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Research Article

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Rehabilitation of Infrastructure After Road Slips on Steep Slopes

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Abstract
Roads in the urban or rural environment may undergo severe deterioration due to flood events, erosion and drop of shear strength in the supporting infrastructure. Common features of this type of road deterioration are: [a] narrow head of slide [b] rotational or plane failure, [c] bottom-up distress due to soil erosion and degradation. In several cases, upgrading interventions can be very difficult because of limited access of mechanical equipment, necessary for rehabilitation operations. Especially, in case of road slides on steep natural slopes, rehabilitation of the soil infrastructure may encounter serious impediments: limited access to equipment, risk of total collapse in case of further excavation, hand transport of materials, limited width of the geostructure to be restored. Geotechnical engineers have to deal with all these constraints and conclude to the most suitable and the most realistic design of reconstruction for a safe road infrastructure. To this end, the geotechnical designer is driven to think "out of the box" and renounce the common supporting and buttressing techniques: retaining walls, pretensioned bolts, soil nailing. Instead, low-cost methods, alternative techniques and small-scale operations, may prove effective: staged excavation and reconstruction, nailed parapets, soldier-pile walls and other. These alternative techniques should be suitable for portable drilling equipment and hand-driven site works to rehabilitate the damaged road infrastructure and restore rideability on the roadway. In this paper, some of these alternative techniques are presented and related considerations on the geotechnical stability are outlined. Moreover, design sketches are displayed, aiming at guiding the geotechnical designer to small-scale rehabilitation solutions in case of flood- distressed road infrastructure on steep slopes.

Keywords: Road, Infrastructure, Slide, Restoration, Stability

1. Background

Road infrastructure is a composite structure consisting of the subgrade, bearing the pavement and traffic loads, the embankment, serving to adjust the elevation of the roadway, and the foundation, the natural ground where all loads finally land up. Road infrastructure is made of earth materials designed and put in place in a way to effectively support external loads and is meant to exhibit a satisfactory performance along the service life of the transport corridor. Either due to inherent construction defects, or to external loads, this essential part of the road may undergo permanent deformation, degradation, subsidence and geotechnical instability. Among the latter, slides are generally, the most important. Slides of road infrastructure occur due to drop of shear strength and may be designated as a special type of landslide, that is, a movement of the road pavement and infrastructure downward [5]. Road slips are slides, either rotational or translational, where the slide head is of limited width (transverse to the road axis), while the failure depth may be significant. They usually occur on steep natural or engineered slopes, following a severe dynamic loading (seismic vibration) and, more often, as a result of heavy hydraulic charge generating soil erosion, saturation and drop of shear strength.

Effective and updated preventive measures are the best option to fight against road slips [1] . These measures must be taken at the construction stage but they can be completed at a posterior stage of maintenance and rehabilitation. They are classified into four major categories with respect to the objective: (a) manage runoff water, (b) impede underground water infiltration, (c) increase the shear strength of the geostructure, (d) decrease external and driving (to failure) loads [2].

Road infrastructure distress is generally held through methods and techniques pertaining to landslides, namely slope stabilization and landslide repair [3]. Practically, all these methods are established on an assumption of a construction process where the mechanical equipment (excavators, loaders, bulldozers, wagon-drills) plays a major role. In reality, however, this is not always the case: limited or inexistent access of mechanical equipment to the work site restrains the field of options. This paper aims to present alternative techniques for rehabilitating road infrastructure on steep slopes in a context, where conventional methods may not be feasible due to access constraints. Road Engineers must accurately assess the road context and the access possibilities and elaborate an effective, realistic and "out-of-the box" method of rehabilitation of the damaged infrastructure.

1.1 Slope Stabilization

In general, the issue of slope stabilization seems well established nowadays. Measures for earth slope protection and for surface runoff and groundwater management, taken during road construction and maintenance operations, can reduce erosion effects and enhance the long-term performance of slopes and embankments [4]. A combination of adequate drainage, installation of protective devices and elements, and establishment of desirable vegetation offers the best means for soil conservation [5]. These means include erosion control techniques, soil bioengineering, geogrid reinforcement and earthwork operations. There are many methods and techniques offering convincing solutions of stabilization to the road infrastructure, which can be classified as follows (Table 1) [6].

	ShallowFailure	DeepFailure
MitigationSolution: Excavate		
Option 1: Remove or Replace Material at the Top of the Slope	√	
Option 2: Build Benches or Terraces	√	
Option 3: ReduceSlopeAngle	√	
Mitigation Solution: Reinforce or Strengthen		
Option 1: InstallGeosynthetics	√	√
Option 2: Construct a Toe Buttress or Berm	√	√
Option 3: Conduct Deep Soil Mixing	√	
Option 4: InstallSoilNails	√	
MitigationSolution: InstallDrainage		
Option 1: Construct an Interceptor Trench	√	
Option 2: InstallSubsurfaceDrains	√	√
Option 3: InstallCheckDams	√	
Mitigation Solution: Install Retaining Walls		
Option 1: Install a Mechanically Stabilized Earth Wall	√	
Option 2: Install a Timber Pile Wall	√	
Option 3: Construct a Gabion Wall	√	
Option 4: Construct a Crib Wall	√	
Option 5: Construct a Bin Wall		
Mitigation Solution: Install Nature-Based Solutions		
Option 1: Use Natural and Hybrid Approaches	√	

Table 1: Common Mitigation Solutions for Earth Slope Stabilization Solutions and Options

However, most of these techniques are applicable, either at the initial stage of construction or at a maintenance stage, where abundant mechanical equipment is available to perform effectively specific earthwork operations. This is not the case of road slips on steep slopes, especially, In distant settlements, where difficulties of access to site is combined with limited possibilities of excavation or backfilling.

1.2 Road Slips Due to Extreme Flood

Rainstorms and floods can severely damage road infrastructure and create disruption of road traffic. Despite measures of protection, taken in the case of some principal corridors, floods often turn out to disastrous events damaging local and main roads. It seems that, in the presence of abundant floodwater, the deterioration of any road network is possible. Far more than the impact on transport infrastructure, floodwaters inundate homes, destroy properties and pose threats to human beings and living organisms. One may reasonably argue that these threats are more significant than the road distress issue. Why, therefore, bother so much about roads? Roads are versatile infrastructure elements and keystones to human activities. Especially, in case of floods, roads serve traffic and move needs, provide emergency and evacuation routes and offer refuge to residents driven out of homes. It is important to keep them safe and to restore their integrity and trafficability, in case of natural hazards.

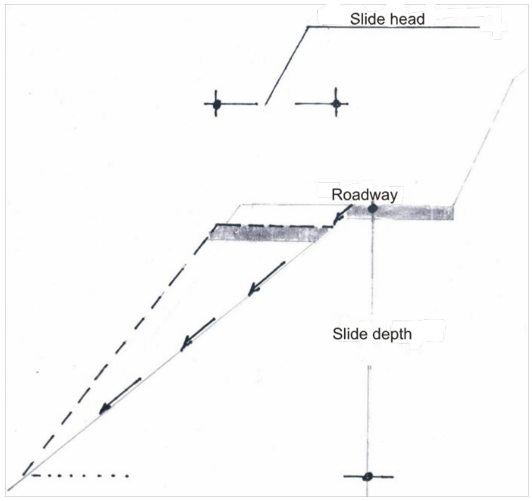

Figure 1: A Typical Road Slip on Steep Slope. A Part of the Pavement and the Earth Structure Moves Downward.

In most cases of distressed road structures due to flooding, the issue of rehabilitation is principally a geotechnical problem. Floodwater may infiltrate in the road subgrade and generate drop of shear strength, erode slopes and infrastructure and produce landslides. In either case, the Designer should address the problem by restoring the geotechnical stability and by providing additional drainage conduits. The problem is tortuous and demanding, since it is often combined with access and space difficulties.

Road slips are a special case of slides: the sliding mass has a narrow head with respect to the slide depth and the stable part of the ground has a steep slope (Figure 1). Hereafter, earth slopes of a gradient of 1:1,5 (35o) or higher are considered as "steep slopes".

This creates additional problems to the geotechnical designer, namely:
• Access difficulties, that is, inability of mechanical equipment to access the work site uphill or downhill the road
• Difficulty in backfilling, due to steep ground. Inability to reshape embankments on steep terrain (Figure 2)
• Risk of collapse following any excavation which is necessary for footings, retaining walls, etc.

Figure 2: Road Collapse on Steep Ground

2. Means and Techniques

With view to restoring the road corridor and to achieve a satisfactory level of structural integrity and traffic safety, the Geotechnical Engineer must search for conventional and less conventional or uncommon methods of stabilization of the infrastructure. Some of these methods are outlined hereafter:

2.1 Staged Excavation and Construction

At slope failures of significant length (along road axis), soil removal from the failure toe, at only one stage, may generate further destabilization (Figure 3). Excavation and construction of a retaining wall should take place by small segments of 3-5 m to prevent total collapse of the soil mass (Figure 3).

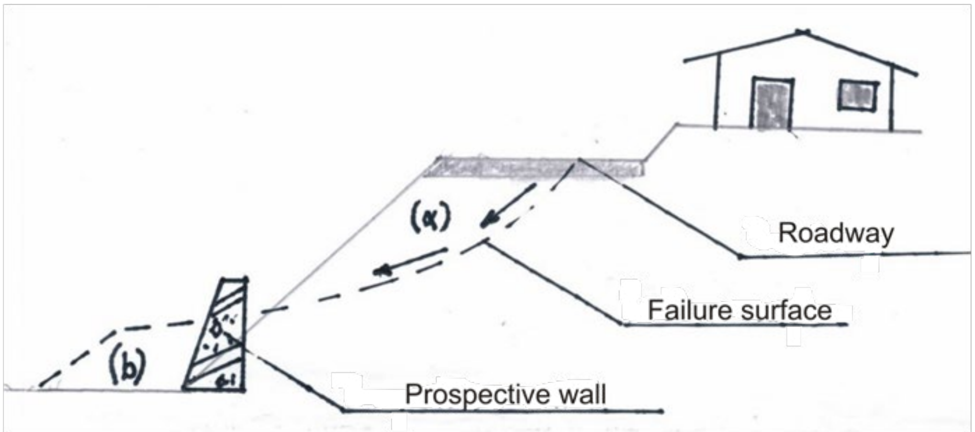

Figure 3: Staged Construction: (a) Gradually Remove Soil Mass Along the Embankment Toe and (b) Construct Retaining Wall.

2.2 Soldier Pile Walls
This is a variation of the traditional retaining walls, applicable in earth slopes where the shallowest excavation risks generating collapse. Soldier pile walls exhibit significant retaining strength depending on their geometric design [6]. However, their construction requires the use of drilling equipment for the piles to be installed. Apart from the pile holes that need drilling, no other excavation is required. Depending on the power of the drilling equipment, the pile depth usually varies from 2 to several meters. Drainage pipes must be installed at the lowest part of the wall, at a spacing of up to 3m.

2.3 Nailed Parapets
Nailed parapets are low walls (height =50-80 cm) from reinforced concrete with a number of steel bars nailed manually to the ground prior to construction. Usually, the nailing depth equals half the bar length. Nailed parapets serve as low strength retaining elements where no excavation is possible (Figure 4). They are mostly applied in slope failures where the thickness of the sliding mass is limited.

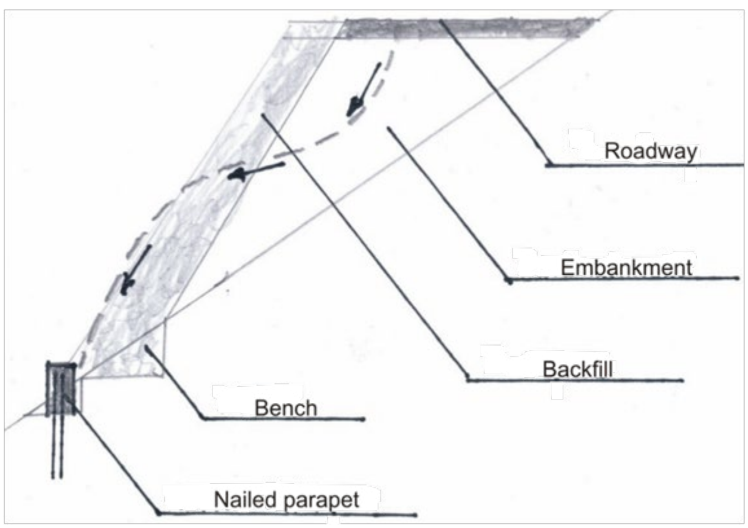

Figure 4: Nailed Parapet on Steep Slope.

2.4 Temporary Fiber Shotcrete
In case of road slips, where the ground slopes are very abrupt, the bottom-up construction presents obvious risks for the working personnel. Reinforced or fiber shotcrete on the ground slopes increases stability during construction. Subsurface drainage must be taken into consideration.

2.5 Benching
Quasi-horizontal layers or benches, of a width of 3m or more, cut into the ground slope, prior to backfilling, increase the resistance to sliding. Before any backfilling operation, the bulldozer must cut these benches, parallel to the road axis, with view to stability improvement. Depending on the gradient of the ground slope, backfilling may be combined with soil reinforcement by geogrids for stability improvement.

2.6 Gabions with Base Extension
Gabion nets are made of wire mesh or of reinforcing steel mesh. Gabions may be equipped with a horizontal wire mesh extension, at the bottom part, which, after backfilling, provides additional

resistance to the active earth pressure on the inner vertical face of the gabion.

2.7 Hydroseeding and Geocells

In case of unstable earth slopes or of degrading rock slopes, the option of additional vegetation needs to be considered. Depending on the accessibility to the slope toe, hydroseeding or other techniques [5] may be applied. Geocells (Figure 5) seem to offer a stable cover of degrading rock slopes up to a gradient of 2:1. Both techniques aim at stability improvement by additional vegetation on slopes prone to failure due to erosion and surface degradation.

Figure 5: Geocells on Cut Slope for Stability Improvement

2.8 Double Stabilizing Sheet (Geotextile + Wire Mesh)

Where backfilling operations, especially compaction, are driven by moderate mechanical equipment and the result is questionable, a double external sheet (geotextile or geogrid/inner cover and wire mesh/ outer cover) may be used to safely hold back the backfill. The double sheet technique may also be used for stabilization of fractured rock slopes of smooth gradient (Figure 6)

Figure 6: Double Stabilizing Sheet: Bio-Geogrid + Wire Mesh on a Fractured Rock Slope.

2.9 Tie-back walls

Tie-back walls may be an effective solution to stabilize cracked or slightly damaged stone-block walls either uphill or downhill a road. Excavation and total removal of the damaged wall could generate overall collapse and, consequently, this may be not a realistic option. A tie-back wall, covering the front face of the existing stone-block wall and anchored back by soil nailing, presents the advantage of direct application and low risk of failure. Accessibility of wagon-drill to the toe of the stone-block wall is a prerequisite for the application of this technique.

2.10 Road Deviation

In case of road failures on very abrupt slopes, where any attempt of repair and rehabilitation seems pointless, a relocation of the road axis uphill may be envisaged. This option, however, may encounter other difficulties, such as, environmental constraints and land expropriation, but in some cases, it is the only way.

It must be stressed out that, in case of short detours of a road deviation, a minimum repair of the failure area must be conducted. Otherwise, the earth slope will keep on degrading and sliding with a negative impact on the natural ground and, eventually, on the road infrastructure.

2.11 Drainage Options and Erosion Control

Management of runoff water and of subsurface flow is a precondition for the stability and the integrity of road infrastructure. Increase of discharge capacity and decrease of potential and kinetic energy in a watercourse are the main objectives. Riverbed widening, gabions, stepped channels, stilling basins, artificial ponds, are some of the measures to be taken with view to minimizing the hazardous event of excessive flow and erosion of the road infrastructure.

3. Geotechnical Stability Considerations

In the frame of a rehabilitation design study after a road slip on steep slope, there are two main issues to be addressed by the Geotechnical Engineer: the lateral earth pressure on retaining structures (retaining walls, gabions, soldier-pile walls) and the sliding risk of earthwork along steep slopes [7]. Undrained conditions in the soil mass should be prevented through adequate drainage options [9]. Lateral earth pressure depends on the backfill height, the surcharge and the density of the backfill material. Since it is difficult to alter the geometry of the road and its infrastructure, the geotechnical engineer should consider a lightweight backfill material to reduce active pressure on the retaining structure. Drainage, in every geotechnical problem, but much more in the case of roads on steep slopes, is a major issue. Main stormwater systems may need to be redesigned and provide increased capacity in a context of escalating figures of rainfall and flow discharge. With respect to subsurface drainage, a reliable technique consists of placing a geomembrane along the failure surface before backfilling to prevent infiltration and generation of undrained conditions into the backfill. Sliding risk along steep slopes is also a major concern for the geotechnical engineer. Effective drainage uphill is a requisite in this case, but additional measures, such as, benching and toe stabilization are equally important for the integrity of the geostructure. Quality of backfill material is also an issue for consideration. Clays, silts and organic soils should not be prescribed for earthworks on steep slopes. However, if high quality fill material is not available, these soils of significant plasticity and low permeability may be used only after adequate reinforcement (geosynthetics) of the backfill layers. An important issue, in the case of remote settlements and access difficulties, is the on-site strength of retaining concrete structures. The Geotechnical Engineer must take into consideration the low prospective strength of concrete produced on site. The traditional concrete mixer is unlikely to produce high strength concrete and, consequently, the design of concrete structures must comply with this limitation [8,9].

4. A Case Study of Staged Excavation and Reconstruction

Following an extremely heavy rainstorm and flood conditions in Thessaly (2023), local roads in mountainous settlements underwent severe damage due to landslides. Insufficient drainage and low discharge capacity of water streams at the toe of road embankments led to severe degradation and distress of these earth structures.

Figure 7: Road Damaged by Landslide After Heavy Rainstorm

In the present case study, road slides occurred along a segment of 40 m long and the slide crown extended to almost half the roadway width (Figure 7). The risk of further sliding, under ordinary traffic conditions, was imminent, therefore, the reconstruction had to start shortly after the incident. Moreover, the risk of total collapse due to an eventual excavation and removal of loose material at the toe of the earth structure led to the option of staged reconstruction. The reconstruction concept consisted of 3 basic elements: a) staged process, that is, break down the 40m long segment into 4 subsegments of 10m and proceed to earthwork operations at alternate parts at 2 stages, b) double waterproof sheet (geomembrane and geotextile) on the slide surface and c) riprap (φ>40o) backfilling (Figure 8). The non-successive subsegments, repaired and stabilized, are clearly shown in the photo.

Figure 8: Staged Reconstruction of Damaged Road for Improved Safety

After the first stage of operations, the road was significantly stabilized and was open to traffic. Subsequently, the second stage of operations was carried out, to be followed, at a final stage, by pavement reconstruction.

5. Conclusions

Restoration of roads on steep slopes, having undergone slides due to erosion and flooding, may require unconventional means and techniques. This may probably be due to the limited accessibility downhill and the abrupt gradient of the natural ground. The Geotechnical Engineer must keep in mind that, in these cases, excavation at the toe of the slide may generate high risk of total collapse and must work on solutions based on uncommon or alternative construction techniques, supported by hand-held or portable drilling equipment. Alternative construction techniques, such as staged excavation and construction, nailed parapets, gabions with extension of wire mesh, double stabilizing or waterproof sheet, may prove effective and realistic. Moreover, all these techniques and many other, aiming at effective preservation and stabilization of earth structures, must be combined with radical drainage measures to control runoff and subsurface rainwater. Restoration of road infrastructure after slope failure is a complex geotechnical subject, requiring scientific knowledge combined with clear perception of the options and means available. The Geotechnical Engineer must consider both, conventional and uncommon, techniques, to identify the best restoration process and must estimate and take into consideration the impact of these options on the budget and the timeline of the reconstruction project.

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