Forecasting of slope stability at the object "Redevelopment of the territory "Mill of Emelyan Bashkirov and his sons"

I A Gandelsman¹,² and A I Gandelsman¹

¹Department of civil engineering and architecture, Vladimir State University named after Alexander and Nikolay Stoletovs, 87 Gorky street, Vladimir, Russia
²igvlisu@mail.ru

Abstract. The article analyzes the current state of the landslide slope of the river Oka, an assessment of landslide risks was made. Various models of ground base behavior in flat setting in the current state and taking into account prospective development are considered. A geometric model of the slope was simulated, using the software complexes "Plaxis" and "GeoStab," factor of safety and critical sliding surfaces were determined, various anti-landslide designs for maintaining the stability of the slope were considered, technical solutions for performing landslide control were proposed.

1. Introduction

Many cities are built on high riverbanks, on hilly terrain. In the course of the society's life, hydrogeological conditions are changing. They are influenced by technogenic impact, including emergency work on engineering networks, poor-quality operation of previously erected landslide structures and drainage systems, and green spaces.

The above-mentioned complex of factors can lead to the loss of stability of slopes, the formation of landslides that threaten existing buildings and people living in them [1, 2, 3, 4, 5, 6, 7, 8, 9]. The development of society inevitably leads to the need to reconstruct previously erected facilities, or to build new, heavier constructions that leads to additional loads on the slope. So, we need to monitor the condition of the slopes, to make forecasts of their reliable operation when the initial conditions of their operation change.

The theoretical foundations and methods of slope calculations are described in the works of domestic researchers S S Vyalov [10], Yu K Zaretsky [11], V M Gumensky [12], Z G Ter Martirosyan [13-15], A A Bartolomey [16-18], V V Simonyan [19-20], A A Mikhalin [21], A I Kazeev [22-23], G V Postoyev [24-25], A B Ponomarev [26, 27], A Torgoev [28] and foreign scientists A Bishop [29], N Morgenstern [30], N Yanbu [32], V Price [31], E Bromhead [33], D Griffiths [34], A Federico [35], A Malkawi [36], O Zienkiewicz [37], M Saito. [38], A Komamura [39], L Wu [40] et al.

Despite many researches, it is still relevant to ensure the stability of specific slopes in various localities [41, 42, 43, 44, 45, 46].

In the article the questions of the survey of the current state landslide of the slope, the results of calculation by engineering and finite element method taking into account different models of the ground base are given. The factor of safety in its current state and considering future construction with the possibility of saturation is determined. Landslide prevention worksare suggested.
2. Methods
Geomorphologically, the survey site is located on the right-bank slope of the Oka River. The marks of the earth’s daily surface range from 71.7 m to 146.8 m in the Baltic system. The territory is a steep slope up to 45 m, covered with turf, deciduous trees and shrubs. The slope has three terraces: upper, middle and lower terraces. The upper and middle terraces of the slope are built up with residential buildings. Deciduous trees on the slope are inclined by 3-50. In rare cases, the roots of the trees come to the surface. The lower terrace is located on the right bank of the river. It is a waterfront. Streams outlet streams, sloughing was not detected. There may be landslide processes in the surrounding area, associated with overwetting of the soil during snowmelt and heavy rains. The absence of river washout, a counterberm and the ravines are the factors that increase stability. Surveys revealed the landslide deposits, which indicate the landslide processes on the right-bank slope of the Oka River in the past.

The climate of the project area is temperate continental with moderately severe and snowy winters and moderately warm summers.

The geological structure of the site up to the studied depth of 70.0 m includes deposits of Quaternary age (Q) and deposits of the Tatar stage of the upper Permian system (P<sub>2t</sub>). In turn, the Quaternary system is represented by bulk soils (tQ<sub>IV</sub>), landslide clay soils, clays, marls, polymictic sands (dlQ<sub>IV</sub>) and alluvial sands of medium size (aQ<sub>IV</sub>). See table 1.

The hydrogeological conditions of the site up to a depth of 70.0 m at the time of the survey are characterized by the presence of aquifers associated with Quaternary and Permian deposits.

The groundwater is unconfined. The water-bearing soils are landslide deposits and alluvial sands of medium size. The Upper Permian clays (P<sub>2t</sub>) serve as a water barrier. The aquifer is fed by the infiltration of atmospheric precipitation in the zone of rock outcrop on the day surface.

| № | Name of the engineering-geological element, modulus of soil deformation | Standard values | calculated values (α=0.95) | calculated values (α=0.85) |
|---|------------------------------------------------------------------------|-----------------|-----------------------------|----------------------------|
| 1 | Landslide deposits (clay, with layers of marl, sandstone, siltstone) (dlQ<sub>IV</sub>), E=23 MPa | 1.88 29/21(13) 25/17(11) | 1.88 25/18(11) | 22/15(10) |
| 2 | Sand medium grain, medium density, saturated with water (aQ<sub>IV</sub>), E=32 MPa | 2.01 1.2 36 | 2.01 0.8 | 33 |
| 3 | Clay semi solid, with interbedded marl clay dolomite (P<sub>2t</sub>), E=26 MPa | 1.97 61/35(25) 27/18(12) | 1.97 51/28(20) | 24/15(10) |
| 4 | Sand dusty polymictic (P<sub>2t</sub>), E=15 MPa | 1.99 15 32 | 1.99 13 | 29 |
| 5 | Clay dolomite marl (P<sub>2t</sub>) | 1.88 60/31(18) 30/24(16) | 1.84 33/23(14) | 27/20(15) |
| 6 | Sandy rock varieties (weakly cemented siltstones and sandstones, polymict sand) (P<sub>2t</sub>) | 1.89 80/47(30) 22/19(17) | 1.83 48/47(30) | 17/19(17) |
In the area under consideration, erosion processes are common, leads to the erosion of the banks, the formation of cliffs and slopes along the entire bank of the river. Oka and the expansion of the river valley. The highest degree of destruction occurs during the spring flood. 

Assessment of the slope stability in the conditions of a complex geological structure of the ground mass was carried out using the software systems "Plaxis" and "GeoStab". The stability margin coefficient is calculated using the Morgenstern-Price method [19, 20, 47, 48, 49, 50]. The landslide pressure is calculated using the Maslov-Berer method [31, 51]. 

The basis for assessing the stability of soil massifs is to compare their actual calculated stress state with the maximum possible one. The stability assessment of structures is based on the concept of the stability margin coefficient [30]. 

The estimated coefficient of stability \( K_u \) must be greater than or equal to the regulatory proceeding from terms условия \( \psi F \leq \gamma_d R_n \), where \( F \) is the estimated value of the generalized force on the structure or structural elements (power, torque, tension); \( \psi \) - ratio combinations; \( R \) - the present value of the generalized bearing capacity, strength, deformation (displacements) or other parameter that is set by the relevant design standards, depending on the type of construction and materials used taking into account safety factors for material \( \gamma_m \) and (or) ground \( \gamma_g \); \( \gamma_s \) - the reliability coefficient of the structure responsibility \( \gamma_\delta \) is the coefficient of working conditions, taking into account the nature of the impacts, the ability of materials to change the properties over time, the degree of accuracy of the input data, the approximate calculation schemes, the type of facility, structure or foundation, material and other factors. 

The minimum stability coefficient is found by iterating over the fixed positions of one of the nodes of the shear surface, for which, in turn, the value of the minimizing radius of curvature of one of the sections of the shear surface is iterated over. 

Calculations of the overall slope stability are performed for the conditions of the flat problem, in four calculated sections in the current state and taking into account the water saturation of the water-containing soils. The position of the calculated cross-sections of figure 1.

![Figure 1](image1.png)

Figure 1. Calculation schemes for determining the stability of the slope in the current state (a) and taking into account the prospective development (b).
The loads from buildings, depending on the type of building, were assumed to be 80-360 kN/m². The loads from transport for parking areas and street carriageways were 35 kN/m², and the load from a group of people was 5 kN/m².

3. Results and Discussion
The results of calculations of slope stability showed that the overall static stability of the slope in the current state and taking into account the prospective development is provided (figure 2). The coefficients of the stability margin (Ku=1.119-1.286), corresponds to the maximum permissible values of the current building codes and regulations. Water saturation of the water-bearing layers of the soil leads to a decrease in the overall stability of the slope. The overall static stability of the slope in the water-saturated state is not provided. The coefficient of stability margin (Ku=0.944-1.119) does not correspond to the maximum permissible values of the current building codes and regulations.

![Figure 2. Results of slope stability calculation in "GeoStab" (a) and "Plaxis" (b) software packages.](image)

The calculation data has some minor discrepancies [51]. The Plaxis collapse prisms have a much smaller volume than the GeoStab prisms. The calculations have shown that the slope is in a state of
dynamic equilibrium. To prevent the development of landslide processes, according to the results of the analysis of the state of the slope, several options for strengthening the slope were proposed.

The anti-landslide design No. 1. Retaining structure made of bored cast-in-place piles Ø 750 mm, double-row construction, \( L_{\text{pile}} = 16-25 \) m (pile pitch 2.2 - 3.1 m). Class of reinforcement of piles with reinforcement is A300 Ø25 mm. Class of concrete is B25, F150, W6. The depth below the sliding surface is at least 7.4 m. In front of the retaining structures, it is proposed to arrange wall drainage with a branch to the tray to the road. To collect surface water from the slope, a system of trays with discharge into the storm sewer is provided. Service life of at least 50 years. The model is shown in the figure 3.

The use of heavy construction equipment to implement this solution can have a negative impact on the stability of the slope. It is more appropriate to use small-sized drilling rigs (such as Morat BW-600 or analogs) and other specialized equipment that allows you to work on slopes of any steepness, perform vertical and inclined nagels (dowel pins) [52].

![Figure 3](image3.png)

**Figure 3.** Variant No. 1 of the anti-landslide design.

The anti-landslide design No. 2. Construction of a reinforced ground holding structure, which is a retaining wall in the form of reinforced ground construction, fixed on a flexible pile foundation grillage that combines 4 rows of drill-injection piles «Titan» 103/51 with spacing of reinforcement 2.0 x 2.0 m. The thickness of the grillage is 0.45 m. The grillage is made of crushed stone of the 40-70 fraction and geotextile «Armostab» AR2P-40/40. The width of the grillage is variable. In addition, in the places of the layout, the filling is made of crushed stone. Geotextile «Dornit» D-200 g/m² is additionally laid on the slope. The height of the reinforced ground holding structure is variable. The primary bearing layer of the reinforced ground holding structure is the biaxially oriented geogrid «Armostab» AR2P-40/40 with spacing of reinforcement of 1 m. The lower cell is made of geotextile «Armostab» AR2P =40/40. The side of the front face is laid with the thermally bonded geotextile «Miakom-T-250». It is suggested to use temporary fixing of the slope with self-opening ground anchors «Geoanchor type 1.2»-3 m with a step of 2.0 x 2.0 m and a double torsion grid in the most dangerous places to prevent local collapse of the soil. Service life is at least 50 years. The model is shown in the figure 4.
Figure 4. Variant No. 2 of the anti-landslide design.

The anti-landslide design No. 3. The inclined drill-injection micropiling. The holding structure consists of 15 rows (in cross-section) of drill-injection micropiles «Titan» 40/16 of various lengths with increments of 3.0x2.0 m and drilled at an angle of 30 degrees from the vertical. The «Tecco» G65/3 mesh system is used for surface fixing of the entire slope and also starts for the edge at 1.5-2.0 m, where it is fixed with additional self-opening anchors «Geoanchor type 1.2». A geomat "X-Mat" is placed in front of the mesh system to prevent erosion processes on the slope. To restore the vegetation cover on the slope, hydro-mulching (hydraulic application of a mixture of sticky wood mulch) is performed. Service life is at least 50 years. The solution was carried out with the technical support of representatives of LLC «Ishebeck Titan» (Russia) and "ISCHEBECK" (Germany). The calculation results are shown in the figure 5.

The anti-landslide design No. 4. The vertical drill-injection micropiling. The holding structure consists of 4 rows (in cross-section) of drill-injection micropiles «Titan» 103/51 with a step of 2.0x2.0 m. To fix the surface of the slope, the «Tecco» G65/3 mesh system is used. The system runs on an area of the slope, and put the edge at 1.5-2.0 m affirm the additional drop-down anchors «Geoanchor type 1.2». Before the mesh system geomat "X-Mat" is put to prevent erosion on the slope. To restore the vegetation cover on the slope, hydro-mulching (hydraulic application of a mixture of sticky wood mulch) is performed. The calculation of the pins are manufactured in accordance with DIN 1054-2005. Service life of at least 50 years. The option gives the minimum allowable stability coefficient.

Figure 5. Variant No. 3 of the anti-landslide design.

Variant 5. Construction of a retaining wall with a «Terramesh system» along the entire slope. The holding structure is the base of 3 rows (in cross-section) of drill-injection piles Titan 40/16 with a step of 2.0x2.0 m, united by a flexible grillage made of crushed stone. The thickness of the grillage is 0.45 m. The grillage is made of crushed stone of the 40-70 fraction and geotextile «Armostab» AR2P-
40/40. The width of the grillage is variable. In addition, in the places of the layout, the filling is made of crushed stone. On the slope is additionally laid geotextile «Dornit» D-200 g/m². The construction height of the «Terramesh system» is variable. The «Terramesh system» is made of GSI-KA-6.0x2.0x1.0-C60-2.7-CAMMP gabions installed in cascades with a displacement of each stage of 0.5 m (crushed stone with a fraction of 70-120). The model is shown in the figure 6. During the construction period (the installation of a pile foundation and a flexible grillage), it is planned to temporarily fix the slope with self-opening ground anchors of the «Geoanchor type 1.2»-3m with a step of 1.5x2.0 and a double torsion grid in the most dangerous places to prevent local soil collapse. Service life of at least 75 years. Due to the considerable length and height of the slope, this option requires a significant amount of supply to the object of stone for the device of gabions.

![Figure 6. Variant No. 5 of the anti-landslide design.](image)

4. Conclusions
When solving geotechnical problems for determining the stability of a landslide slope, the use of software complexes in the "GeoStab" and "Plaxis" complexes showed sufficient convergence of the results for practical purposes. It is advisable to perform the calculation using the Morgenstern-Price method. This indicates the possibility of applying engineering methods in the calculation of slopes.

At the moment, the slope is in a state of dynamic equilibrium. In this situation, cutting the slope and using heavy equipment is impractical and can lead to a loss of stability of the slope. Based on the analysis, five anti-landslide designs were developed for providing engineering protection of the territory, buildings and structures from dangerous geological processes within the framework of the project "Redevelopment of the territory "Mill of EmelyanBashkirov and his Sons".

The most effective solution is the use of inclined drill-injection piles "Titan". In this case, the slope stability coefficient in the water-saturated state will be 1.370, the bearing capacity of the piles is sufficient for the bearing of landslide pressure.

References
[1] Demin A M 2007 Assessment of landslide hazard by critical deformations Proc. of the jubilee conf. on the 50th anniversary of ROMGGIF “Russian geotechnics – step into the 21st century” (Moscow: ROMGGIF) 2 pp 324–8
[2] Du J, Yin K and Lacasse S 2013 Displacement prediction in colluvial land slides, three gorges reservoir China Landslides 10 (2) 203–18
[3] Hutchinson J and Bhandari R 1971 Undrained loading, a fundamental mechanism of mudflows and other mass movements Geotechnique 21(4) 353–8
[4] Gulakyan K A, Kuntcel V V and Postoev G P 1970 The mechanism and dynamics of the landslide process on the example of the landslide in Zeravshan valley Materials of the scientific-practical meeting on methods and forecast of debris flows, avalanches, and landslides (Dushanbe) pp 59–65
[5] Xie J et al 2020 Predicting the sliding behavior of rotational landslides based on the tilting measurement of the slope surface Engineering Geology 269
[6] Chowdhury R and Flentje P 2003 Role of slope reliability analysis in landslide risk management Bulletin of Engineering Geology and the Environment 62(1) 41–6
[7] El-Ramly H, Morgenstern N R and Cruden D M 2002 Probabilistic slope stability analysis for practice Canadian Geotechnical Journal 39(3) 665–83

[8] Ahlberg P, Stigler B and Viberg L 1988 Experiences of landslide risk considerations in land use planning in Sweden 5th Int. Symp. on Landslides, Lausanne 2 pp 1091–6

[9] Burland J, Longworth T and Moore J 1977 A study of ground movement and progressive failure caused by a deep excavation in Oxford Clay Geotechnique 27(4) 557–91

[10] Vyalov S S 1978 Rheological foundations of soil mechanics (Moscow: Higher school)

[11] Zaretsky Yu K 1988 Viscoplasticity of soils and structural strength (Moscow: Stroyizdat)

[12] Gumensky B M 1950 Driving piles into thyrotrophic soils J. Equipment of Railways 3

[13] Ter-Martirosyan Z G and Luzin I 2019 The long piles interaction with the surrounding and underlying soils, taking into account the linear and nonlinear rheological properties IOP Conference Series: Materials Science and Engineering 2019 698(2) 1–8

[14] Ter-Martirosyan Z, Ter-Martirosyan A and Ermoshina L 2019 Creep of clayey soil with kinematic shear, taking into account internal friction, adhesion and viscous resistance IOP Conference Series: Materials Science and Engineering 661(1) 1–9

[15] Ter-Martirosyan Z G, Ter-Martirosyan A Z and Angelo G O 2019 Interaction of gravel piles with the surrounding soil and raft Soil Mechanics and Foundation Engineering 56(3) 151–6

[16] Bartholomey A A, Omelchuk I M and Yushkov B S 1994 Prediction of the sediment pile foundations (Moscow: Stroyizdat)

[17] Bartolomey A A, Omelchak, I M and Shardashk VN 1991 Pile settlements in visco-ela-sto-plastic medium Proc. of the Int. Conf. on Soil Mechanics and Foundation Engineering 2 pp 659–60

[18] Bartholomey A A 1989 Prediction of pile capacity, settlements and stability of piles and pile foundations Proc. of the Int. Conf. on Soil Mechanics and Foundation Engineering 2 pp 779–82

[19] Simonyan V and Kochiev A 2019 Mathematical model of landslide stable equilibrium Vestnik MGSU 10 1292–8

[20] Simonyan V V, Tamrazyan A G and Kochiev A A 2015 About development of a model of landslide process for assess its effects on buildings and structures Industrial and Civil Engineering 4 37–40

[21] Mihailin A A and Filonov S V 2015 Comparative analysis of mathematical models of sustainability deeply loosened saturated with water slopes Engineering Journal of Don 35(2-1) 47

[22] Kazeev A I and Postoev G P 2011 About protection strategy on territories with deep landslides. Environmental Geosciences and engineering survey for territory protection and population safety: to proc. EngeoPro-2011 (Moscow: N V) pp 108-109

[23] Kazeev A I, Postoev G P and Lapochkin B K 2009 Theoretical solutions for an effective pit edge stability management Modern management of mine producing, geology and environmental protection: conf. proceeding SGEM-2009 vol 1 pp 301–7

[24] Postoev G P, Lapochkin B K and Kazeev A I 2007 Landslide deformation of engineering objects Journal "Construction Engineering" 10(34) 62–9

[25] Postoev G P et al 1989 Artificial activation of landslides (Moscow: Nedra)

[26] Ponomarev A B, Bezgodov M A 2014 Load-bearing capacity of driving piles in weak water-saturated soils taking into account the time factor PNRPU Bulletin. Construction and Architecture 7 7–15

[27] Sychkina E and Ponomaryov A 2020 Experimental investigation of rheological properties of Permian claystones and sandstones 16th Asian Regional Conf. on Soil Mechanics and Geotechnical Engineering AR 2019 pp 1–6

[28] Torgoev A, Havenith H-B 2016 2D dynamic studies combined with the surface curvature analysis to predict Arias Intensity amplification Journal of Seismology 20 711–31

[29] Bishop A W 1954 The use of the slip circle in the stability analysis of earth slopes Geotechnique 5(1) 7–17
[30] Bishop A W and Morgenstern N R 1960 Stability coefficient for earth slopes Geotechnique 10(4) 129–50
[31] Morgenstern N R and Price V E 1965 The analysis of stability of general slip surfaces The institution of civil engineers 79–93
[32] Janbu N 1954 Application of composite slip surfaces for stability analysis Proc. European conf. on stability of Earth Slopes (Stockholm) 3 pp 43–9
[33] Bromhead E and Ibsen M 2004 Bedding-controlled coastal landslides in southeast britain between axmouth and the Thames estuary Landslides 1(2) 131–41
[34] Griffiths D and Lane P 1999 Slope stability analysis by finite elements Geotechnique 49(3) 387–403
[35] Federico A et al 2012 Prediction of time to slope failure: a general frame work Environmental Earth Sciences 66 (1) 245–56
[36] Malkawi A I H, Hassan W F and Abdulla F A 2000 Uncertainty and reliability analysis applied to slope stability Structural Safety 22(2) 161–87
[37] Zienkiewicz O, Humpheson C and Lewis R 1975 Associated and non-associated visco-plasticity and plasticity in soil mechanics Geotechnique 25(4) 671–89
[38] Saito M 1965 Forecasting the time of occurrence of a slope failure Proc. of the 6th Int. Conf. on Soil Mechanics and Foundation Engineering (Montreal, Canada) 2 pp 537–41
[39] Komamura F and Park B 1988 On the forecast of time to failure of slope-approximate forecast in the early period of the tertiary creep Landslide 25 295–301
[40] Wu L Z, Li S H, Huang R Q and Xu Q 2020 A new grey prediction model and its application to predicting land slide displacement Applied Soft Computing 95 257–69
[41] Berknopf R L and Campbell R H, Brookshire D S and Shapiro C D 1988 A probabilistic approach to landslide hazard mapping in Cincinnati, Ohio with applications for economic evaluation Bulletin American Association of Engineering Geologists 25 (1) 39–56
[42] Gulakyan K A, Kuntzel V V and Postoyev G P 1977 Forecasting of landslide processes (Moscow: Nedra)
[43] Petley D N et al 2008 Development of progressive landslide failure in cohesive materials Geology 36 201–4
[44] Singh R, Umrao R K and Singh T N 2014 Stability evaluation of road-cut slopes in the Lesser Himalaya of Uttarakhand, India: conventional and numerical approaches Bulletin of Engineering Geology and the Environment 73(3) 845–57
[45] Zhu C, Tao Z, Shen Y and Zhao S 2019 V shaped gully method for controlling rockfall on high-steep slopes in China Bulletin of Engineering Geology and the Environment 78 (4) 2731–47
[46] Yin Y, Wang H, Gao Y and Li X 2010 Real-time monitoring and early warning of landslides at relocated wushan town, the three gorges reservoir, China Landslides 2 (7) 339–49
[47] Uglenko E B and Timchenko O N 2010 Mathematical model of soil landslip origin forecasting Bulletin of Kharkov National Automobile and Highway University 49 72–4
[48] Zieher T, Schneider-Muntau B and Mergili M 2017 Are real-world shallow landslides reproducible by physically-based models? Four test cases in the Laterner valley (Vorarlberg: Austria) Landslides 14(6) 2009–23
[49] Rawat S and Gupta A K 2016 Analysis of a nailed soil slope using limit equilibrium and finite element methods. International Journal of Geosynthetics and Ground Engineering 2(4) 1–23
[50] Wang W D, Qu X and Liu P 2019 Prediction on land slide displacement using a combination model with optimal weight Natural Hazards 96 1121–39
[51] Malinin A G et al 2008 Computer programs for geotechnical analyses Soil Mechanics and Foundation Engineering 45(1) 13–6
[52] Malinin D and Malinin A 2013 “Atlant” anchor pile technology and capacity experimental results Springer Geology 251–4
[53] Alimbetova A Z 2015 A mathematical model of the occurrence of landslides according to the force pattern when exposed to the aquatic environment Technosphere Security: XVII Int.1 Scientific and Technical Conf. 17 pp 174–6
[54] Asch T W J V, Malet J P and Beek L P H V 2007 Techniques, issues and advances in numerical modelling of landslide hazard *Bulletin De La Societe Geologique De France* **178** (2) 65–88

[55] Barla G, Antolini F and Barla M 2013 Slope stabilization in difficult conditions *The case study of a debris slide in NW Italian Alps. Landslides* **10**(3) 343–55

[56] Beville S H et al 2010 Using simulated hydrologic response to revisit the 1973 Lerida Court landslide *Environmental Earth Sciences* **61** (6) 1249–57

[57] Hutchinson J 1969 A reconsideration of the coastal landslides at folkestone warren Kent *Geotechnique* **9**(1) 6–38

[58] Hwan A P 2006 A Possible model of a landslide *Construction and technogenic safety* **15-16** 55–6

[59] Gitirana G, Santos M A and Fredlund M D 2008 Three-dimensional analysis of the Lodalen landslide *GeoCongress Geosustainability and Geohazard Mitigation* 186–90

[60] Gschwind S, Loew S and Wolter A 2019 Multi-stage structural and kinematic analysis of a retrogressive rock slope instability complex (Preonzo: Switzerland) *Engineering Geology* **252** 27–42

[61] Guzzetti F, Carrara A, Cardinali M et al 1999 Landslide hazard evaluation: A review of current techniques and their application in a multi-scale study, Central Italy *Geomorphology* **31**(1-4) 181–216

[62] Kallol S and Sujit M 2020 Assessment of slope stability using general limit equilibrium (Gle) method in South Sikkim Himalaya, India *Disaster Advances* **13**(8) 55–63

[63] Komac M 2006 A landslide susceptibility model using the analytical hierarchy process method and multivariate statistics in perialpine Slovenia *Geomorphology* **74**(1-4) 17–28

[64] Mergili M et al 2014 Spatially distributed three-dimensional slope stability modelling in a raster GIS *Geomorphology* **206** 178–95

[65] Monahov V V, Ovchinnikov V I and Urusova A V 2005 Opportunities and the prospect of application of geophysical methods for diagnostics of railways *Modern problems of projection, construction and exploration of railways and structures. Proc. of the second scientific-technical conf. (Moscow: MSU of railway engineering (MIIT))* pp 76–8

[66] Narbut R M 1972 *Work of piles in clay soils* (Leningrad: Publishing house of literature on construction)

[67] Yin K and Yan T 1996 Landslide prediction and relevant models *Chinese Journal of Rock Mechanics and Engineering* **1** 1–8

[68] Yuan R et al 2019 Local structural and geomorphological controls on landsliding at the Leigu restraining bend of the Beichuan-Yingxiu fault system during the 2008 *Wenchuan earth quake. Landslides* **16**(12) 2485–98