Instability of slopes along the Nymphopetra to Strymonas section of the Egnatia Highway in N Greece

MARIA CHATZIANGELOU[1] & BASILE CHRISTARAS[2]

[1] *J&P - AVAX Co. (e-mail: mcha@geo.auth.gr)*
[2] *Aristotle University of Thessaloniki (e-mail: christar@geo.auth.gr)*

Abstract: The Nymphopetra to Strymonas section of the Engatia Highway is about 60km long, and is located in northern Greece, to the North-East of Thessaloniki. It is divided into two parts: i) Nymphopetra-Asprovalta, about 40km long and ii) Asprovalta-Strymonas, about 20km long. The Asprovalta-Stymonas section has already been constructed while the Nymphopetra-Asprovalta section is under construction.

Driving from the west to the east, the highway, at the beginning of Nymphopetra-Strymonas section, passes near to Volvi Lake, at the foot of Vertiscos Mountain. Further to the east it crosses Kerdillia Mountain.

The area of Nymphopetra to Strymonas is geologicaly located into Serbomakedonian zone. There are gneiss, amphibolite and thin layers of marble that belong to the Vertiscos union, under lake deposits dated to Pleio-pleistokene. The lake deposits consist generally of gravel and sand layers. At the east part of the highway there is the Keldilia union, which consists generally of gneiss and marble being crossed by pegmatitic veins. There are also alluvial deposits along the rivers.

The area is characterized by a variety of geological formations and numerous faults, which create several difficulties in slope excavations, as instability phenomena take place. Rock mass quality is poor because of cracking and weathering. Landslides have already occurred along the eastern part of the highway causing a delay in construction. Landslides have formed due to the sliding of soil on circular planes or absolutely weathered material in addition to planar sliding along discontinuity planes, or intersection of two or three discontinuity planes, which form potential wedges. Some instability phenomena have also taken place along the highway still under construction. Taking into account the geological structure of the area, more landslides shall occur during and after the construction of new part of the highway. In the present paper, instability phenomena are described and the mechanism of sliding is studied, so that support measures and methods of excavation can be proposed.

For this purpose, tectonic data was collected and rock mass quality classification systems, RMR and SMR were used in order to study the quality and estimate the stability along the slopes. In slope stability analysis, the Markland and Bishop Methods were used.

Résumé: La région, où la section «Nymphopetra-Strymonas» de l'autoroute Egnatia, est situ , se caractérise par une variété de formations géologiques (gneiss, marbres, pegmatites) et de failles. La qualité de la roche masse, est généralement basse, à cause des diaclases et de l'altération. De phénomènes d'instabilité de pentes ont été cré s pendant la construction de l'autoroute. De glissements de terre ont été déjà cré s, le long de la partie Est de l'autoroute, retardissant le progres du travail. Les glissements de terre sont dus soit à glissement circulaire du sol et des roches bien altérées, soit à de glissements le long des planes des joints et des couches ainsi que le long de la section de deux planes. Tenir compte que la structure géologique de la région, il est très possible que de nouveaux glissements de terre seront créés pendent et après la fin de la construction de l'autoroute.

Dans cet article, les phénomènes d'instabilité des pentes sont décris et les mécanismes du glissement ont été étudiés, pour que les méthodes d'excavation les plus appropries soient utilisées. Pour cette raison, les données tectoniques ont été analysées et la qualité de la roche masse a été classifiée par les méthodes RMR et SMR, pour que la stabilité des pentes, le long de l'autoroute, soit estimée. L'essai de Markland (1972) et la méthode de Bishop (1955) ont été utilisés pour analyser la stabilité des pentes.

Keywords: slope stability, landslides, failures

INTRODUCTION

The "Nymphopetra – Strymonas" section of the Engatia Highway, is about 60km long, and is located in North Greece, to the North-East of Thessaloniki. Actually, the highway is divided into two parts: i) the "Nymphopetra-Asprovalta" subsection, which corresponds to the western part, is about 40km long (Figure 1) and ii) the "Asprovalta-Strymonas" subsection (Figure 2), which corresponds to the eastern part, is about 20km long. The "Asprovalta-Stymonas" subsection has been already constructed, while the "Nymphopetra-Asprovalta" subsection is still under construction. Driving from the west to the east, the highway passes near to Volvi Lake, at the foot of Vertiscos Mountain while to the east, it crosses Kerdillia Mountain. The under study section of the highway crosses geological formations included in the Serbomacedonian zone, which contains metamorphic rocks. At the western part of this section, gneiss, amphibolite and thin layers of marble that belong to Vertiscos subzone of the above mentioned zone, are covered by lake deposits dated to Pleio-pleistokene. The lake deposits consist generally of gravel and sand. At the east part of the highway, Keldilia subzone consists mainly of gneiss and marble being crossed by pegmatite veins.

GEOTECHNICAL INVESTIGATION ALONG THE SLOPES

In the present paper seven slopes are studied. Three of these slopes had already failed. The first two belong to "Asprovalta – Strymonas" subsection, being located at the ch.9+700 and between ch.10+500 and ch.10+700, while the other one is located to the west, between the ch.21+215 and ch. 25+373, belonging to "Nemphopetra – Redina" part of "Nymphopetra-Asprovalta" subsection.

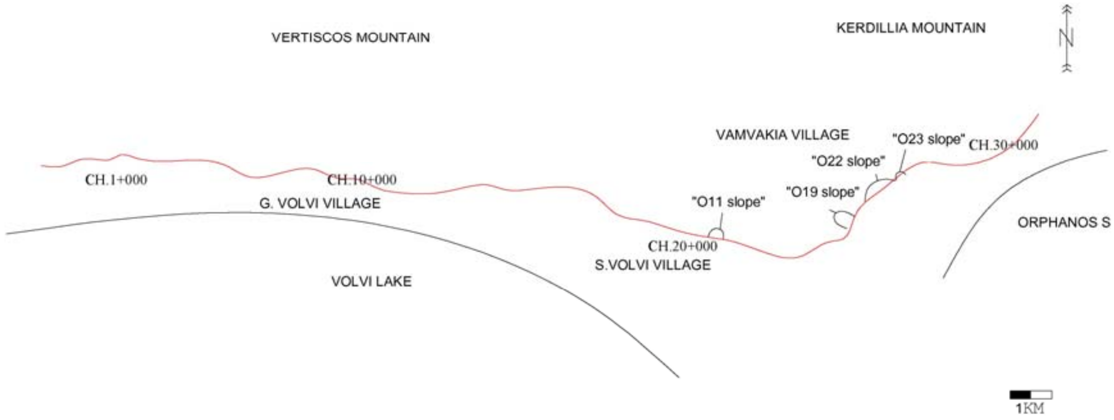


Figure1. "Nymphopetra – Asprovalta" subsection of Egnatia Highway.

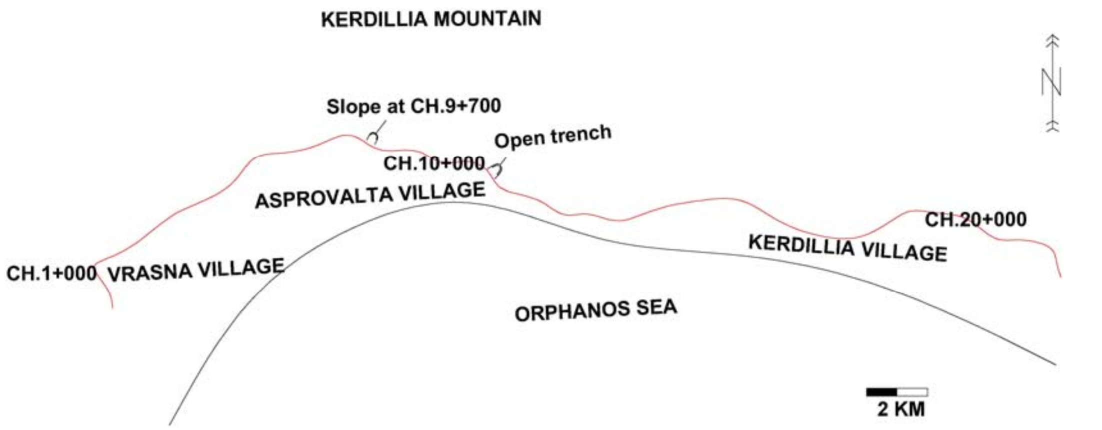


Figure 2. "Asprovalta – Strymonas" subsection of Egnatia Highway

The slope "O11", which is located between ch.20+500 and ch.20+800, consists of lake deposits (Figure 3). A fault of 255/46 cuts these deposits; the bedding is 162/39 and the main joint set is directed to 101/84.

The slope "O19" is located between the ch.25+215 and ch.25+373. It consists of biotitic gneiss with pegmatitic veins. The rock mass is cracked providing RQD=35%. A fault of 195/60 is measured, during the site investigation. Joints, with smooth planar surfaces and spacing of 10-50cm, are developing parallel to the fault. The rockmass is very weathered and jointed. The following three major discontinuity sets are determined; i) the schistosity, with a direction of 211/36, consisting of slightly rough surfaces with spacing of 3-15cm, ii) a joint set of 134/66 consisting of slightly rough surfaces with spacing of 5-35cm and pegmatitic intercalations 5cm thick and iii) a joint set of 357/52 consisting of slightly rough surfaces with spacing of 3-50cm and pegmatitic veins 30cm thick.

The slope "O22" is located between ch.26+057 and ch.27+162. It consists of very cracked and totally weathered gneiss (RQD = 5%), covered by sand formation of Pleistocene. A fault of 124/57 is measured, and four major discontinuity sets were determined: i) the schistosity, with a direction of 267/68, consisting of slightly rough surfaces with spacing about 5cm, ii) the joint set of 163/54 consisting of slightly rough surfaces with spacing of 10cm and pegmatitic veins 5-10cm thick, iii) the joint set of 201/69 consisting of slightly rough surfaces with spacing of 2m and iv) the joint set of 99/72 consisting of slightly rough surfaces with spacing of 5cm.

The slope "$O23_r$", is located at the right side of the road between ch.27+242 and ch.27+422, consists of marble and gneiss with pegmatite veins. The quality of marble is medium (III category), while the quality of gneiss is good (II category). Three major joint sets were measured in the marbles; i) 287/71, ii) 232/57 and iii) 83/53. Four major joint sets were measured in the gneiss; i) 212/58, ii) 279/43, iii) 5/54 and iv) 158/49. The RQD is estimated between 80 and 90%. The spacing of discontinuities is less than 20cm. The surfaces of discontinuities are smooth and slightly weathered.

Figure 3. Unstable slope O11, between ch.20+500 and ch.20+800

The slope “$O23_I$” is located at the left side of the road between ch.27+242 and ch.27+422. It consists of medium quality gneiss with RQD about 75%. Two major joint sets of 210/64 and 295/70 with smooth surfaces, and a fault of 143/72 were measured. Thin pegmatite veins (1-5mm thick) are developed parallel to the fault.

The slope at the “ch.9+700” is located on the Asprovalta-Strymonas section of the highway. The slope consists of medium to highly weathered, cracked (RQD = 36%) biotitic gneiss, of pour quality (category IV), and lenses of blue and white marble. Ophiolitic intercalations consisting of peridotite, serpentinite and sipoline also exist. Two joint sets of north to south (197/59) and southwest to northeast (34/65) directions are determined, having smooth surfaces. The schistosity planes are directed from west to south (72/22). A fault of NW-SE (117/68) direction, with grey clay infilling material, has been also determined.

The open trench is located on the Asprovalta-Strymonas section, between ch.10+500 and ch.10+700. A geological investigation was performed during the excavation of the three upper benches which consist of folded gneiss, marble and amphibolite. The upper bench has been divided in six areas relative to their geotechnical properties. Between ch.10+505 and ch.10+542, gneiss is highly weathered (IV category). The RQD is 40-56%. Two discontinuity sets were determined: a) the schistosity; its direction is 213/35 and the inner surfaces are completely closed and slightly rough; the spacing is 6-15cm and b) joints of 355/50 direction, with infilling material consisting of sand and gravels 0,5m thick; the spacing is 6-8cm. Between ch.10+542 and ch.10+556, the gneiss is highly weathered (IV category). The RQD is about 10%. Two discontinuity sets were recognized; a) schistosity 213/35 with separation surface spacing of 6-15 cm; the separation surfaces are completely closed and slightly rough, b) joints 341/50 with planar smooth surfaces and spacing 3cm. Between ch.10+556 and ch.10+597, the marble is moderately or highly weathered (III-IV category). The RQD is about 10%. Two tectonic sets were recognized; a) schistosity 31/50 with completely closed, slightly rough surfaces and spacing 5-10cm, b) joints 172/47 with planar smooth surfaces and spacing 6-8cm. The contact between marble and gneiss is characterized by a completely weathered rock mass, so the collection of tectonic data was impossible. The amphibolite is highly weathered (IV category), between ch.10+597 and ch.10+638. The RQD is about 56%. Two discontinuity sets were recognized; a) schistosity 182/10 with completely closed and slightly rough surfaces and spacing 10cm, b) pegmatite intercalations 198/60 0.2mm thick. Between ch.10+638 and ch.10+685, amphibolite, which is placed at the lower part of the third bench, is highly weathered (IV category). The RQD is about 22%. Two discontinuity sets were recognized; a) schistosity 201/9 with complete closed slightly rough surfaces and spacing 10-20cm, b) pegmatite intercalations 161/77 having a thickness of 7cm and spacing 5-10cm. The formation of marble, which is placed at the upper part of the the bench, is moderately and highly weathered (III-IV category). The RQD is about 42-59%. Three discontinuity sets were recognized; a) schistosity 207/32 with completely closed slightly rough surfaces and spacing about 10-20cm, b) very closed joints 203/75 and c) 167/82 with slightly rough surfaces and spacing between 20cm and 10cm. The tectonic contact between marble and amphibolite, with infilling sandy material 0.5mm thick, was measured 107/11.

The lower bench has been divided into seven areas with different geotechnical data. Gneiss is highly weathered (IV category), between ch.10+490 and ch.10+510. The RQD is 29%. Five discontinuity sets were recognized; a) smooth planar joint surfaces of 202/77 with infilling clayey material 10cm thick, b) and c) joints of 266/59 and 336/84 having slightly rough surfaces and spacing 30cm, with infilling sandy and kaolinite material 3mm thick, d) pegmatite intercalations of 144/29, 6mm thick, e) very closed and slightly rough schistosity surfaces 94/35. Between ch.10+510 and ch.10+520, gneiss is completely weathered (V category). The RQD is 46%. Three discontinuity sets were recognized; a) rough joint surfaces of 22/52, b) slightly rough schistosity surfaces of 246/42 with infilling sandy material 3mm thick and spacing 5-10cm, c) slightly rough joint surfaces of 143/40 with infilling clayey material 6mm thick being come from completely weathered gneiss, spacing 40cm. Between ch.10+520 and ch.10+560, the folded gneiss is highly weathered (IV category). The RQD is 10%. The schistosity surfaces, of direction 42/29, are very closed and slightly rough with spacing 3mm. The schistosity surfaces 105/20 are smooth and planar, with infilling clayey material 4mm thick and spacing 6cm. The contact between gneiss and amphibolite was formed by two faults 282/20 and 333/70. The rock mass near the contact is completely weathered. Kaolinitic material, 4-10cm thick, was observed along the fault 282/20. Pegmatite intercalations are developed parallel to the fault 333/70. The spacing of pegmatite intercalations is 6-20cm. The amphibolite is moderately weathered (III category), between ch.10+560 and ch.10+600. The RQD is 36%. Three discontinuity sets were recognized; pegmatite intercalations (8-12cm thick) of 14/47 direction and spacing 20-25 cm, very closed and rough joint surfaces of 148/39 with spacing 3cm, and schistosity of 70/46 having very closed slightly rough surfaces with spacing 3cm. Between ch.10+600 and ch.10+670, the contact of marble and amphibolite is oriented to northeast (65/47).

The upper marble formation extends from ch.10+600 to ch.10+640 and the lower amphibolite formation extends from ch.10+600 to ch.10+670. The tectonic mélange (ch.10+600 – ch.10+660) consists of weathered marble and amphibolitic pieces. The RQD is 32%. Three tectonic sets were recognized; a) pegmatite intercalations of 192/77 with thickness of 0.5-40cm and spacing 40cm, b) completely weathered, rough joint surfaces of 250/44 with spacing 4-10cm, and c) joints 126/52, with infilling clayey material 2mm thick and spacing 3m. The marble is slight to moderately weathered (II and III category). Four discontinuity sets were determined; a) very closed and slightly rough joint surfaces 73/51 with spacing 2.7cm, b) very closed and rough joint surfaces 196/71 with spacing 3cm, c) schistosity of marble directed to 195/39 and d) very closed and slightly rough joint surfaces 278/76 with spacing 6mm. The formation of amphibolite is very weathered (IV category) and cracked (RQD = 22%). Two tectonic sets were recognized; a) Very closed and slightly rough surfaces 259/56 with spacing 9cm and b) pegmatite intercalations 166/73, 10cm thick with spacing 1m. The tectonic surfaces are covered by clayey material 0.5mm thick, deriving from weathered amphibolite. Between ch.10+670 and ch.10+680, gneiss is completely weathered (V category) at the upper part of bench, and moderately weathered (III category) at the lower part of bench. There is a fault (328/33), which lies northwest, that separates the completely and the moderately weathered gneiss. Four discontinuity sets were recognized on the rockmass of completely weathered gneiss; a) eroded pegmatite veins 169/53, 25cm thick, which are placed between smooth surfaces of gneiss with spacing 1m, b) schistosity surfaces 229/48 with spacing 4-8cm, c) aplitic intercalations 125/85 being located between smooth surfaces 5mm thick with spacing 1m, d) pegmatite intercalations 37/26 being placed between rough surfaces having a thickness of 5cm and spacing 16cm. Two tectonic sets were recognized in the rock mass of moderately weathered gneiss; a) completely closed joint set 217/24 having slightly rough surfaces with spacing 16cm, and b) pegmatite veins 191/83 placed between smooth surfaces having major thickness of 70cm and spacing 1m. There is the tectonic contact 312/56 of completely weathered marble (RQD=82%) and gneiss, between ch.10+680 and ch.10+695. The contact is full of pegmatite 4cm thick. Two major tectonic sets were recognized; a) pegmatite intercalations 115/75 having a thickness of 3mm and spacing 30cm, and b) very closed joints 209/58 with spacing 15cm.

Geotechnical classification

Two classification systems were used; RMR (Bieniawski 1989) and SMR (Romana 1985). As the "O11" slope consists of lake deposits (soil), the classification systems are not applied. According to RMR classification system, the rock mass quality of the "O19" slope (ch.25+215-ch.27+373), is poor (RMR_{bas} = 33). The quality of gneiss of the "O22" slope is poor as the rock mass is very weathered and absolutely cracked (RMR_{bas}=28). For this reason, the rock mass behaves like a soil. The rock mass quality of "$O23_r$" slope is medium (RMR_{bas} = 53) in the marbles, and good (RMR_{bas} = 68) in the gneiss. The quality of gneiss at the "$O23_l$" slope is medium (RMR_{bas} = 57). The quality of the rock mass of "ch.9+700" slope is poor (RMR=38), as the rock mass consists of medium to highly weathered, cracked gneiss, also behaving like a soil.

Finally, the rock mass quality at the open trench is generally characterized as poor (RMR_{bas} = 22-40). There is a part of a slope between ch.10+570 and ch.10+640 consisting of amphibolite and marble formations with better rock mass quality (RMR_{bas} = 42-49) than the rest part of the slope.

Taking into account the orientation of tectonic data along the road, rock mass quality is characterized as very poor (RMR=3-87), and only between ch.10+550 and ch.10+640 (open trench) the rock mass quality is characterized as poor (RMR=24-35) (Table 1).

According to the SMR classification system, the "O19" slope is moderately stable. The "O22" slope is unstable. The marble formation on "$O23_r$" slope is moderately stable, although the gneiss formation on the same slope is stable. The "$O23_l$" slope is moderately stable. The slope located at "ch.9+700" is very unstable. Finally, the open trench is generally unstable, except some places where is stable. In details, the 4th bench is unstable. The 3rd bench from ch.10+505 to ch.10+577 and from ch.10+638 to ch.10+685 is very unstable and it needs to be transformed. The 3rd bench from ch.10+638 to ch.10+685 and from ch.10+646 to ch.10+695 is unstable.

There is a part of third bench between ch.10+577 and ch.10+638 being stable. The second bench from ch.10+490 to ch.10+510, from ch.10+600 to ch.10+640 and from ch.10+650 to ch.10+670 is very unstable.

Table 1. Quality (Bieniawski, 1989) and stability (Romana, 1985) classification

CH.-CH.	**RMR_{bas}**	**Rock mass quality**	**RMR**	**Rock mass quality using orientations of tectonic data**	**SMR**	**Stability**
Nymphopetra – Redina's part, Slope "O11", ch.20+500-ch.20+800						
20+500-20+800 (lake deposits)	-	soil	-	soil	-	-
Nymphopetra – Redina's part, Slope "O19", ch.25+215-ch.25+373						
25+215-25+373 (gneiss)	33	V (poor quality)	5	V (very poor quality)	F:48 S:44,3 J1:48 J2:48	Moderately stable (III)
Nymphopetra – Redina's part, Slope "O22", ch.26+057-ch.27+162						
26+057-27+162 (gneiss)	28	V (poor quality)	5	V (very poor quality)	S:24,4 F:28 J1:48 J2:48 J3:25,6	Unstable (IV)
Nymphopetra – Redina's part, ch.27+242-ch.27+422 (right side)						
27+242-27+422 (gneiss)	68	I (good quality)	18	V (very poor quality)	J1:68 J2:68 J3:68 J4:68	Stable (II)
27+242-27+422 (marble)	53	II (medium quality)	3	V (very poor quality)	J1:52 J2:53 J3:53	Moderately stable (III)
Asprovalta – Strymona's part, ch.9-700						
9+700 (gneiss)	33	V (poor quality)	5	V (very poor quality)	J1:29 J2:29 F:17 S:34.4	Unstable (IV)
Asprovalta – Strymona's part, Open trench, ch.10+500-ch.10+700 (4th bench)						
10+555-10+625 (gneiss)	37	V (poor quality)	12	V (very poor quality)	J1:34,5 J2:48 J3:48 S:46	Unstable (IV)
Asprovalta – Strymona's part, Open trench, ch.10+500-ch.10+700 (3rd bench)						
10+505-10+542 (gneiss)	35	V (poor quality)	5	V (very poor quality)	S:12,5 J:30	Very unstable (V)
10+542-10+556 (gneiss)	36	V (poor quality)	5	V (very poor quality)	S:15 J:43	Very unstable (V)
10+556-10+577 (marble)	36	V (poor quality)	31	V (poor quality)	S:16 J:31	Very unstable (V)
10+577-10+638 (amphibolite)	49	III (moderately quality)	24	V (poor quality)	S:58 J:58	Stable(II)
10+638-10+685 (amphibolite)	28	V (poor quality)	3	V (very poor quality)	S:35,5 F:40 J:39	Unstable (IV)
10+638-10+685 (marble)	40	V (poor quality)	15	V (very poor quality)	S:13 F:54 J1:30 J2:51	Very unstable (V)
10+646-10+695 (marble)	40	V (poor quality)	15	V (very poor quality)	S:54 F1:37 F2:50 J1:51 J2:51	Unstable (IV)

Table 1 (Continues)

CH.-CH.	RMR_{bas}	Rock mass quality	RMR	Rock mass quality using orientations of tectonic data	SMR	Stability
Asprovalta – Strymona's part, Open trench, ch.10+500-ch.10+700 (2nd bench)						
10+490-10+510 (gneiss)	30	V (poor quality)	5	V (very poor quality)	J1:20 J2:44,1 J3:45 J4:45	Very unstable (V)
10+510-10+520 (gneiss)	28	V (poor quality)	5	V (very poor quality)	J1=43 S=43 J2=43	Moderately stable (III)
10+520-10+560 (gneiss)	22	V (poor quality)	5	V (very poor quality)	S1=37 F1=37 S2=37 F2=33,25	Unstable (IV)
10+560-10+600 (amphibolite)	40	V (poor quality)	35	V (poor quality)	J1=47,5 J2=55 S=47,5	Moderately stable (III)
10+600-10+640 (marble)	42	(moderately quality)	17	V (very poor quality)	J1=57 J2=32 S=6 J3=57	Very unstable (V)
10+600-10+660 (tectonic mélange)	28	V (poor quality)	3	V (very poor quality)	J1=21,75 S=43 F=43 J2=35,5	Unstable (IV)
10+650-10+670 (amphibolite)	40	V (poor quality)	15	V (very poor quality)	J1=55 J2=18,1	Very unstable (V)
10+670-10+680 (completely weathered gneiss)	28	V (poor quality)	5	V (very poor quality)	J1=31,5 S=23 J2=39,25 J3=43	Unstable (IV)
10+670-10+680 (moderately weathered gneiss)	31	V (poor quality)	6	V (very poor quality)	J1=29,2 F=46 J2=24,75	Unstable (IV)
10+680-10+695 (completely weathered marble)	39	V (poor quality)	14	V (very poor quality)	J1=50,25 F=53,1 J2=48,9	Moderately stable (III)

The second bench from ch.10+520 to ch.10+560, from ch.10+600 to ch.10+660 and from ch.10+670 to ch.10+680 is unstable. The 2nd bench from ch.10+510 to ch.10+520, from ch.10+560 to ch.10+600 and from ch.10+680 to ch.10+695 is moderately stable.

Taking into account the above results, the excavation of the slopes is usually unstable and failures are expected (Table 1).

SLOPE STABILITY

The stability of the slopes was estimated using Markland test (1972) – Hocking improvement (1976) and Bishop's method (1955).

The lake deposits on "O11" slope may slide along the direction of the bedding 162/39. Two potential wedges are formed by; i) bedding 162/39 and fault 255/46 and ii) joints 101/84 and bedding 162/39. The sliding takes place at SSW direction (Figure 4). Also, the critical slip cycle was estimated using slope geometry of 15m high and slope inclination of 90^o. The radius of the critical circle is estimated 15m and the safety factor for saturated conditions is calculated 3 (Figure 16).

Studying the stability of "O19" slope, the slope may slide along the planes of: i) the gneiss schistosity 221/36, and ii) the fault 195/60. Three potential wedges are formed by; i) joints 134/66 and the fault 195/60 (sliding at south direction), ii) the joint 134/66 and schistosity 221/36 (sliding at SW direction), iii) fault 195/60 and schistosity 221/36 (sliding at west direction) (Figure 5). Gneiss rock mass is easily eroded and weathered by air or water. So, it becomes quickly uncohesive behaving like soil material. For this reason, the critical slip circle was estimated using slope geometry. The safety factor for saturated and unsaturated conditions was also calculated. The slope stability analysis took place using unit weight of gneiss equal to 2,65gr/m^3, friction angle equal to 22^o and no cohesion. Two benches

10m high form the slope geometry, inclined to 34^o (2:3). Low vertical benches, having width equal to 5m and height of 2,5m – 3,25m, designed to be created at the site of the embankment, so as the friction between the embankment and the slope to be increased. Using the geometry above, the slope in study is stable on unsaturated conditions (S.F. = 2) and it is unstable on saturated conditions (S.F.=1) (Figure 17, Figure 18). After the construction of the embankment, the safety factor, on unsaturated conditions, was estimated equal to 2 and the safety factor, on saturated conditions, was estimated equal to 1 (instability) (Figure 19, Figure 20).

Studying the stability of “O22” slope, the gneiss rock mass may slip along; i) the fault 124/57 and ii) the joints of 99/72. Potential wedges are also formed by joints 201/69, 99/72 and joints 124/57 parallel to fault. Sliding may occur at SSE direction (Figure 6).

According to stability analysis of the “$O23_r$” slope, the type of probable sliding is; i) a planar sliding of gneiss rock mass along the joints directed to 279/43 and ii) a potential wedge sliding at west direction. The planes of joints 212/58 and 279/43 form the wedge (Figure 7). The marble rock mass may slide along the joints of 287/71. As the rock mass is slightly weathered, there is no possibility of circled sliding (Figure 8).

The gneiss rock mass of the “$O23_l$” slope may also slide along the planes of joints 210/64. A potential wedge, being formed by the joints of 210/64 and joints parallel to fault 143/72, may slide at South direction. As the rock mass is slightly weathered there is no possibility of circled sliding (Figure 9).

Five benches, with inclination of 45^o for their sub-slopes, form the slope at “ch.9+700”. The slope is 60m high. As the rock mass is absolutely weathered, the critical slip circle was estimated. The critical circle, in saturated conditions caused by rainfall, is 50m deep and the safety factor is estimated 1.16 (Figure 22, Figure 23). So, the stability is ultimate in saturated conditions. Taking into account the orientation of discontinuities sets, the slope may slide along the fault 117/68. The joints of 197/59, 34/65 and the schistosity 72/22 form potential wedges, which they may slide at SE direction (Figure 10).

Taking into account that the friction angle of the rock mass is about 35^o, gneiss formation, being placed between ch.10+505 and ch.10+556 of the third bench of the open trench, may slide along the direction of schistosity 213/35 (Figure 11, Figure 12). The same formation, being placed between ch.10+510 and ch.10+520 of the 2nd bench, may slide along the direction of schistosity 246/42 (Figure 13). There is a part of completely weathered gneiss, being placed between ch.10+670 and ch.10+680 of the 2nd bench, which may slide along the direction of the section being formed by schistosity 229/48 and joints 169/53 or 125/85 (Figure 15). Marble formation, being placed between ch.10+600 and ch.10+640 of the 2nd bench, may slide along the direction of the section being formed by schistosity 195/39 and joints 278/76 (Figure 14).

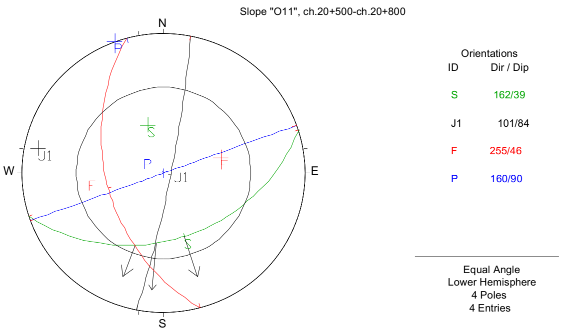


Figure 4. Major discontinuities’ planes at slope “O11”

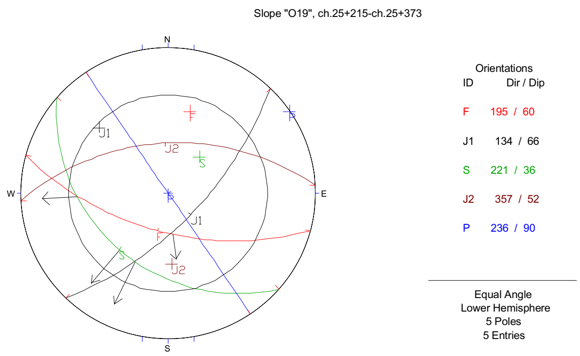


Figure 5. Major discontinuities’ planes at slope “O19”

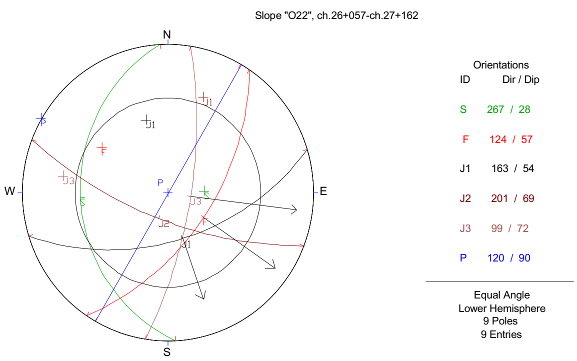


Figure 6. Major discontinuities’ planes at slope “O22”

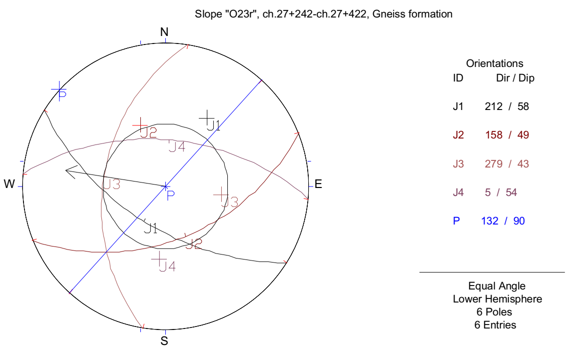


Figure 7. Major discontinuities planes at slope “$O23_r$”(gneiss)

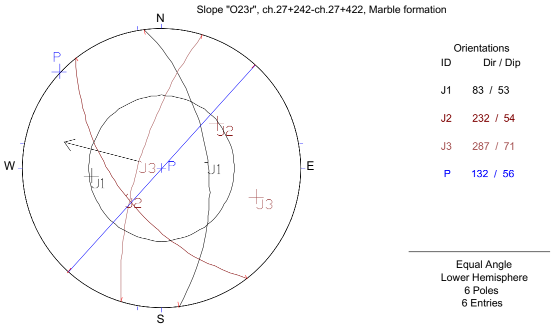


Figure 8. Major discontinuities' planes of marble at slope "O23$_r$"

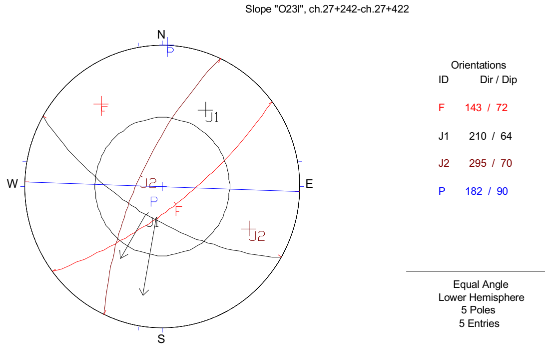


Figure 9. Major discontinuities' planes at slope "O23$_l$"

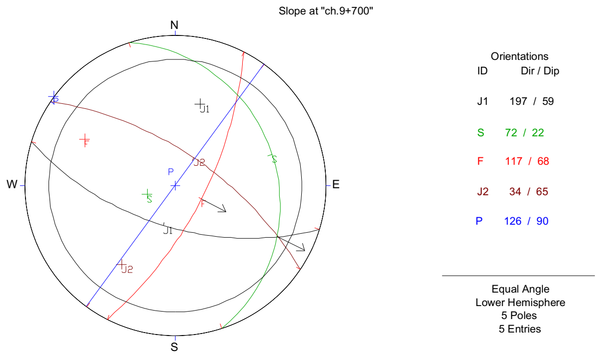


Figure 10. Major discontinuities' planes at slope at "ch.9+700"

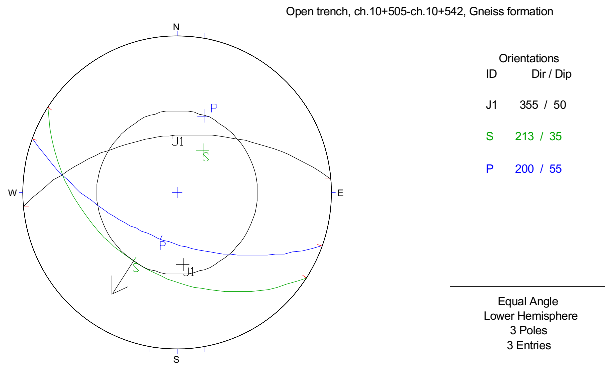


Figure 11. Major discontinuities' planes at the open trench between ch.10+505 and ch.10+542

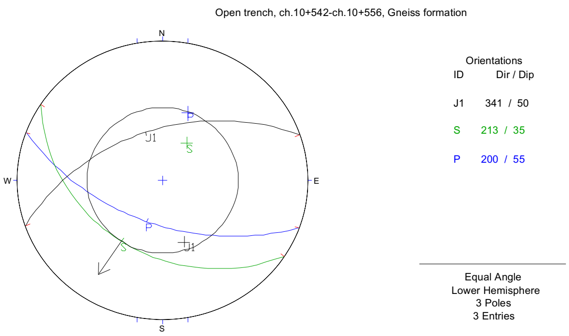


Figure 12. Major discontinuities' planes at the open trench between ch.10+542 and ch.10+556

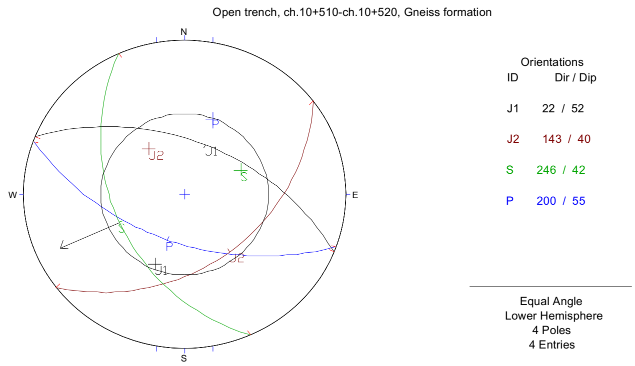


Figure 13. Major discontinuities' planes at the open trench between ch.10+510 and ch.10+520

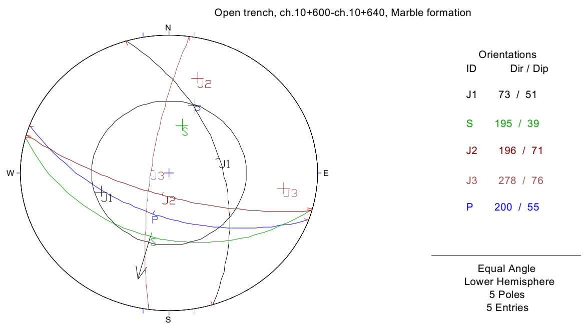


Figure 14. Major discontinuities' planes at the open trench

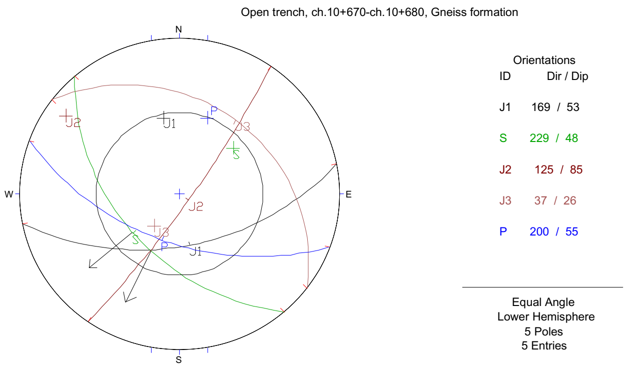
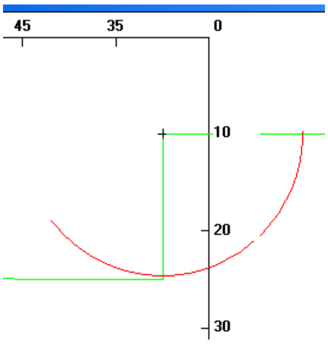


Figure 15. Major discontinuities' planes at the open trench between

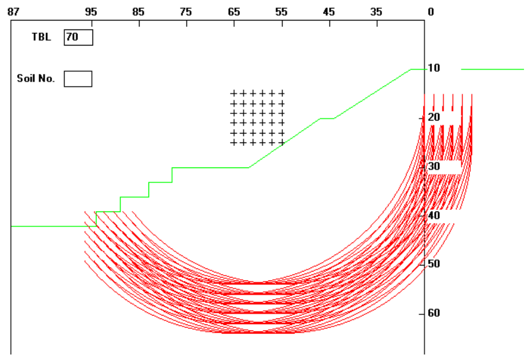
between ch.10+600 and ch.10+640 ch.10+670 and ch.10+680



Critical Circle for all Sets:

X Cen	Y Cen	Radius	Slices	Safety Fac
5,00	10,00	15,00	15	3,00

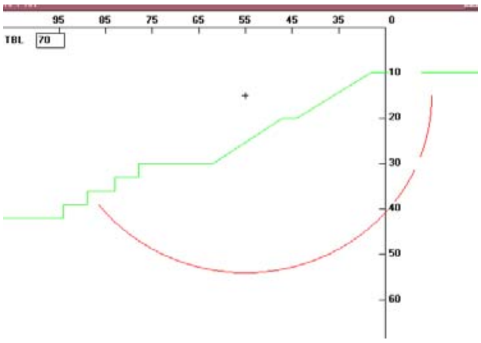
Figure 16. Critical slip circle and safety factor of slope "O11" , in saturated conditions



Critical Circle for all Sets:

X Cen	Y Cen	Radius	Slices	Safety Fac
30,00	15,00	40,00	74	2,00

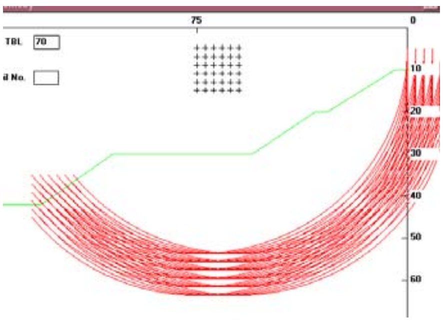
Figure 17. Circle sliding analysis and safety factor of slope "O19" before the embankment's construction , in unsaturated conditions



Critical Circle for all Sets:

X Cen	Y Cen	Radius	Slices	Safety Fac
38,00	5,00	50,00	84	1,00

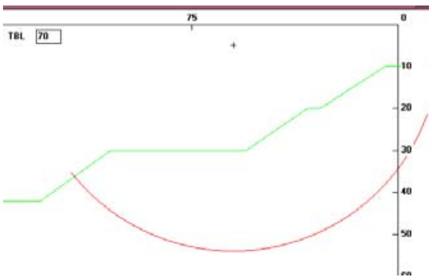
Figure 18. Critical slip circle and safety factor of slope "O19" before the embankment's construction , in saturated conditions



Critical Circle for all Sets:

X Cen	Y Cen	Radius	Slices	Safety Fac
40,00	5,00	50,00	89	2,00

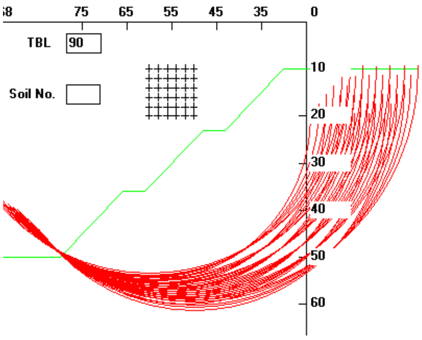
Figure 19. Circle sliding analysis and safety factor of slope "O19" after the embankment's construction , in unsaturated conditions



Critical Circle for all Sets:

X Cen	Y Cen	Radius	Slices	Safety Fac
40,00	5,00	50,00	89	1,00

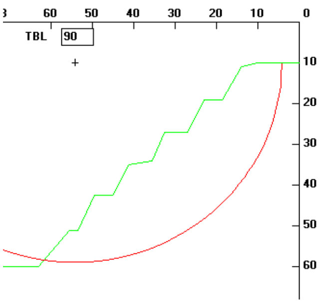
Figure 20. Critical slip circle and safety factor of slope "O19" after the embankment's construction , in saturated conditions



Critical Circle for all Sets:

X Cen	Y Cen	Radius	Slices	Safety Fac
25,00	10,00	50,00	80	7,00

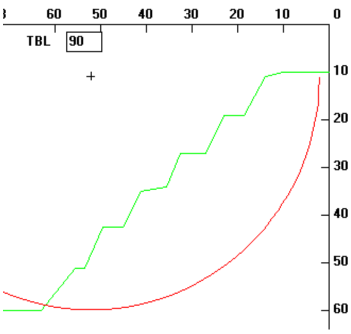
Figure21. Circle sliding analysis and safety factor of slope "O22" , in saturated conditions



Critical Circle for all Sets:

X Cen	Y Cen	Radius	Slices	Safety Fac
54.00	10.00	50.00	58	1.66

Figure 22. Critical slip circle and safety factor of slope at "ch.9+700" using the begging geometry in unsaturated conditions



Critical Circle for all Sets:

X Cen	Y Cen	Radius	Slices	Safety Fac
52.00	11.00	50.00	61	1.16

Figure 23. Critical slip circle and safety factor of slope at "ch.9+700" using the begging geometry in saturated conditions

LANDSLIDES ALONG NYMPHOPETRA – STRYMONAS SECTION

Important landslides phenomena took place during the highway construction. The landslides were activated at the slopes "O19", "ch.9+700" and open trench.

The landslide of the slope "O19" was activated by the excavation performed for the construction of an embankment. The unfavourable orientation of schistosity 221/36 affects the slope stability causing failure (Figure 5).

A short rainfall, which has taken place on March 2002, created a landslide of the half part of the slope at "ch.9+700", which was just excavated using a beginning geometry. The slope consists of small rock blocks. A cyclical sliding of loose material is bounded at east side of slope, where is the fault surface (115/65) and at west side of slope, where is a long sliding surface (120/76). Rainfall is the main cause of landslide as the safety factor (1.16) in saturated conditions is ultimate (Figure 23).

The formation of the upper three benches (fourth, third and second) of the open trench had just completed when an extensive landslide took place. The landslide was placed between ch.10+533 and ch.10+620. The sliding of wedge between ch.10+600 and ch.10+620, located in the marble of the second bench, caused the beginning of landslide. The sliding was performed toward to the section of the schistosity 195/39 and joints 278/76. The sliding of the wedge activated new sliding in the neighbour part between ch.10+533 and ch.10+600. The new sliding took place along the direction of gneiss schistosity 213/35. The excavation was interrupted for a long time and a new design of cover and cut was chosen to restore the failure.

SUPPORT MEASURES AGAINST PROBABLE FAILURE AND LANDSLIDES' RESTORATION

The activated landslides and probable failures need to be taken into account in order to avoid dangerous events. So, the suitable formation and support measures need to be implemented.

In order to protect the slope "O11" against sliding, a slope inclination of 34^o is proposed. Using the proposed inclination, the radius of the critical circle is estimated at 29m and the safety factor is calculated 5 in saturated conditions (Figure 24).

Referring to the slope"O19", the unfavourable orientation of schistosity and the presence of potential wedges affect the stability causing failure. Taking into account that using a slope inclination less than 34^o, the size of slope will be reduced very much and the morphology relief will be changed significantly. Using an average inclination equal to 34^o (2:3), the slope will be moderately stable and sliding of rock pieces will occur. Wire mesh investment is proposed for highway protection from falling rock. The proposed geometry consists of two benches 10m high being inclined to 34^o. Low vertical benches, having width equal to 5m and height 2.5m – 3.25m, are proposed at the site of embankment. The safety factor on unsaturated conditions was estimated as 2 and under saturated conditions was estimated as 1 (Figures 15-18). The stability will be achieved if the resistance force of the embankment is higher than the shear strength, which causes the sliding. Wire mesh is enough to protect absolutely weathered rock pieces from falling on the road.

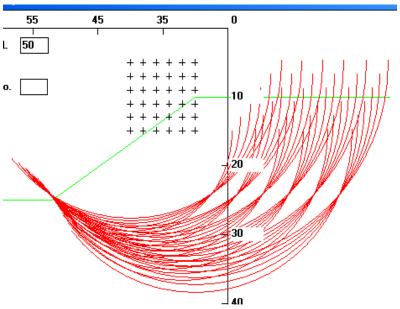
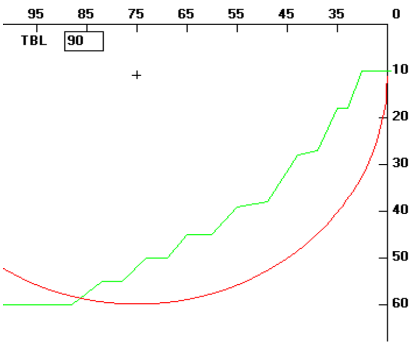


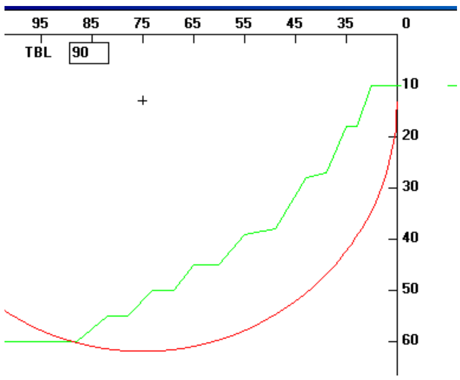
Figure 24. Circle sliding analysis of slope "O11" using the proposed geometry in saturated conditions. Critical circle;(x,y):(5,5)



Critical Circle for all Sets:

X Cen	Y Cen	Radius	Slices	Safety Fac
50.00	11.00	50.00	62	2.08

Figure 25. Critical slip circle and safety factor of slope at "ch.9+700" using the proposed geometry in unsaturated conditions



Critical Circle for all Sets:

X Cen	Y Cen	Radius	Slices	Safety Fac
50.00	13.00	50.00	67	1.57

Figure 26. Critical slip circle and safety factor of slope at "ch.9+700" using the begging geometry in saturated conditions

Terraces inclined at 45° are proposed to form the "O22" slope in order to be protected from planar sliding. The maximum height of the slope is about 50m. Taking into account that the slope consists of absolutely weathered gneiss (γ=2,65gr/cm^3, φ=26°, c=O), there is a potential cycled sliding. But according to slope stability analysis in saturated conditions, the slope is stable as the calculated safety factor of the critic circle is 7 (Figure 21).

The GSI of marble formation of the slope "O23" is estimated between 60 and 63. So, the friction angle the rock mass is 35° (Marinos *et al*., 2005). In addition to this, the GSI of gneiss formation of the same slope is estimated between 53 and 57, the friction angle of the rock mass is 43°. In order to protect the slope from rock mass sliding, an inclination of slope equal to 45° is proposed.

The GSI of gneiss formation of the slope"O23" is estimated between 33 and 37. So, the friction angle of the rock mass is 38°. In order to protect the slope from rock mass sliding, an inclination of slope equal to 45° is proposed.

Studying the stability problem of the slope at "ch.9+700" a new geometry of slope is proposed for landslide's restoration. For this reason, dips of downstairs are proposed to be smaller (heigh/width=1/1.5, and 1/1) than dips of upstairs (height/width=2/1). Using this new geometry, the safety factor is 25% higher (SF=2.08) in unsaturated and 35% higher (SF=1.57) in saturated conditions than using the beginning geometry. The benches of the slope are designed about the same length so as the length does not affect the safety factor and pore pressure (Figures 25-26). Thus, safety factor depends only on inclination of benches. According to the new geometry, big dips are formed downstairs and small ones are formed upstairs. When the height is also increased, restrained powers are increased and sliding powers are decreased. So, the safety factor of every part is progressively increased downstairs to upstairs making slope stable according to Chatziangelou & Christaras (2005a & 2005b).

The slope stability is tested without having benches, keeping the same length of the slope. In saturated conditions the safety factor is calculated 1.28. In this case, slope is not stable. The dip of the slope needs to be increased in order to achieve a stable condition.

The slope stability was tested without having benches, keeping the same length of slope, but reducing the dip of slope. The slope needs to be excavated 7m at the vertical axis in order to succeed the same safety factor with the proposed geometry using benches having different inclinations. So, the proposed geometry with benches with different inclinations is the best applicable and economical. Furthermore, drainage constructions are proposed in order to protect rock mass from water irruption. The top of the slope is proposed being covered by membrane and terraces are proposed to be covered by shotcrete. Also, some drainage pipe will need to move the rainfall water away.

Wire mesh, which will cover slope, is restraining small wedges and rock bolts (1.5 x 1.5) are also restraining wire mesh and rock bolts.

Finally, the sliding of the open trench's rock mass could be avoided if the inclination of the benches was about 34°. Nevertheless, a cover and cut was proposed for the landslide restoration, so as the highway being protected by the rock falls.

CONCLUSIONS

The "Nympopetra-Strymonas" section of the Egnatia highway crosses geological formations that create unstable slopes. Three of the seven slopes in the study have already slipped. The orientation of the discontinuities and the poor quality of the rock mass, are responsible for that instability. Probable failures and landslides can be prevented if the inclinations of a) the low slopes (lower than 50m), are reduced to lower than 45°, and b) the high slopes (higher than 50m), decrease down-slope. Furthermore, the following solutions are also proposed: a) the construction of embankments in order to restrain the sliding of the slopes, b) the construction drainage systems in order to increase retaining forces, c) wire mesh in order to restrain small wedges and d) rock bolts in order to restrain wire mesh and wedges.

Corresponding author: Dr Basile Christaras, AUTH (Aristotle University of Thessaloniki), School of Geology, Thessaloniki, 54006, Greece. Tel: +30 2310998506. Email: christar@geo.auth.gr.

REFERENCES

BIENIAWSKI, Z.T. 1989. *Engineering rock mass classification*. New York: Wiley.

BISHOP, A.W. 1955. The use of the slip circle in the stability analysis of slopes, *Geotechnique,* **1**, 7-17.

CHATZIANGELOU M. & CHRISTARAS B. 2005a. Influence of rainfall on slope stability at Egnatia highway, Asprovalta-Strymonas part (chainage 9+700*), Journal of the Mechanical Behavior of Materials*, **16** (1-2), 21-26

CHATZIANGELOU M., CHRISTARAS B. 2005b. A landslide along the "Asprovalta-Strymonas" part of Egnatia Highway in Northen Greece, *In: Geology and linear infrastructures. Prococeedings of the Geoline International Symposium, Lyon.*

HOCKING, G. 1976. A method for distinguishing between single and double plane sliding of tetrahedral wedges. *Int. Journal of Rock Mechanics.&Mining Science,* **13**, 225-226.

MARINOS, P., HOEK, E., KAZILIS, N., AGISTALIS, G. & MARINOS, V. 2005. The tunnels of Egnatia highway, Greece. Design and construction in a variety of rock masses under difficult geological conditions. *In: Geology and linear infrastructures. Proceedings of the Geoline International Symposium, Lyon*.

MARKLAND, J.T. 1972. A useful technique for estimating the stability of rock slopes when the rigid wedge sliding type of failure is expected. *Imperial College Rock Mechanics Research Report*, **19**, 1-10.

ROMANA, M. 1985. New adjustment ratings for application of Bieniawski classificaton to slopes. *Proceedings of the International Symposium on Rock Mechanics, Excavation, Mining & Civil Works, ISRM*, Mexico City, 59-68.