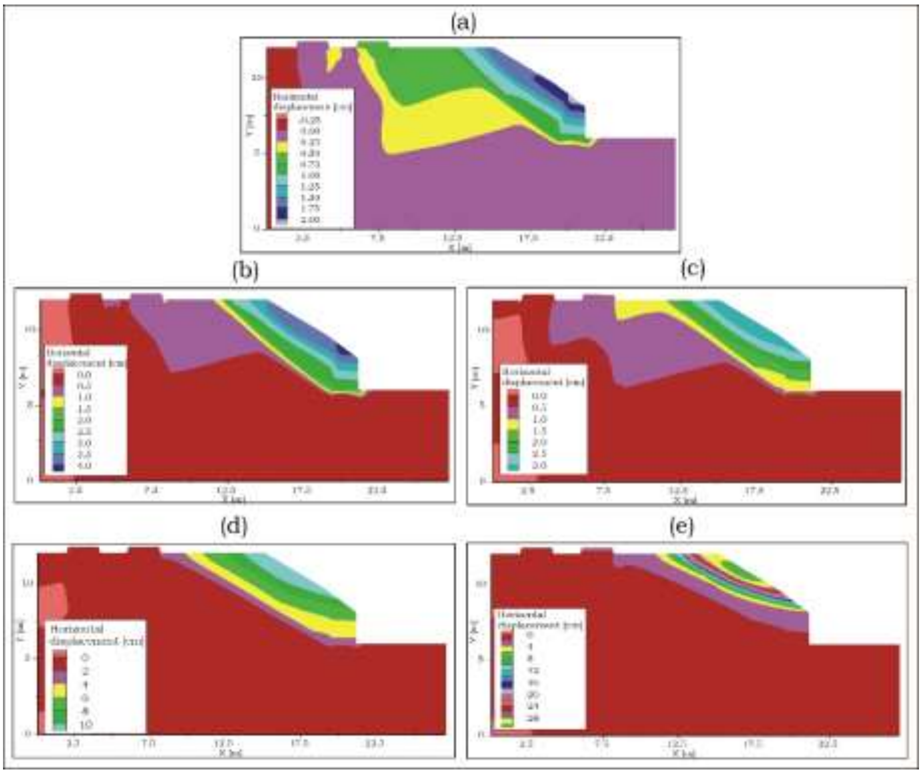

Fig. 7. Horizontal displacement in cross-section I-I; angle of the inclination of acceleration vector from vertical (Fig. 6): a) 0°; b) 5°; c) 10°; d) 15°; e) 20°

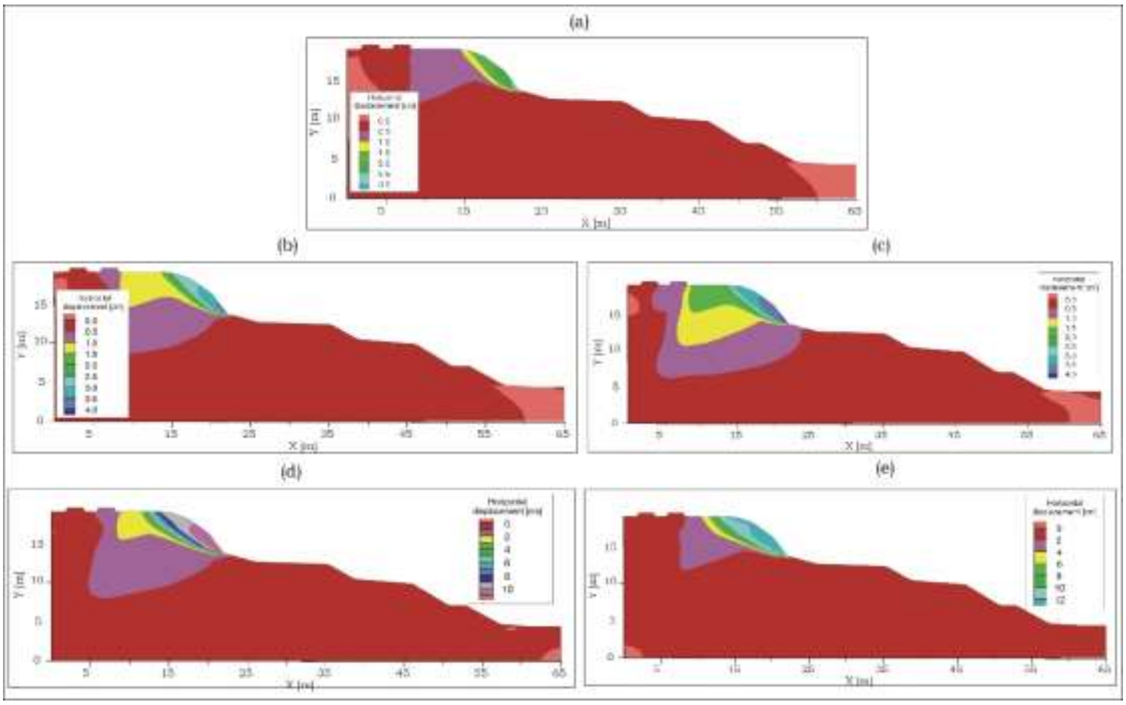

Fig. 8. Horizontal displacement in cross-section II-II; angle of the inclination of acceleration vector from vertical (Fig. 6): a) 0°; b) 5°; c) 10°; d) 15°; e) 20°

5. SUMMARY AND CONCLUSIONS

The method of seismic coefficient of the earthquake intensity determined through the pseudo-static way and horizontal component of the acceleration, that is, k_h coefficient, is appropriate and recommended as it is simple and the factor of safety can be calculated in the same way as in conventional stability calculations. No advanced analysis is necessary, and it significantly contributes to the improvement of seismic (dynamic) safety conditions.

The analysis carried out showed that the movement of freight trains on the projected railway line would generate mainly horizontal seismic waves and, consequently, adverse forces in the slope. This study also showed that even low-intensity seismic waves would have a significant negative impact on slope stability, causing a high probability of slope failure.

References

1. Bober Lesław, Kazimierz Thiel. 1980. „Badania stateczności zbocza osuwiskowego w Lipowicy koło Dukli” [In Polish: „Stability investigations of the landslide slope in Lipowice near Dukla”]. *Biuletyn Instytutu Geologicznego* 324: 239-282.
2. Bragato Pier Luigi, Dario Slejko. 2004. „Empirical ground motion attenuation relations for the eastern Alps in the magnitude range 2.5-6.3”. *Bulletin of the Seismological Society of America* 95: 252-276. DOI: http://dx.doi.org/10.1785/0120030231.
3. Bray Jonathan, Thaleia Travasarou. 2007. „Simplified procedure for estimating earthquake-induced deviatoric slope displacements”. *Journal of Geotechnical and Geoenvironmental Engineering ASCE* 133: 381-392. DOI: 10.1061/(ASCE)1090-0241(2007)133:4(381).
4. Bray Jonathan, Thaleia Travasarou. 2009. „Pseudostatic coefficient for use in simplified seismic slope stability evaluation”. *Journal of Geotechnical and Geoenvironmental Engineering* 135:1336-1340. DOI: 10.1061/(ASCE)GT.1943-5606.0000012.
5. Bray J., E. Rathje, A.J. Augello, S.M. Merry. 1998. „Simplified seismic design procedure for geosynthetic-lined solid waste landfill”. *Geosynthetic International* 5: 203-235. DOI: 10.1680/GEIN.5.0119.
6. Bromhead Edward Nicolas. 2019. *The Stability of Slopes (2nd edition).* New York: CRC Press. ISBN: 9780367865122.
7. Chopra Aditya. 1967. „Earthquake response of earth dams”. *Journal of Soil Mechanics and Foundations Division ASCE* 93(2): 65-81. DOI: 10.1061/JSFEAQ.0000960.
8. Cotecchia Vincenzo. 1987. “Earthquake-prone environments”. In: *Slope stability, geotechnical engineering and geomorphology*, edited by M.G. Anderson, K.S. Richards. P. 287-330. New York: John Wiley & Sons. ISBN-10: 047191021X. ISBN-13: 978-0471910213.
9. Dawson E. Michael, William H. Roth, Andrzej Drescher. 1999. „Slope stability analysis by strength reduction”. *Géotechnique* 49: 835-840. DOI: 10.1680/geot.1999.49.6.835.

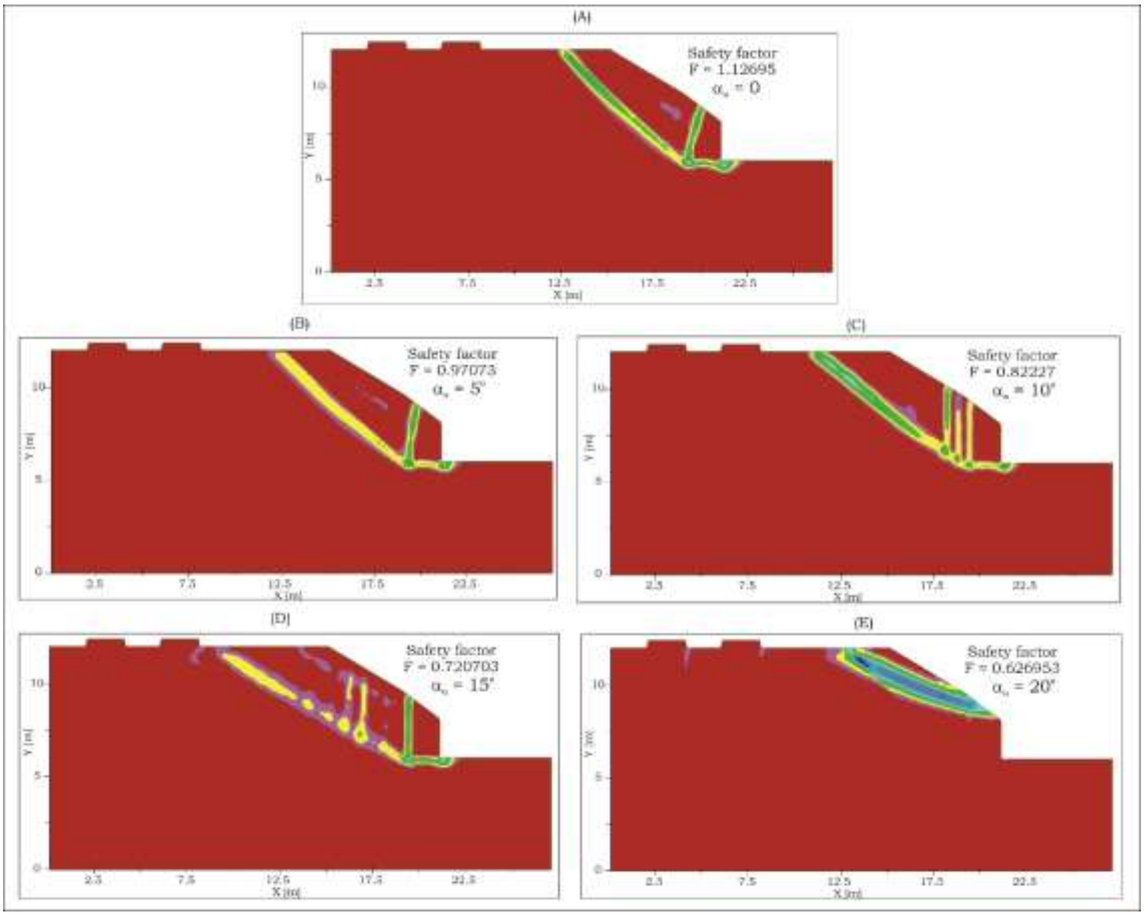

Fig. 9. Concentration of slide zones in the cross-section I-I; angle of the inclination of acceleration vector from vertical (Fig. 6): a) 0^o; b) 5^o; c) 10^o; d) 15^o; e) 20^o

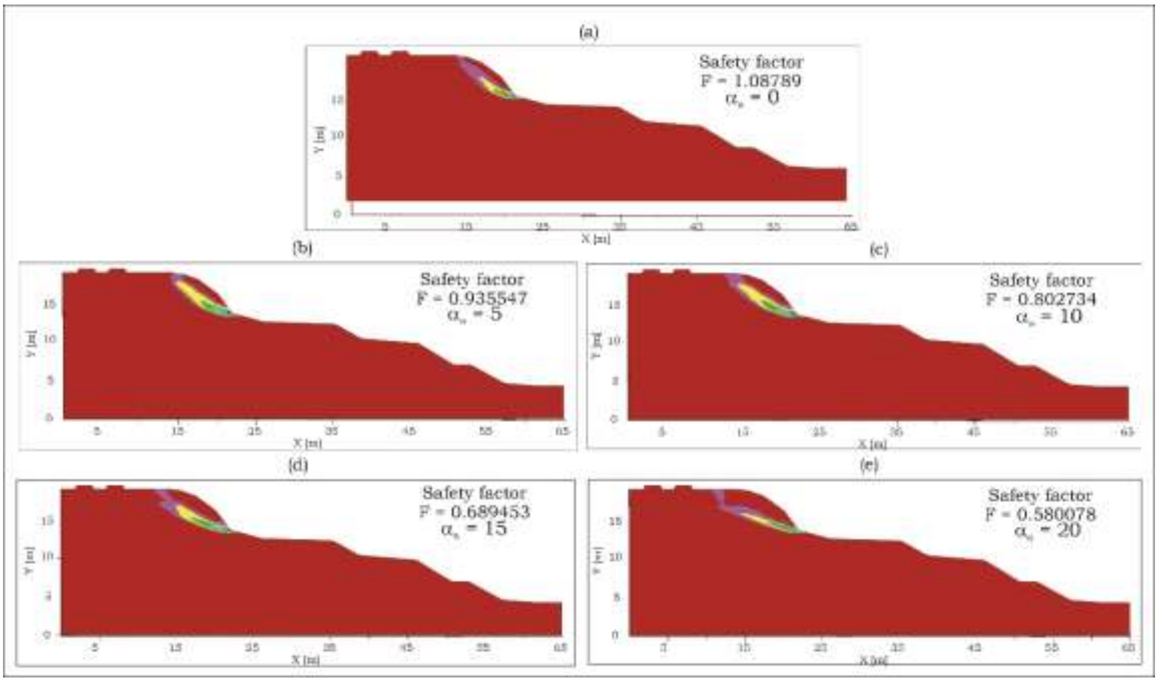

Fig. 10. Concentration of slide zones in the cross-section II-II; angle of the inclination of acceleration vector from vertical (Fig. 6): a) 0^o; b) 5^o; c) 10^o; d) 15^o; e) 20^o

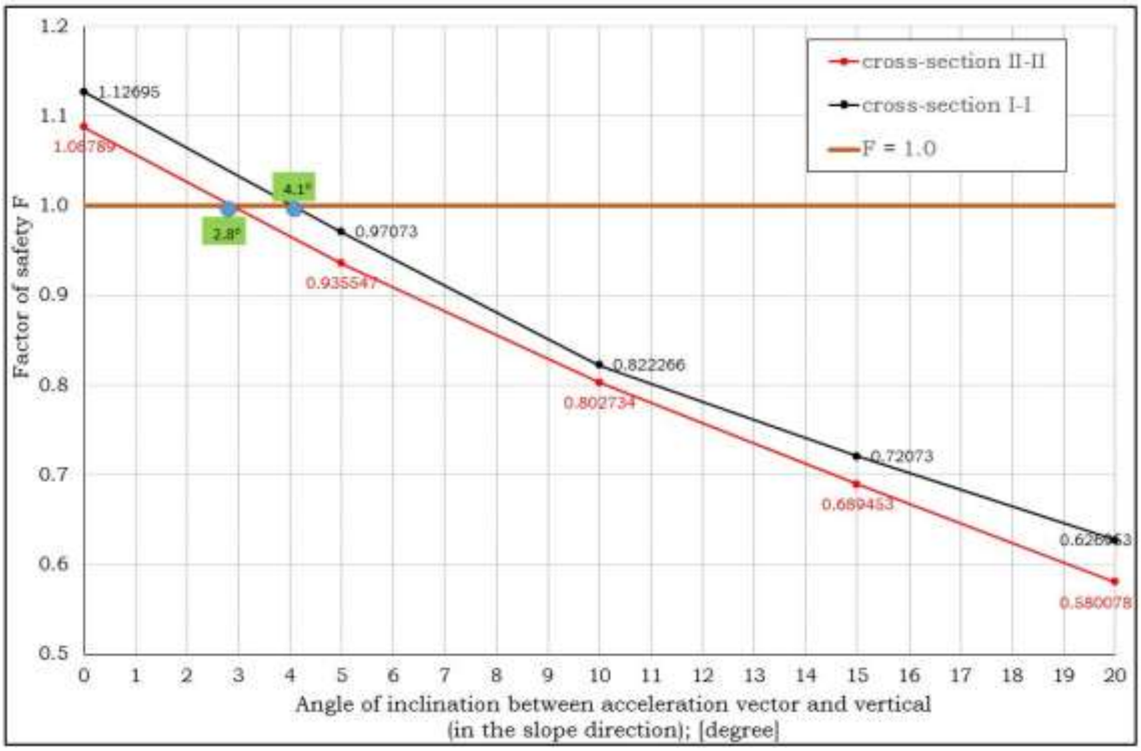

Fig. 11. Angle of inclination between acceleration vector and vertical versus factor of safety

10. Egis Poland Sp. z o.o, 2019. Dokumentacja geologiczno-inżynierska dla określenia warunków geologiczno-inżynierskich w podłożu modernizowanych linii kolejowych nr 201 na odcinku od km 136+096 do km 163+250 i 214 od km -0+229 (proj. 0+915) do km 7+131 (część A) realizowanej w ramach projektu „Prace na alternatywnym ciągu transportowym Bydgoszcz-Trójmiasto – etap I" . [In Polish: Geological-engineering documentation for determination of the geological-engineering properties in the foundation of the upgrading railways No. 201, section from km 136+096 to km 163+250 and No. 214 from -0+229 (designed 0+915) to km 7+131 (part A) realized in frames of the project "Activities on the alternative transport line Bydgoszcz – Trojmiasto – stage, Internal report]. Warsaw.
11. EUROCODE 8:2003. *Projektowanie ziemnych struktur oporowych. Fundamenty, struktury oporowe i aspekty geotechniczne*. Projekt końcowy. [In Polish: *Design of structures for earthquake resistance. Part 5: Foundations, retaining structures and geotechnical aspects*, Final draft].
12. Gurudeo Chavan Ashwini, Digambar Mudgundi Rajani. 2017. „Pseudostatic Slope Stability Analysis". In: *International Journal Research Publications in Engineering and Technology (IJRPET). National Conference of Innovative Trends in Engineering and Technology-2017*: 80-83. 15th and 16th March 2017. Conference Proceeding. ISSN: 2454-7875. DOI: 10.5281/zenodo.1461396.
13. Itasca C.G. 2011. *FLAC 7.0 Manual*. Minneapolis, USA.
14. Jibson Randall W. 1993. „Predicting earthquake-induced landslide displacements using Newmark's sliding block analysis". *Transportation Research Record* 1411. ID: 92987550. DOI: 10.1.1.733.2736.

15. Kandolkar Sumitra, Smita Aldonkar, Purnanand Savoikar. 2010. "Rational Pseudo-static Stability Analysis of Embankments". In: *Indian Geotechnical Conference - 2010*: 135-138. IGS Mumbai Chapter & IIT Bombay. ID: 114011106.
16. Kondracki Jerzy. 2002. *Geografia regionalna Polski*. [In Polish: *Regional Geography of Poland*]. Warsaw: PWN. ISBN: 83-01-13897-1.
17. Kramer Steven L. 1996. *Geotechnical Earthquake Engineering*. New Jersey: Prentice Hall. ISBN-13: 978-0133749434.
18. Makishi Faiz, Bolton H. Seed. 1978. „Simplified procedure for estimating dam and embankment earthquake-induced deformations". *Proceedings of the American Society of Civil Engineers, Journal of Geotechnical Engineering* 104: 849-867. DOI: 10.1061/AJGEB6.0000668.
19. Marcato Gianluca, Fujisawa, Mateo Mantovani, Alessandro Pasuto, Sandro Silvano, Fabrizio Tagliavini, Lesław Zabuski. 2007. "Evaluation of seismic effects on the landslide deposits of Monte Salta (Eastern Italian Alps) using distinct element method". *Natural Hazard and Earth Systems Sciences* 7: 695-701. DOI: 10.5194/nhess-7-695-2007.
20. Melo Cristiano, Suni B. Sharma. 2004. "Seismic coefficients for pseudostatic slope analysis". *13th World Conference Earthquake Engineering.* Paper No. 269. Vancouver, Canada. August 1-6, 2004. ID: 17467633.
21. Nash David. 1987. A comparative review of limit equilibrium methods of stability analysis. In: *Slope stability, geotechnical engineering and geomorphology* edited by M.G. Anderson, K.S. Richards. P. 11-76. New York: John Wiley & Sons. ISBN-10: 047191021X. ISBN-13: 978-0471910213.
22. Newmark Nathan M. 1965. „Effects of earthquakes on dams and embankments". *Geotechnique* 15: 139-160. DOI: 10.1680/geot.1965.15.2.139.
23. Geocentrum P.G. 2021. *Geotechniczne warunki posadowienia. Opinia geotechniczna dokumentacja badań podłoża gruntowego*. [In Polish: *Geotechnical foundation conditions. Geotechnical opinion documentation of subsoil tests*]. Internal report. Gdańsk.
24. Przewłócki Jarosław. 2021. „Brief literature review and classification system of reliability methods for evaluating the stability of earth slopes". *Sustainability* 13: 9090. DOI: 10.3390/su13169090.
25. Pushpa K. Prasad, Prabhuswamy Nanjundaswamy. 2017. „Simplified pseudostatic analysis of earthquake induced landslides". *Indian Journal of Advances in Chemical Sciences* 5: 54-58. DOI: 10.22607/IJACS.2017.501008.
26. Saygili Gokhan, Ellen Rathje. 2008. „Empirical predictive models for earthquake-induced sliding displacements of slopes". *Journal of Geotechnical and Geoenvironmental Engineering ASCE* 134: 790-803. DOI: 10.1061/(ASCE)1090-0241(2008)134:6(790).
27. Seed Bolton H. 1979. „Considerations in the earthquake resistant design of earth and rockfill dams". *Geotechnique* 29: 215-263. DOI: 10.1680/geot.1979.29.3.215.
28. Slejko Dario, Alessandro Rebez. 2002. „Probabilistic seismic hazard assessment and deterministic ground shaking scenarios for Vittorio Veneto (N.E. Italy)". *Bolletino di Geofisica Teorica ed Applicata* 43: 263-280. ID: 132355227.
29. Slejko Dario, Laura Peruzza, Alessandro Rebez. 1998. „Seismic hazard maps of Italy". *Annali di Geofisica* 41: 183-214. DOI: 10.4401/AG-4327; ID: 127519730.

30. Tołkanowicz Elżbieta, Krzysztof Żukowski, Jerzy Król, Sylwia Maruńczuk, Paweł Kwiecko, Anna Pasieczna, Izabela Bojakowska, Hanna Tomassi-Morawiec. 2009. *Objaśnienia do mapy Geośrodowiskowej Polski 1:50000. Arkusz Kartuzy (25).* [In Polish: *Explanations for Geoenvironmental map of Poland 1:50000. Sheet Kartuzy (25*)]. Warsaw: Państwowy Instytut Geologiczny.
31. Towhata Ikuo. 2008. *Pseudostatic Limit Equilibrium Analysis, Geotechnical Earthquake Engineering*. Berlin-Heidelberg: Springer. DOI: 10.1007/ 978-3-540-35783-4.
32. Wilson Raymond, David Keefer. 1983. „Dynamic analysis of a slope failure from the 6 August 1979 Coyote Lake, California earthquake". *Bulletin of the Seismological Society of America* 73: 863-877. DOI: 10.1785/BSSA0730030863.
33. Xin-guang Yang, Zhai En-di, Yuan Wang, Hu Zhoung-bo, 2018. „A comparative study of pseudo-static slope stability analysis using different design codes". *Water Science and Engineering* 11: 310-317. DOI: 10.1016/J.WSE.
34. Zabuski Lesław, Jarosław Przewłócki. 2019. "Stability Analysis of a Road Scarp in the Carpathian Mountains and Methods of its Protection". In: *IOP Conference Series: Materials Science and Engineering* 471: 042004. DOI: 10.1088/1757-899X/471/4/042004.

Received 15.10.2022; accepted in revised form 29.12.2022