Modelling the Stability of the Aleksotas Hill Slope in Kaunas

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Abstract. Main causes of slope failures in soils are: geological activities (earthquakes), hydrological influence (rise of the groundwater table), topographical features, weathering processes (a rainy season, snowmelt), human activities (vibrations from explosions, machinery, road and air traffic, loading the slope crest, etc.) and vegetation and climatic conditions. As a result, the shear strength of the soil decreases and factor of safety of the slope reduces to a low value that may trigger failures. The slope of the Aleksotas Hill was sliding in 2015. To protect the slope from future landslides, the reconstruction work began in 2018. Geotechnical modelling software SLOPE/W was used for determination of the factor of safety. Model with three modifications (variants) was created by SLOPE/W software for the slope behaviour modelling. The Aleksotas Hill slope stability calculations of original (natural) slope and excavated slope with constructing subsurface drainage was performed in order to evaluate the solutions proposed in the reconstruction project.

1. Introduction
Slope failure is the most frequent disaster faced by many countries, especially when slopes are cut extensively for area development. Most failures of man-made slopes are caused by design errors which include geometric design i.e. slope inclination, slope height and inability to estimate the load and the soil resistance. During excavation work on natural slopes, the slope face may deform and results in the reduction in shear strength which can lead to slope failure [1].

Slope failures depend on the soil type, soil stratification, groundwater, seepage and slope geometry. Triggering factors (causes of the slope failure) are: erosion, rainfall, earthquakes, geological features, external loading, construction activities (excavated slopes, fill slopes), rapid draw down, increase of pore water pressure, change in topography, etc. Landslide causes are classified into - external causes which result in increase of the shearing stress (e.g. geometrical changes, unloading the slope toe, loading the slope crest, shocks and vibrations, drawdown, changes in water regime) and internal causes which result in decrease of the shearing resistance (e.g. progressive failure, weathering and seepage erosion) [2].

Process recognition is the most important task when dealing with slope instabilities. A clear conception of the failure process represents the basis for:
1. Monitoring and interpretation of landslide monitoring results,
2. Slope stability modelling and analyses,
3. Risk assessment,
4. Design of measures for decreasing instability and for warning.
Landslide field recognition and identification (remote sensing techniques, field techniques), investigation (field investigations, laboratory testing), modelling (landslide mechanics and simulation models), hazard, risk assessment and prediction (landslide inventories and susceptibility, hazard mapping methods, damage potential), landslide monitoring and warning (monitoring techniques and technologies, early warning systems), disasters and relief (case studies, emergency measures, first aid, civil protection measures), mitigation, remediation and stabilization (landslide protection works, landslide stabilization and remediation and landslide non-structural measures) were analysed during the World Landslide Forum [3]. The information on geological processes (karst and landslide) is provided by Lithuania's geological information system GEOLIS. According to the data of the inventory of landslides in Kaunas city, landslides usually occur where the natural environment is prone to landslides due to human economic activities (excavation, new buildings erection, etc.) (Figure 1). The location of investigated Aleksotas Hill landslide is near the crossing of the biggest Lithuania Rivers – the Nemunas and the Neris Rivers as can be seen from Figure 1.

![Figure 1. Map of landslides in Kaunas city (GEOLIS).](image)

The objective of a gross slope stability analysis is to determine the factor of safety of an existing or proposed slope. Gross slope stability analyses can either be performed in terms of a total stress analysis (e.g., short-term condition using the undrained shear strength), or an effective stress analysis (e.g., long-term condition using the drained shear strength).

The aim of the research was to perform gross slope stability analysis for the Aleksotas Hill of the original (natural) slope and excavated slope with constructed subsurface drainage. Slope stability analysis was performed in terms of a total stress analysis. The most critical section (I-I) was selected for this study. Data required for these analyses was retrieved from Kaunas city Municipality Company "Kaunoplanas’s" prepared project report.

2. Methodology
2.1. Methods of slope stability analyses

Gross slope stability analyses are generally divided into two categories as follows:

1. A translational slope failure can develop on a steeply inclined weak layer. A wedge analyses is often used to determine the factor of safety for translational slope failures. The wedge method is a two-dimensional analysis based on a unit length of a slope. The assumption in this slope stability analysis is that there is a wedge type failure of the slope along a planer slip surface.

2. If the soil is relatively homogeneous, then a rotational slope failure could occur. In a rotational slope failure, the slide mass moves downwards and outwards. The most commonly used method of gross slope stability analysis is the method of slices, where the failing mass is subdivided into vertical slices and the factor of safety is calculated based on the force equilibrium equations. A circular arc slip surface and rotational type of failure mode are often used for the method of slices, and for homogeneous soil, a circular arc slip surface provides a lower factor of safety than assuming a planar slip surface. These calculations are similar to the wedge type analysis, except for the resisting and driving forces which are calculated for each slice and then summed up in order to obtain the factor of safety of the slope. There are different types of methods of slices: Ordinary method of slices
For slopes in relatively homogeneous soil, the failure surface is approximated by a circular arc, along which the resisting and rupturing forces can be analysed. Various techniques of slope stability analysis may be classified into three broad categories:

1. **Limit equilibrium method** used in geotechnical practice assumes the validity of Coulomb’s failure criterion along an assumed failure surface. The method of slices, which is a rotational failure analysis, is most commonly used in limit equilibrium solutions. The minimum factor of safety is computed by trying several circles.

2. **Limit analysis method** considers yield criteria and the stress-strain relationship. It is based on lower bound and upper bound theorems for bodies of elastic (perfectly plastic) materials.

3. **Finite element method** is extensively used in more complex problems of slope stability and where earthquake and vibrations are part of total loading system. This procedure accounts for deformation and is useful where significantly different material properties are encountered. The finite element method makes it possible to calculate various types of stressant deformations state in a rock mass, subjected to its self weight with the assumption of the behaviour law adopted [5].

### 2.2. Slope stability analysis with computer software

Analysis was performed using Limit Equilibrium program SLOPE/W [6].

**Ordinary Method of Slices.** Stability of vertical slope slice may be expressed by Fellenius equality:

\[ T = \rho \sin \alpha \leq N \tan \varphi + c \]

And of the whole slope by:

\[ \sum T = \sum \rho \sin \alpha \leq \sum N \tan \varphi + \sum c \]

Where \( T \) – friction force; \( \rho \) – weight of slope slice; \( N \) – normal force; \( \varphi \) – angle of internal friction; \( c \) – soil cohesion; \( l \) – sliding length of the slope slice.

Slope stability may also be evaluated by its factor of safety:

\[ F = (\sum N \tan \varphi + \sum c L)/\sum T \]

Where \( L \) – total length of the slide surface.

During calculations, the plane problem (the section of 1m width) was analysed. Values of physical-mechanical characteristics (unit weight \( \gamma \), internal friction angle \( \varphi \) and cohesion \( c \)) were obtained by geological investigations. Phreatic line was calculated by a computer program. It was assumed that slope may slide along cylindrical surfaces and the sliding part of the slope remains undeformed.

Under these circumstances, slope stability was evaluated by minimal factor of safety \( F \) given by

\[ F = \frac{M_{pass}}{M_{act}} \]

where \( M_{pass} \) – total moment of passive forces supporting slope stability which are: force of internal friction \( F \) and force of cohesion \( C \); \( M_{act} \) – total moment of active forces stimulating slope sliding which are: soil weight force \( G \) and seepage head force \( U \).

Values of minimal factor of safety \( F \) are presented in Table 1.

| Factor of safety \( F \) | State of the slope |
|--------------------------|-------------------|
| < 1.0                    | Unsafe            |
| 1.0–1.25                 | Doubtfully safe   |
| 1.25–1.4                 | Sufficiently safe |
| > 1.4                    | Sufficiently safe for dams |
3. Case study: Aleksotas Hill in Kaunas

The investigated area is in the eroded Garliavalinoglacial plain near the Nemunas River valley near Vytautas Magnus Bridge, Aleksotas eldership, in Kaunas city. Absolute heights is from 70.5 to 32.5 m. Research Department of JSC “Kelprojektas” under contract with Kaunas municipality company "Kaunoplanas" carried out engineering geological research in January-February 2017. The results of research show altitude below 49 m, where the slope is 35° and even more, on the left side of the slope there was an unexploded gully of up to 1.5 m deep, apparently formed during the construction of the drainage for a telephone line as no signs of landslide activity have been observed recently.

At the same level, in the middle of the slope, there are cracks in soil and first signs of emerging small landslides; small terraces formed below can be seen. This landslide is formed at the location of water supply main trench, almost at the same level, where a slight landslide has already been formed a few years ago (April-May 2015) (Figure 2a). In the same year (2015) landslide stabilization and remediation work was performed (Figure 2b).

![Figure 2a. Landslide on the Aleksotas Hill near Vytautas Magnus Bridge.](image1)

![Figure 2b. Landslide stabilization and remediation work finished in 2015.](image2)

The past landslide processes and present formed cracks as well as formed terraces indicate that the slope is unstable at this location and during each rainy period (in the spring or after rain when weathering takes place) there are deformations of the slope and landslides can occur. In order to prevent future landslides, Kaunas municipality company "Kaunoplanas" prepared project of the Aleksotas Hill reconstruction with designed drainage system (Figure 3a). As part of the anticipated work on the renovation of the Aleksotas observation site, a colourful band created from dwarf shrubs, dominated by national motifs, was created (Figure 3b).

Academic research, standard engineering practice, and worldwide experience have produced many slope stabilization methods; most fit into four categories: controlling groundwater with drainage, using surface cover, excavating and regrading and adding reinforcing support structures. The Aleksotas Hill slope stability calculations of the original (natural) slope and excavated slope with constructing subsurface drainage were performed in order to evaluate the solutions proposed in the reconstruction project.
4. Results and Discussion
The slope stability calculations were performed by modelling slope stability using the Geostudio Slope/W computer program [6]. Process of slope stability simulation is shown in Figure 4.

Calculations were carried out under the three following conditions: dry, saturated, semi-dry condition.

Soil properties of top layer (technogenical soil): unit weight $\gamma = 18 \text{kN/m}^3$, angle of internal friction $\varphi = 10^\circ$, cohesion $c = 5 \text{kPa}$.

The Aleksotas Hill slope stability calculations of the original (natural) slope under dry (Figure 5a) and saturated (Figure 5b) conditions show values of factors of safety $F = 1.129$ and $F = 0.489$. According to Table 1, sufficient values of minimal factor of safety are $F_{\text{min}} = 1.25–1.40$. So calculation results presented in Figure 5 show that factual factors of safety are too low and state of the slope under dry conditions is doubtfully safe ($F = 1.129 \leq 1.2$), under saturated conditions, it is unsafe ($F = 0.489 < 1$).
There are many methods for stabilizing the slopes, three main groups of remedial measures are [2]:

**Geometrical Method.** This method is usually simple and less costly. Changing of the slope angle from steep slope to a gentler slope may increase the slope stabilization and the angle is usually supported by grass bonding together with soil. This conventional method of angle grading requires some excavation. This type of method does not require heavy load resistance and naturally stabilize the slope with the creepy grass surface.

**Drainage Method.** One of the slope failure factors is saturation and pore water pressure building up in the subsoil. If drainage system had been provided, the chances of building up pore water pressure and saturation of subsoil can be minimized. This method can be very effective.

**Retaining Structures Method.** This method is generally more costly. The principle of this method is to use a retaining structure to resist the downward forces of the soil mass.

Subsurface drainage and excavation of formed terraces (drainage and geometrical methods were used) were designed to increase slope stability in the investigated object. Requirement and selection of slope stabilization method should consider the problems that may occur due to the excavation activities. During construction of the drainage system, the excavated soil cannot be stored on the slope - it would be additional load on the slope and further reduction of its stability. Any additional load was not taken into account during slope stability calculations. The Aleksotas Hill slope stability calculations on excavated slope with constructed subsurface drainage was performed analysing semi-dry state (low groundwater level) and minimal factor of safety has increased – $F = 1.377\geq1.2$, state of the slope is sufficiently safe (Table 1). Results of the Aleksotas Hill slope stability modelling show slope stabilization method using drainage and geometrical methods increasing minimal factor of safety by 182% (from $F = 0.489$ (under saturated conditions) to $F = 1.377$ (under semi-dry conditions). Similar results with the effect of cutting off natural slope (from steep slope to a gentler slope) on its stability are both due to the change in geometry (slope angle) and the change in shear strength parameters related to the strain induced by the movement of slope face which are presented in paper [1,5]. The researchers [1,3] suggest installation of equipment for monitoring the movement of a cut slope (from gentler slope to a steep slope) because the failure may occur at any time after construction.

5. Conclusion

The Aleksotas Hill slope stability calculation results show that when technogenic soils cohesion value $c = 5$ kPa is used, the slope is practically unstable $F = 0.489$ (under saturated conditions), and in the case of dry conditions, slope stability is not ensured $F = 1.129$.

The changing of the slope angle from steep slope to a gentler slope by excavation of formed terraces and construction of the drainage system has a positive effect on minimal factor of safety – it was increased to $F = 1.377$ which means that the condition of the slope is sufficiently safe.

References

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