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THE ENGINEERING GEOLOGICAL BEHAVIOUR OF DISTURBED AND WEATHERD GNEISS IN SLOPES. THE CASE OF THE "VERTICAL AXIS" OF EGNATIA MOTORWAY, KOMOTINI – NYMFEA, NORTHERN GREECE

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Abstract

Sound gneiss forms evidently very competent rock masses with minor problems in geotechnical works. However, poor rock masses and problematic behaviour can be encountered in engineering projects in a geological environment characterized by intensive and sequent tectonic disturbance, where, weathering may be strongly favoured. Case studies with slope instability problems are analysed from the Egnatia Motorway along the vertical axis from Komotini to Nymfea, in Northern Greece.

The basic engineering geological consideration focuses on the weathering degree, the tectonic disturbance, the foliated structure and the presence of shear zones. In the paper the gneissic rock masses are categorized in a number of specific rock mass types according to key engineering geological characteristics that define the rock mass behaviour in slopes. Subsequently, the slope behaviour of each rock mass type is discussed. The geotechnical properties of such failure surfaces are very difficult to be estimated due to the heterogeneous nature of these planes and back analysis is the best method to obtain reliable parameters. Back analysis results from two case studies showed significant differences to the laboratory test results. Finally, the concepts of the appropriate support measures based on the mechanism of failure of two case studies are presented in the paper.

Key words: *slope stability, weathered gneiss, rock mass types, slope behaviour, back analysis.*

Περίληψη

Ο υγιής γνεύσιος διαμορφώνει πολύ ικανές βραχόμαζες με περιορισμένα προβλήματα στα γεωτεχνικά έργα. Ασθενείς όμως βραχόμαζες και προβληματικές συμπεριφορές μπορεί να προκύψουν στα τεχνικά έργα μέσα σε ένα γεωλογικό περιβάλλον που χαρακτηρίζεται από έντονη, πολλαπλών φάσεων, τεκτονική διαταραχή όπου ευνοείται η αποσάθρωση. Στην παρούσα εργασία παρουσιάζεται η συμπεριφορά των γνευσιακών βραχομαζών στην διαμόρφωση ορυγμάτων κατά μήκος της Εγνατίας Οδού στον κάθετο άξονα Κομοτηνή-Νυμφαία.

Τα κύρια τεχνικογεωλογικά χαρακτηριστικά εντοπίζονται στον βαθμό αποσάθρωσης, στη τεκτονική διαταραχή, στην ένταση της σχιστότητας και στην παρουσία διατμημένων ζωνών. Στο άρθρο αυτό οι βραχόμαζες κατηγοριοποιούνται σε τύπους

ανάλογα με τα τεχνικογεωλογικά χαρακτηριστικά – «κλειδιά»- που ορίζουν τη συμπεριφορά τους στα πρανή. Έτσι, εξετάζεται ο πιθανότερος μηχανισμός αστοχίας στην διαμόρφωση πρανών για κάθε τύπο βραχόμαζας. Οι γεωτεχνικές ιδιότητες των επιφανειών αυτών είναι αρκετά δύσκολο να εκτιμηθούν λόγω της φύσης των γεωυλικών που αναπτύσσονται σε αυτές ενώ οι ανάστροφες αναλύσεις είναι η καλύτερη μέθοδος για να προσδωθούν αξιόπιστες παράμετροι σχεδιασμού. Εδώ παρουσιάζονται τα αποτελέσματα δύο ανάστροφων αναλύσεων, μία για πλήρως αποσαθρωμένο γνεύσιο και μία για διατημένες επιφάνειες. Τα αποτελέσματα αυτά παρουσιάζουν σημαντικές διαφορές με τις εργαστηριακές δοκιμές. Τέλος, συζητούνται πιθανά μέτρα σταθεροποίησής ανάλογα με τον μηχανισμό αστοχίας για τις δύο περιπτώσεις.
Λέξεις κλειδιά: *ευστάθεια πρανών, αποσαθρωμένος γνεύσιος, τύποι βραχομάζας, συμπεριφορά πρανούς, ανάστροφες αναλύσεις.*

1. Introduction

Fresh gneiss forms evidently very competent rock masses with minor problems in geotechnical works. However, under certain geological conditions gneiss can produce poor to very poor rock masses. This environment is produced by intensive and sequent tectonic disturbance and thus weathering and alteration is favoured in various degrees and depths. In such conditions, the intact rock and rock mass strength present a wide range in values and the behaviour concerning slope stability can be from simple to extremely complex and problematic.

The rock mass characteristics and their properties against slope instabilities are described in the paper along the so-called vertical axis of Egnatia Motorway, Komotini-Nymfea, in Northern Greece. More specifically, the slide phenomena of a tunnel portal cut and a road cut are presented. The vertical axis “Komotini – Nymfania – Hellenic-Bulgarian borders (75.0)” is of 22.5km length, links the Egnatia Highway with the Hellenic-Bulgarian borders and is a part of the European road network. The construction works involve several road cuts and five tunnels.

The area of study mainly consists of the metamorphic rocks of the Rhodope massif and more specifically of the Sidironero Unit. In general, crystalline – schistosed rocks like gneisses, gneissic schists, amphivolites and marble layers are met. The area of study is built-in in the Rhodope massif, which consists of two large units: the tectonically lower Unit of the Pangaio and the tectonically overlaid Unit of Sidironero. The area belongs in the Sidironero Unit, which thrusts over the Pangaio Unit from the North to the South, along a great tectonic line of NW-SE direction that ends to E-W (Mountrakis, 1985). The tectonical analysis of this metamorphic mass shows three folding phases (Mountrakis, 1985). The first phase, of Paleozoic age, consists the main metamorphic event of the crystallic-shistosed mass with a general N-S direction. The second folding phase has axis direction NE-SW to ENE-WSW, while the third has a tectonic deformation with folds of NW-SE axis, which folds again the previous folding phases. The third folding phase, of Oligocene age, is believed that is connected with the thrust of the Sidironero Unit upon to the Pangaio Unit (Mountrakis, 1985). This tectonic deformation had strongly affected the fracturation and quality of the rock mass formations in the studied area.

The evaluation of the geological conditions of the area and the differentiation of the geological units are of major importance. Here, the geological model is based on discontinuities, the orientation of schistosity, the material properties but also on the weathering profile and on the frequent participation of shear zones The definition of the geotechnical characteristics and the critical mechanisms of failure are based on the site investigation data and the results of back analysis after the slide phenomena in two case studies. Thus, geotechnical properties of completely weathered geomaterials and sheared gneisses are developed from back analysis here and compared to the laboratory test results. These engineering geological characteristics are distinguished in rock mass types according to their behaviour in slopes. The assessment of the possible solutions to prevent or control the slope stability problems is also discussed in certain examples.

2. Engineering Geological Characteristics - "keys" for the Stability of Slopes

2.1. General

In general, weathering is a very important factor in slope stability of gneissic rock masses. Gneissic rock masses can vary from massive and very well interlocked to highly or completely weathered because of the feldspar alteration to clayey minerals. Fresh gneiss is a very competent geomaterial with high mechanical properties showing very good slope stability, presenting only some structural instabilities like planar and wedge sliding and toppling failures. In its weathered form (above grade III in ISRM characterisation, Anonymous 1981) the behaviour is dramatically different, presenting circular or multi-planar landslides. Weathering intensity is generally dictated by the climate conditions and the fracturing degree, formed by the tectonic disturbance and the foliation or schistosity of the rock mass. In this study weathering has resulted mainly by fracturing. It is noted that cases of residual soils are not examined here.

Weathering starts from the surface and continues in depth through the fracturing system. If there are no significant weak zones, like faults or aplitic-quartzitic veins, which helps weathering penetration, weathering is limited close to the surface (e.g. few meters to few tens of meters depth) along the discontinuities. In highly disturbed areas, where shear surfaces and satellite fractures create a dense tectonic fabric, weathering may extend to greater depths. Moreover, if the parent rock is schistosed and already deformed, shearing is enhanced. Shearing thickness may be extended in zones from few to several meters. These shear zones are crucial for the slope instabilities, since sliding is favoured along these surfaces, especially if they are highly laminated and weathered and contain sandy-clayey materials.

The geotechnical characteristics of the ground types were estimated from a site investigation program, including laboratory and in situ tests. Gneiss, schistosed gneiss and gneissic schists are the fundamental rocks in the studied area. Gneisses are fractured by several joint systems and are slightly to completely weathered. The principal engineering geological considerations here are: a) the thick weathered cover that can give some circular slides, b) the weak nature of the jointed rock mass that can behave isotropically presenting greater, but again circular, slides and c) the presence of certain shear zones that can guide to an anisotropical behaviour with one or combined multi-surfaces envelops. The general engineering geological characteristics of the gneissic rock mass towards slope stability are presented in Table 1.

2.2. Hydrogeological Conditions

Gneiss formations are generally classified as of low permeability. Groundwater percolates along the fresh discontinuities but is blocked when these are filled or composed of clayey impermeable gauge, imposing a higher hydrostatic level. No significant aquifer has been identified in the investigated boreholes, while only minor seapages close to the surface has been observed. Some small quantities of water can percolate in certain fractured zones. Weathering cover may present some permeability due to the loosening of the mass and the high presence of sandy materials resulted from weathering. This permeability though is not high due to the existence of clays. This is adverse for the stability of the slopes in weathered rock masses since water cannot be drained easily and pore pressures are developed.

2.3. Rock Mass Types

The general characteristics of the gneissic rocks towards the engineering geological evaluation are based upon their fracturing, the intense of schistosity and the weathering degree. In the next paragraphs these general characteristics are grouped in rock mass types and presented in relation to the slope stability. The case, where rock mass behaviour is strongly affected by the frequent presence of sheared and fault zones, is also discussed in the paper.

Rock mass type I is fresh, massive with minor to medium fractures. The intact rock strength of gneiss here is very high, ranging from 70MPa to 120MPa. The rock mass quality is governed by the fracturing degree. The structure is very tight and the discontinuities are generally very closed with rough surfaces but with considerable persistence. The gneissic texture consist a "sewed" surface and due to the fresh conditions, there are no clear detachable blocks. When this type is met in some depth (~5-10m) it confines and stops any potential circular or multi-surface slide. The rock mass type can be stable or show structural control instabilities (planar and wedge slides, toppling failures) according to the discontinuity and slope geometry.

Table 1 - General engineering geological characteristics of the gneissic rock mass concerning slope stability.

	Engineering geological characteristics	Influence on slope stability
Complex rock mass	Irregular geological contacts of the lithological and engineering geological types	Due to the irregular weathering and fracturing degree and the alternations of gneissic rocks of different schistosity with or without aplitic veins, the mechanical properties can be modified within few meters. The behaviour can change from isotropical to anisotropical and vice versa, according to the in situ engineering geological conditions: • rock anisotropy (schistosity and joint geometry in relation to the slope geometry) • as the weathering and fracturing degree increases the behaviour tends to isotropical • shear or fault zones with very low properties may guide to anisotropical or multi-surface failure
Weak rock mass	Weathering of intact rock and rock mass	The nature of intact rock is altered. Intact rock and overall rock mass strength characteristics can be dramatically reduced.
	High presence of secondary clayey materials	Shear strength along the discontinuities, especially of the foliation or schistosity, is reduced. Rock block interlocking is loosened.
	Tectonic disturbance	High degree of fracturing and weathering Presence of shear zones

Rock mass type II is slightly weathered and medium to highly fractured. The intact rock strength remains very high. The rock mass quality is mainly defined from the fracturing degree and less from the weathering one, which is only confined along the discontinuities. The structure is not very tight and the joints are generally open with fair to poor surface characteristics. The gneissic foliation band is the basic discontinuity surface, since weathering is favoured along the foliation planes and easier separates the - great size - rock blocks. Clay minerals from weathering have minimum presence along the discontinuities. The behaviour of this rock mass type is not very different comparing with the type I that is controlled by the presence and direction of the discontinuities according to the slope geometry and the joint characteristics. In this type, however, the probability of the occurrence of these slides increases significantly due to the reduced shear strength.

Rock mass type III has similarities with the type II but its difference lays to the frequent foliation planes and the weathering extent, since alteration is favoured here. The intact rock strength remains high and only slightly decreased due to weathering. Weathering is mainly produced along the gneissic bands producing a sandy-clayey "coating". Although clay minerals have minimum presence along the discontinuities, they are more frequent and separate the rock mass in smaller size blocks. Rock blocks have medium size and decreased friction along the joints. In this case, rock blocks that will fall or slide are smaller in size and the weathering cover is thicker. Hence there may be some minor circular slides and/or a number of falls of small blocks.

The rock mass quality in type IV is moderately weathered with new clayey surface zones. The intact rock strength is significantly reduced and becoming friable but it remains medium to fairly high. The structure of the rock mass is loosened with open discontinuities and poor to very poor surface conditions. The joints have low persistence, since the clayey weathering products interrupt them. Gneissic bands are still the principle joint surfaces, while clayey zones (~5-10cm) further disintegrate the rock mass. These zones can also extend along other joints, with an angle to the foliation planes, creating smaller blocks, which have poor interlocking and friction. A characteristic of the behaviour of this rock mass type and its poor quality is the presence of several circular slides. Only few planar or wedge slides in small blocks can be now possible.

The rock mass type V is moderately weathered, highly schistosed and highly fractured. Weathering easily extends through the frequent foliation planes, which are consequently divided every 5 to 10cm by the clayey zones. Fracturing is very intensive not only due to tectonic disturbance, but also to the frequent gneissic bands. Weathering extends to the whole mass without though the pieces becoming friable and the structure is loosened with open discontinuities and poor to very poor surface conditions. These surfaces-thin zones extend parallel and normal to the fissility, present low friction and produce even poorer interlocking. Rock blocks or slabs are sized around 5-15cm and have poor assemblance. The intact rock strength is significantly reduced. The principal behaviour of the rock mass is isotropic, due to the very close separation by the schistosity and the dense sandy-clayey zones along them. This results in mainly circular failure mode.

Highly weathered and fractured rock mass quality (type VI) is mainly defined from the weathering and the clayey products. Weathering extends to the whole mass dividing in small – partially friable - blocks the non-weathered pieces. The microtectonic structure and gneissic band have been however almost preserved. The structure is very loose and the discontinuities are open with poor surfaces, since they separate with clayey - sandy fillings the less weathered gneissic slabs. The foliation planes have great persistence, while soil materials interject the vertical joints. These zones (~10-30cm) are more frequent than in the rock types IV and V and disintegrate the mass in very small pieces. Hence, the less weathered blocks cannot come in immediate contact and thus can rotate easier along the soil zones. The intact rock strength has been significantly decreased, since weathering has penetrated into the rock itself. Groundwater presence decreases not only the mechanical properties of the clayey surfaces but the rock mass in total. Circular slides or multi-surface (polygonal) slides are the typical mode of failure due to the high presence of the sandy-clayey weathered zones that separates the blocks.

In its completely weathered form (type VII) the rock mass has faintly retained its structure. It is highly fractured, and it is classified as very disturbed or disintegrated. The few rock blocks are decomposed and friable. The discontinuities are not clearly defined with certain geometrical characteristics, while the gneissic foliation is highly altered and separated by clayey-sandy zones of significant thickness. The small rock blocks have very poor interlocking and can easily rotate along the low friction soil zones. The intact rock strength has been dramatically decreased (σ_{ci}~5-10MPa). Any kinematic analysis of planar or wedge instability has no point in such case. The principal mechanism of failure is circular or multi-surface failure if combined with other weak elements. Several minor slides and some more significant have been noted in the area. Such failure mechanism is further analysed in case study 1 below.

The final type, type VIII, does not follow the same concept of weathering. This type consist a tectonically sheared and foliated rock mass, where the intact rock strength is generally low to very low. If the parent rock is schistosed then tectonically deformed shearing is enhanced. Shear zones may be extended from few to several meters usually parallel to the gneissic texture. They are often met inside a symmetrical model, where a brecciated cohesionless gneissic material is centered (Laws et. al. 2003). The shear strength of the rock mass is almost similar to the strength along the foliation surfaces. This strength can be further decreased because of the intensive schistosity or the thin particle increased presence or low cohesion between the foliation planes or the increased content in the mica minerals due to weathering. This rock mass type is often formed in specific fault zones and is very important to slope stability since they may consist the failure surface. When more than one shear surface is present in a slope, these may be combined forming a multi-planar slide. An example is presented in case study 2 below.

2.3 Case Studies

Case study 1

The first case study discusses a slide that occurred close to the entrance portal of Nymfea tunnel (Figure 1). The rock mass in the area is comprised of gneissic schists in the surface and schistosed gneiss in depth. The rock mass is highly to completely weathered at the surface (type V and VII) and becomes moderately weathered (type III) in depth. Six boreholes with inclinometers and piezometers were drilled to investigate the slide. The identification of weak zones, the thickness of the weathered cover in the specific area and the evaluation of inclinometer and piezometer measurements were of primary importance. Taking into consideration the above parameters, it was evaluated that the slide was driven within the weathered zone, occurred after the excavations of the tunnel portal. It started several meters above the cut and ended in the second bench of the excavated cut, developing several cracks in the already applied shotcrete. The weathered zone, other geological features and the tensile cracks are highlighted in the Figure 2. It is highlighted here that sliding could have been also assisted by the weathered schistosity that is favourable dipping with 30^{o} towards the slope.

Figure 1 - View of the entrance portal of Nymfea tunnel. The gabion wall is used here for the stabilization of the whole slope. The slide occurred above the gabion wall.

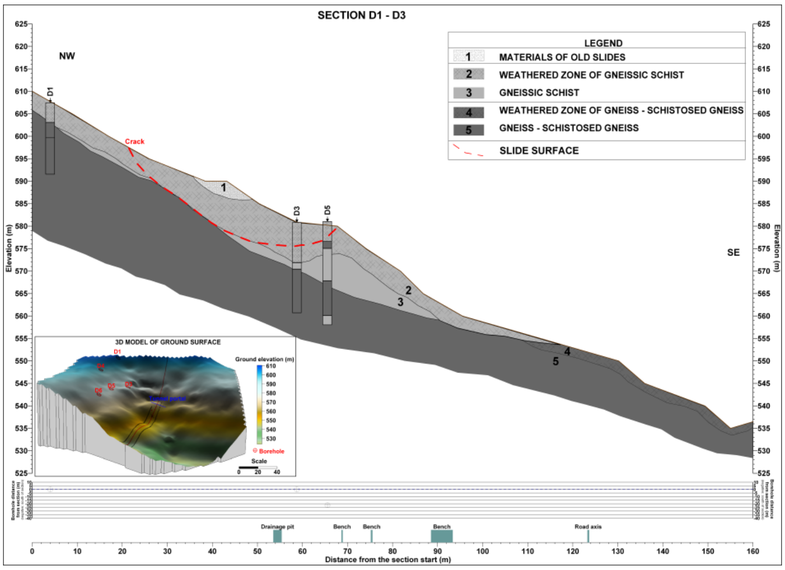

Figure 2 - Geological section along the slide of the Nymfea entrance tunnel portal cut (Case Study 1).

Case study 2

The slope stability problems along the road cut numbered O28 started on summer 2009. The road cut has a height of 30m with 4m wide benches every 10m and consists of schistosed gneiss. After the excavation of the second bench, the first cracks on the slope surface were observed and then a greater slide of a significant part of the slope followed (Figure 3). This failure triggered a greater landslide that developed tension cracks in the natural ground, in a distance 70m behind the scarp of the road cut. The shotcrete along the benches failed and a significant part of the slope has been displaced. After that, the excavation works stopped and the slope was backfilled with a temporary buttress. These temporary actions stabilised the slope since no movement had been observed for two wet periods. In order to face these instabilities permanently, slight modification of the road axis with a horizontal offset of about 15m was decided and a new geotechnical design was implemented.

1. Two shear zones have been recognised in cut O28, one sub-vertical and one sub-horizontal. The first was evident after the slide of the slope and the second was recognised in one of additionally drilled investigation boreholes (Γ19A). The mechanical characteristics of these zones are very poor, since they are consisted of foliated particles of clayey-sandy nature with small rock fragments. The shear zones, other geological features and the tensile cracks are highlighted in the Figure 4. These features can be combined geometrically and it can be presumed that the failure occurred along this surface. It is multi-planar but can be conceptualized in significant degree as circular. It is evident that the excavations of the cut, the design of the slope angles and the presence of shear zones created adverse conditions for the stability of the road cut. Although there are no detailed information about the groundwater conditions at the time of the failure, the fact that sliding occurred during the dry season (summer period), led to the conclusion that the shear zones were the crucial elements triggering the slope failure.

Figure 3 - The slide of the road cut O28. Drain trenches and benches have cracked.

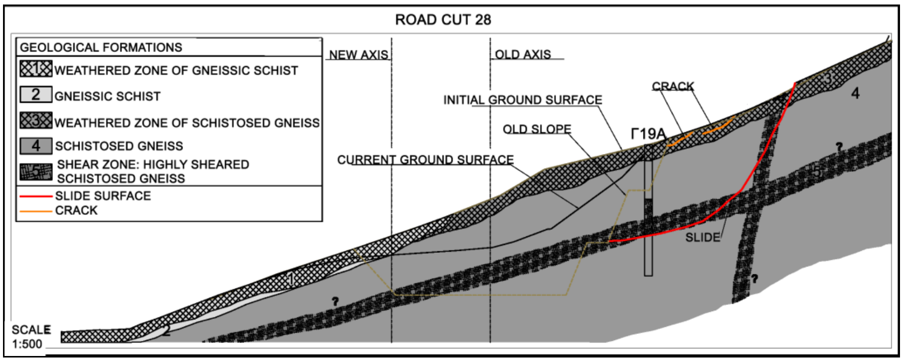

Figure 4 - Geological section along the slide of the road cut O28 (Case Study 2).

3. Geotechnical Properties

3.1. General - Geotechnical Classification

To classify gneissic rock masses, the well-known systems of RMR, Q and GSI can be used. In case of weathered to completely weathered rock mass, a more specific classification might be required. A modified GSI chart has been proposed for gneissic rock masses (Marinos, 2007) with GSI values for every gneissic rock mass type as described above. If the rock mass is not isotropic and the failure mechanism is controlled by several weak elements (shear or fault zones, weak and/or weathered rock mass, foliation planes) the use of geotechnical classification systems is questionable and must be carefully applied. For the back analyses presented in the case studies geotechnical classification systems were generally not applied.

3.2. Geotechnical Properties in the Case Studies

The purpose of the back analysis was to identify the properties of the slided material in the two case studies. In the first case of Nymfea tunnel portal cut the properties of the completely weathered cover (type VII) and in the second case the properties of the sheared gneiss (type VIII) are back analysed. The analyses were based on field observations, borehole logs, geotechnical classification and data from inclinometers. For the analysis process the software Slide v.5.0 of Rocscience corp. was used.

Case study 1

The scope of the back analysis is to estimate the geotechnical properties of the completely weathered gneiss (type VII). The slide was driven within the weathered cover, starting several meters above the cut and ending in the second bench of the excavated cut, developing several cracks in the already applied shotcrete after the excavations of the tunnel portal. From the grain size distribution analysis of the completely weathered soil-like geomaterials it is found that the percentage of sand is around 50-70% and of silt and clay around 20-30%. Plasticity index is around 5-7. The shear strength properties that resulted from laboratory tests (cohesion c=31kPa and angle of friction φ=37º) are considered high and not representative for the material within the failure plane. An important parameter that influences the analysis results is the status of the pore water pressure at the time of the failure. The piezometric surface was assumed along the contact of the weathering cover and the more fresh bedrock. Moreover, due to intense raining before the slide and some infiltration within the weathering cover, a r_u coefficient of 0.25 was considered. It is noted that the weathered cover has some small cohesion since clayey-silty material are present in the mass. The concluded values from the analysis are c = 5 kPa, φ = 28º. It is highlighted that the analyses were done for circular and non-circular surfaces. The results from both the analyses were almost similar (0.998 for the non-circular and 1.029 for the circular surface with the Janbu-corrected method). The actual sliding surface seemed to be the non-circular one as it resulted from the tension cracks, the depth of the bedrock and the cracks in the shotcrete above the portal cut.

Case study 2

In this case study, the sliding occurred along two shear zones, consisting of foliated gneiss that resembles almost to sandy-clayey soil material after its tectonic disturbance. The first shear zone forms the scarp of the slide, and the second - the main sliding surface – is almost parallel to the slope surface. Although the geotechnical parameters of the surrounded gneissic rock mass (type III, γ = 25 kN/m^3, σ_{ci}=35MPa, GSI= 25-35, c= 100 kPa and φ= 30°) were incorporated in the analyses, the critical parameters are the ones of the shear zones. The piezometric surface has been found in a depth of 13m due to the fracturing of the rock mass. The concluded values from the analysis are c = 50 kPa, φ = 23º. Similarly to case study 1, the analyses were done for circular and non-circular surfaces. Although the sliding surface fits better (geometry of shear zones, location of surface cracks on the cut and the natural slope, depth of movement) to a non-circular surface, the results were similar (0.999 for the non-circular and 1.015 for the circular surface).

4. Support Principles

Case study 1

The solutions to stabilize the entrance portal cut of Nymfea tunnel can be categorised in two alternative solutions.

- Measures within the area of the failed rock mass by supporting with a pattern of pre-stressed anchors or removing the failed material.
- Measures at the bottom of the failed rock mass by retaining measures. Support the failed material at the lower to those focused to secure the road from further slides with the construction of passive measures.

Due to the large area and the great depth of the slide it was found, that retaining measures are the economic way to stabilise the slope. Reinforced concrete walls with pre-stressed anchors were combined with the Cut&Cover structure of the tunnel portal and constructed from the road level.

Case study 2

The slide has a length of 150m and a width of 80m. To avoid intensive, costly and time consuming retaining structures the road axis was slightly modified by moving it approx. 15m horizontally away from the side. Due to this the extension and height of the cut slope decreased significantly and it was only necessary to stabilise a small part of the failed rock mass. This was done by cement grouting of the jointed gneiss. Additionally drainage holes were drilled in the rock mass to drain the surface water saturating into the ground and to avoid the development of any water pressure.

5. Conclusions

The paper focuses on the engineering geological characterization and behaviour of disturbed and weathered gneiss in slopes. The case of the vertical axis "Komotini-Nymfea" of Egnatia Motorway in Northern Greece is presented. The area is dominated by intensive and sequent tectonic disturbance, where weathering was favoured. Thence, poor to very poor rock masses have been generated, where the intact rock and rock mass strength present a wide range of values. The behaviour in slope stability of these rock masses can vary from stable to highly unstable causing extremely complex and problematic conditions. The general characteristics of fracturing and weathering degree, the intense of schistosity and the presence of shear and fault zones are grouped in 8 rock mass types (I to VIII) and presented with respect to the slope stability.

Moreover, the behaviour of certain gneissic rock mass types in slopes is presented with two different case studies. Cases of circular or multi-planar failure surfaces on highly weathered and fractured rock masses and sheared zones are studied. As the geotechnical properties of such failure surfaces can hardly be tested in the laboratory, back analysis was used to obtain reliable parameters. The results of the back analysis showed significant differences to the laboratory test results. The concluded values from the analysis are $c = 5$ kPa, $\varphi = 28^{o}$ for the completely weathered type and $c = 50$ kPa, $\varphi = 23^{o}$ for the multi-planar surface, consisted of sheared gneiss. Finally, the support principles according to the mechanism of failure of two case studies are presented.

6. Acknowledgments

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