STABILIZATION OF SLOPE INSTABILITY: APPLIED METHODS FOR LANDSLIDE REMEDIATION

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Abstract

Slope instability and landslides are natural processes of great importance for modeling modern relief. Landslides occur as a result of a complex interaction between geological, geomorphological, hydrological and climatic factors, but also due to various forms of human activity. According to the definition of Cruden (1991), "a landslide is the movement of a mass of rock, debris or soil down a slope, which includes all types of gravitational movements - from landslides and overturning, to rotational and translational landslides, as well as loose material flows". These phenomena are especially pronounced in terrains with pronounced slopes, complex geological structure, high hydrological activity and low vegetation coverage. In addition, inadequate urbanization, deforestation, poorly planned construction activities and transport infrastructure often destabilize the natural balance of slopes, encouraging landslides. The consequences of landslides can be catastrophic — damage to infrastructure, endangering the safety of the population, and degrading the environment. For this reason, understanding the causes and mechanisms of landslides, as well as the application of effective geotechnical methods for their remediation, are a key part of engineering practice and sustainable spatial planning. This paper aims to present modern geotechnical approaches to slope stabilization through a review of landslide remediation methods and an analysis of their application in real conditions.

Keywords: *slope, slide, landslide*
JEL classification: *Q25, Q28, L11*

1. INTRODUCTION

The soil or rock mass in the area of natural slopes and artificial slopes is in equilibrium as long as the shear strength within the slope is greater than the shear stresses. When these equilibrium conditions are violated, the slope is destabilized, which can lead to its movement, failure and sliding. shear. Therefore, when the soil surface is not horizontal, a component of the force of gravity appears that tends to move the soil mass downwards, as shown in Figure 1. The sliding will stop when the shape of the slope changes so much that the change in stress re-establishes equilibrium, or if the influences that caused the disturbances (groundwater level, current pressure, etc.) cease to act. The long-term effect of weathering factors and changes in meteorological conditions in geological periods cause changes in stresses and material properties in the surface layer of greater or lesser thickness, all of which reduces the shear strength. [2]

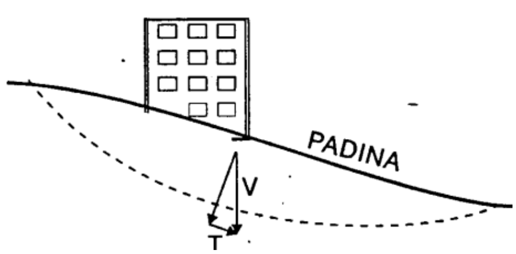

Figure 1. Slope [1]

Based on the above, it can be concluded that a landslide is the movement of soil or rock material caused by a failure within the boundaries of the moving mass. Under the influence of gravity and additional loads, shear stresses arise in the soil, which cause movement down the slope. The speed of this movement can vary significantly - from very slow creep, to sudden and destructive rapid sliding.Therefore, it is important to understand the basic elements of a landslide:

sliding surface– the surface along which a mass of soil or rock moves down a slope.
sliding block– a mass of soil or rock that moves.
breakdown zone- the place where there is cracking or breaking of material within the soil or rocks, which allows the movement of the sliding block.
foot– the lower, front part of the sliding block, which is often compressed and deformed due to the pressure of the mass above

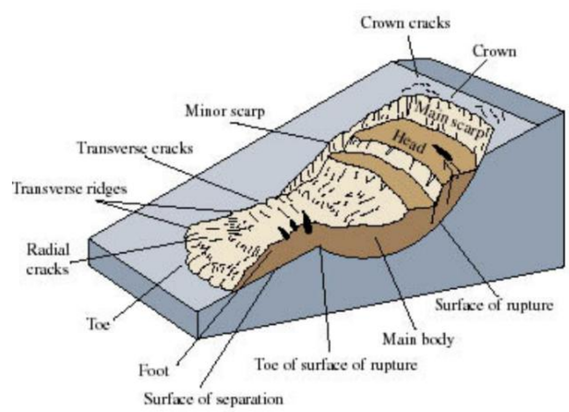

Figure 2. Landslide elements [5]

2. LANDSLIDES – DEFINITION, ELEMENTS, CAUSES OF OCCURRENCE

In nature, landslides occur due to long-term climatic influences, such as heavy and prolonged rainfall, which increase the water content in the soil, reducing its internal strength. Water penetrates into the cracks and pores of the soil, increases the pore pressure and weakens the bond between particles, making the soil significantly more susceptible to sliding. In addition, changes in groundwater levels and seasonal freezing and thawing further contribute to the mechanical instability of soil layers. In addition to natural factors, human activity has a significant impact on the occurrence of landslides. Irrational deforestation, excessive land use, uncontrolled earthworks and the construction of infrastructure on unstable terrain often contribute to the destabilization of slopes. When the natural plant cover is removed, the soil remains unprotected, and its layers become more exposed to erosion and atmospheric influences. Also, improperly designed roads, cuts and embankments can cause changes in the distribution of stresses within the slope, which can be enough to trigger the sliding process. Earthquakes, which abruptly change the stress state within the soil, pose a particular risk. Vibrations due to earthquakes can disrupt the already weakened structure of the slope, especially if it was previously saturated with water. In such cases, the soil loses its load-bearing capacity and there is an immediate sliding of large masses, which often has catastrophic consequences. Finally, the long-term influence of time should not be neglected either. During geological periods, as a result of the continuous action of natural processes such as wear and tear of rock material, the surface layers of the soil gradually lose their mechanical properties. Although these changes take place slowly and imperceptibly, their cumulative effect over decades or even centuries can lead to a decrease in slope stability. At the moment when the balance is disturbed, there is a sudden movement of the ground, which can result in serious consequences.

2.1. Classification of landslides

The formation of a landslide causes changes in the relief, the internal structure of a slope or artificial slope, the position and shape of the terrain surface or the sliding surface along which the moving mass moves. There are several classifications of landslides, which are described in more detail below.

Division of landslides depending on the direction of development of the sliding process:

- delapsive - landslides in which the sliding process develops from bottom to top
- detrusive - landslides where the sliding process develops from top to bottom

Classification of landslides according to the geological environment in which the landslide forms:

- consequential landslides - occur on slopes where there are already predispositions for their formation.
- sequential landslides - occur in homogeneous, non-layered rock masses, where the sliding surface is mostly circular-cylindrical and does not follow the rock layers.
- insequential landslides - occur in heterogeneous, layered rock masses where the sliding surface intersects multiple layers of different properties

Classification of landslides according to the depth of the sliding surface	Clasification of landslides according to the amount of mass moved
❖ surface (> 1m)	❖ small (up to a few thousand m^3)
❖ shallow (1 – 5 m)	❖ medium (up to several tens of thousands m^3)
❖ deep (5 – 20 m)	❖ large (up to several hundreds of thousands m^3)
❖ very deep (> 20 m)	❖ very large (up to several millions of m^3)

Table 1. Classification of landslides based on the depth of the sliding surface and the volume of displaced material.

According to the movement mechanism, there are five types of sliding:

fall-separation of mass from steep slopes on the surface, on which there is little or no shearing, but free fall of material, overturning or rolling occurs;
topple - rotation (forward) of a separate mass around an axis located at its base or near its base;
slide - movement of a more or less coherent mass along one or more well-defined sliding surfaces (failure surface);
spread - the main way of movement is the lateral spreading of blocks, resulting in the formation of shear or tension cracks,
flow - various movements with significant variations in speed and water content, and are manifested as spatially continuous deformation [4]
rotational landslides - characterized by a curved, concave sliding surface, where the soil mass rotates around an axis
translational landslides - a mass of soil or rock slides along an almost flat or slightly inclined sliding surface, often in layered rock formations

3. LANDSLIDES REMEDY METHODS

Stabilization of an existing landslide or prevention of a potential landslide is done with the aim of reducing the forces that trigger the slide, that is, by increasing the resistance forces of the soil or rock mass. For good remediation, it is necessary to carry out thorough engineering-geological investigations of landslides that provide certain data and help to develop a remediation project, i.e. form calculation models, in order to know the level of danger of the area of the building located on a moving slope or on a slope that can be affected by sliding. At the same time, the critical sliding surfaces in the restored state are not always the same ones that were critical in the restored state. The best results in the rehabilitation of landslides are achieved by using a combination of different types of rehabilitation measures that must ensure the maximum effect in stabilizing the slope by implementing the simplest and least demanding rehabilitation measure. Landslide rehabilitation measures are classified into four basic groups: drainage, modification of slope geometry, support structures, internal reinforcement of the slope

3.1.Drainage

Buoyancy, pore pressure and the hydrodynamic action of groundwater are the most common causes of slope instability and landslide initiation. Therefore, drainage is one of the most effective and commonly applied remediation measures.

Drainage can be implemented in practice in three basic ways:

- surface drainage,
- dug drains,
- drilled pipe drains.

3.1.1.Surface drainage

The design of drainage cuts must be such as to ensure their permanent and safe functioning.When designing, care should be taken that the filtration flow of water towards the drain must not cause gradual erosion of the soil from the contact zone between the drainage layer and the surrounding soil, as this could lead to clogging of the drainage system. The drain fill must be designed in accordance with filter rules, whereby the permeability of the drainage material should be at least ten times greater than the permeability of the surrounding soil. The granulation of the drainage material must be carefully matched to the characteristics of the adjacent soil in order to avoid migration of fine particles. At the lower end of the drain, the minimum cross-section must be sufficient to accommodate the entire expected water flow. In practice, the geometry of the cross-section will most often not require a width greater than that technically necessary for the construction, which is usually between 60 and 80 cm. In situations where the drain passes through inhomogeneous material, especially if it includes layers with higher permeability, it is recommended to increase the capacity of the drain, because a greater inflow of water can be expected from these layers, at least occasionally. Placing pipes along the bottom of the drainage channel is an effective way of increasing its ability to drain water. When using pipes made of materials that naturally allow water to pass through, such as highly porous ceramic materials, it is recommended to lay them in a layer of sand to improve the flow. If the pipe material is not sufficiently permeable - which is often the case with baked clay, concrete or asbestos pipes - they must be additionally perforated, i.e. drill holes that allow water to be absorbed from the surrounding soil. When installing such pipes, it is important to ensure that the joints between the segments are precisely made, with a minimum distance, so that water can enter the system without hindrance.

3.1.2. Trenched drains

Dug up dogwoodsare basically rectangular or trapezoidal trenches dug in the groundwater table. Their main function is to intercept water moving through the soil and direct it towards a specific recipient, most often an open channel, recipient or collector. A perforated drainage pipe or a pipe made of porous material is usually laid at the bottom of the trench, whose role is to collect water and transport it out of the critical area. The pipe is then lined with gravel or crushed stone, which allows the water to flow freely towards the pipe. To prevent the system from clogging with fine soil particles, a geotextile material is placed around the drainage layer, which serves as a filter. The dimensions of the drains are determined depending on the amount of groundwater and soil characteristics, but most often the depth is between 1.5 and 3 meters, while the width ranges between 0.6 and 1 meter.

3.1.3. Drilled pipe drains

Drilled pipe drains are a modern method of underground drainage, which is used in cases where the construction of classic dug drains is not possible or technically impractical. This method is used to lower the groundwater level in deeper soil layers, as well as to increase the stability of slopes and landslide zones. The basic principle is based on drilling horizontal or slightly inclined channels into the soil, into which are then installed

perforated plastic pipes(most often PVC or PEHD). The pipes are used to collect water from the ground and safely drain it away from the affected area. During installation, the space around the pipe can be additionally filled with gravel or filter materials to improve permeability and prevent clogging.

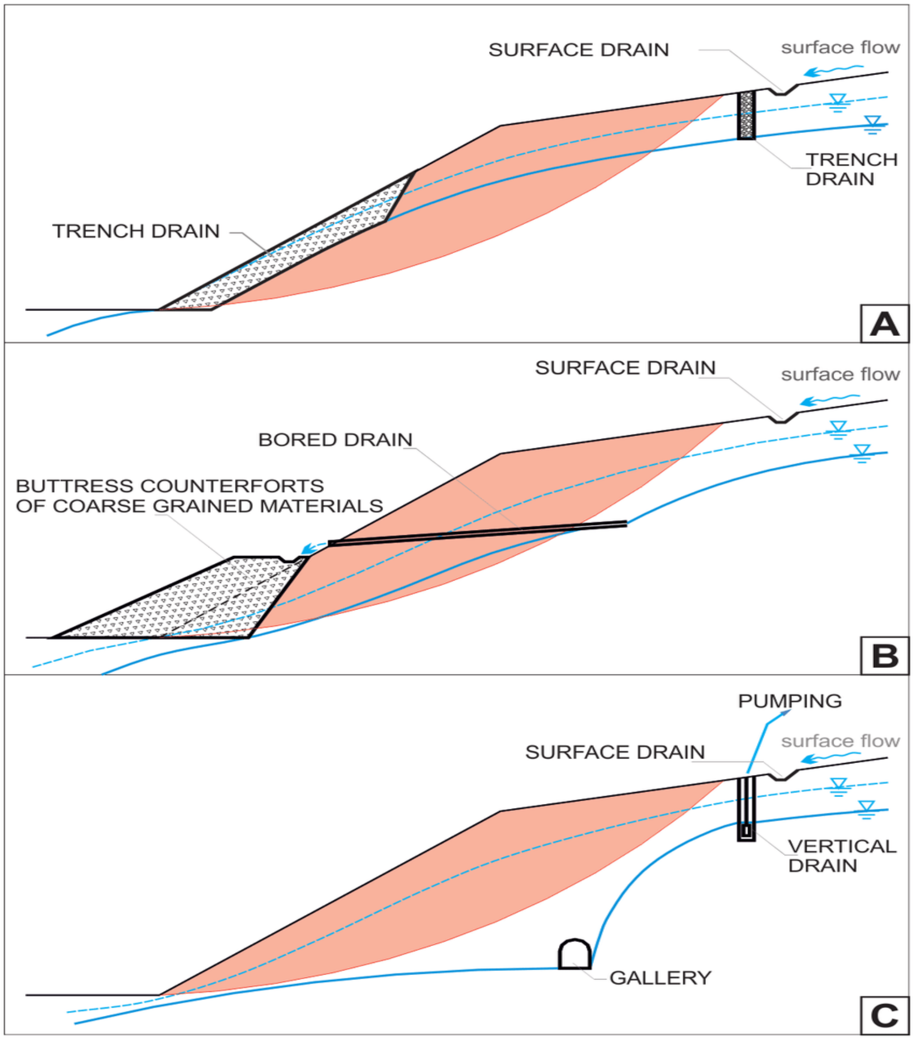

Figure 3. Stabilization of the slope by drainage: (A) Drainage using a combination of surface and trench drains; (B) Drainage using a combination of surface and drilled drains and buttresses (top walls) made of coarse-grained material; (C) Drainage using a combination of surface and vertical drains and a drainage gallery. [8]

3.2. Modification of slope geometry

This method is based on an engineering approach to reshaping the natural configuration of the terrain in order to reduce the forces that cause sliding and increase the stability of the soil mass. The most common form of geometry modification involves reducing the slope slope. By removing excess material from the upper part of the slope (cutting the slope), the weight of the soil acting on the sliding surface is reduced, which directly reduces the forces that cause the mass to move. This intervention is often combined with embankment at the foot of the slope, where the so-called counterweight (stabilization embankment) is built, which increases the soil's resistance to sliding. In certain cases, slope terracing is also used, whereby the slope is formed in a series of horizontal or slightly inclined plateaus. This method not only increases stability, but also allows for better control of surface runoff, and can serve as preparation for urbanization, roads or agricultural cultivation. It is important to note that the change in geometry must be based on a detailed geotechnical analysis, which includes stability testing, determination of safety factors, as well as calculations of sliding surfaces. Improper or excessive intervention can lead to additional instability, especially in stratified or saturated terrains. That is why this measure is often performed in combination with drainage systems (flat, drilled or vertical drains), which reduce pore pressures in the soil and additionally increase the safety of the slope. Support structures, such as gabion walls, gravity walls or reinforced concrete elements, are also often used.

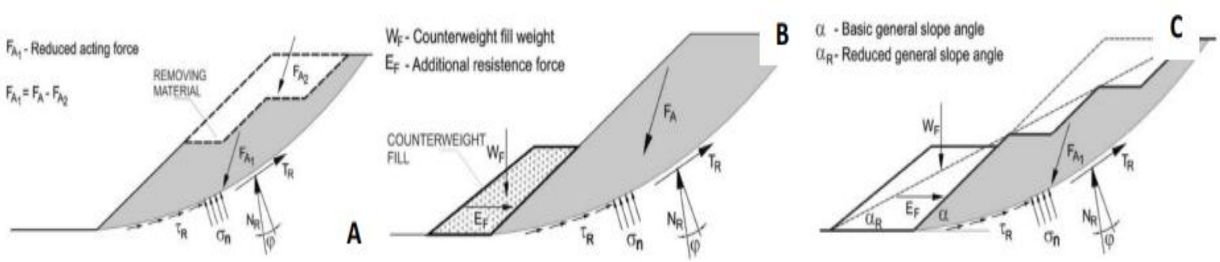

Figure 4. Removing material from the area that triggers the landslide (with possible replacement with lighter material) (A), adding material to the area that maintains stability (counterweight in the form of berms or embankments) (B), reducing the overall slope slope (C). [7]

3.3. Retaining structures

Retaining structures are walls of massive or segmented, permanent or temporary constructions that support uneven natural or filled soil, in such a way that the surface behind the wall is at a higher elevation than in front of the wall. [4] Retaining structures that are built on the lower edge of the moving mass can significantly contribute to the stabilization of landslides. There are different types of retaining walls, and their choice depends on the characteristics of the soil, the height of the slope and the loads to which the soil is subjected. The simplest are gravity walls, which achieve stability by their own weight. They are usually made of concrete or natural stone and are ideal for lower slopes. Their large mass allows them to easily resist soil pressures, but they also require a significant amount of material and space. Therefore, a gravity retaining wall takes on the horizontal or oblique pressure of the fill, and the weight of the wall directs it so that the resultant passes through the base of the foundation to the soil. In situations where walls of greater height are required or when the soil exerts significantly greater pressure, reinforced concrete walls are used. They are thinner and more elegant, but the key to their stability is a quality base and often additional anchoring in the ground. Due to its strength, reinforced concrete walls are often used in urban areas where building space may be limited. Gabion walls are a modern and environmentally friendly alternative. They consist of wire baskets filled with stones, which gives them flexibility and allows water to pass through, thus reducing hydrostatic pressure. These walls are particularly suitable for less steep slopes and natural environments, where speed and simplicity of execution are important. For the most difficult conditions, such as deep and active landslides, more complex structures such as piled and anchored walls are used. These systems, deeply embedded in the ground, additionally ensure the stability and reliability of the renovation, even though they are much more demanding and expensive to perform. An essential part of the renovation is the proper solution for soil drainage behind the wall, because the accumulation of water can significantly increase the pressure and threaten the stability of the entire structure. That is why drainage layers, perforated pipes and geotextile materials are installed that efficiently drain excess water.

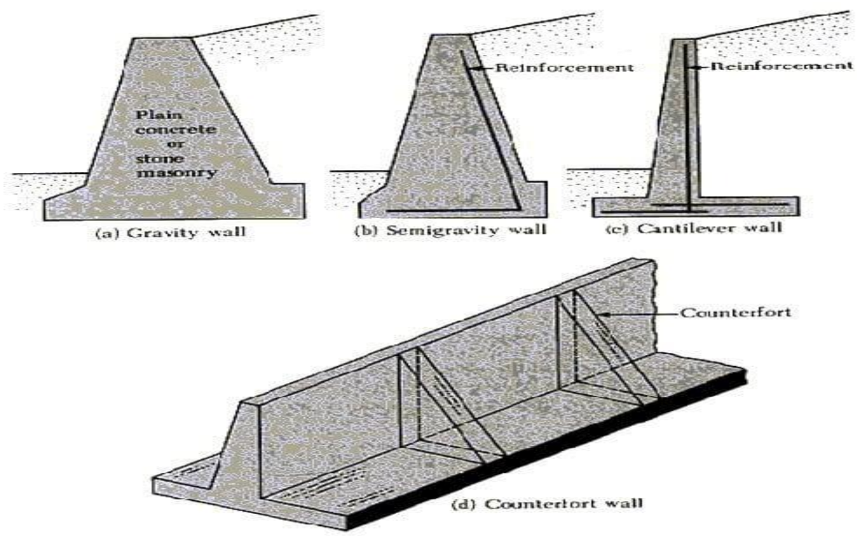

Figure 5. Types of retaining walls [6]

3.4. Internal reinforcement of the slope

Internal slope reinforcement involves the integration of various materials and technologies within the soil mass itself, thereby increasing its resistance to forces that can cause landslides. One of the most common techniques is soil reinforcement using geosynthetic materials – such as geotextiles, geogrids and geocomposites. These materials are placed in layers and act by increasing friction between soil layers, thereby reducing the possibility of movement. In addition to geosynthetics, the soil drilling method is also used, which involves placing steel rods in pre-drilled holes in the slope. These rods are then reinforced with cement injection material, forming a kind of “reinforcement” within the soil. This method is often used to stabilize existing slopes, especially when widening roads or building structures in mountainous areas. Internal reinforcement is often combined with surface protection, such as shotcrete, drainage systems and greening. This also allows for the control of surface water that can contribute to erosion and soil destabilization.

CONCLUSION

The issue of landslides in engineering practice requires a serious and systematic approach, as it represents one of the most common and dangerous phenomena related to terrain stability. The movement of soil mass along a slip surface is the result of a complex interaction between terrain structure, hydrogeological conditions, and external influences—whether natural or caused by human activity.Understanding the mechanisms of sliding, as well as accurately identifying all risk factors, forms the basis for selecting appropriate remediation methods. Whether it involves reducing pore water pressure through drainage systems, modifying slope geometry, constructing retaining structures, or internally reinforcing the soil mass—each intervention must be tailored to the specific field conditions. No solution is universal, but a combination of multiple approaches can achieve long-term slope stability.Ultimately, effective landslide management does not only mean responding after a problem occurs, but also ensuring timely prevention—through proper construction planning, preservation of natural vegetation, and control of impacts on the soil. Prevention is always more cost-effective, safer, and more sustainable than post-failure remediation.

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