Common mechanism of landslide creation along the under construction Egnatia highway, in Pindos mountain range (W. Greece)

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Abstract

The part of the under construction Egnatia highway, that crosses Pindos mountain-range (W. Greece), can be characterized as one of the most difficult parts for the construction, because of the high relief, the mountain slopes are steep and the flysch, which is the dominating geological formation in the area causes important landslides, occurred almost from the beginning of the road construction. According to our investigation the more important landslides occurred in the area are due:
1. to the geometry and the activity of the discontinuities (faults and important joints).
2. to the nature of the tectonic formation that lies under the Pindos nappes overthrusting the Ionian flysch (on the west of Metsovo tunnel),
3. to the nature of the tectonic formation that lies under the ophiolites overlying the Pindos flysch (on the East of Metsovo tunnel).
These “tectonic formations” consist of shales and pelites, containing detached blocks of limestones and deep sea sediments.
Mechanically the above materials behave differently in dry and in wet conditions. In dry conditions they behave like a rock, while in wet conditions they loose rapidly their cohesion and their original structure behaving like a sutured soil causing landslides along an important part of the road.

Keywords: Landslides, Egnatia highway, flysch, Pindos zone.

INTRODUCTION

The Egnatia highway is the most significant traffic artery in Greece. It is also the main artery linking trade and commerce from Western and Central Europe to the Middle East, as part of the traffic network of the European Union (Fig. 1). The Egnatia Highway in North-Western Greece is crossing Pindos mountain range and is considered to be one of the most difficult parts for its construction. It includes complex geological formations that have undergone multiple tectonic deformations. The rock mass, under these conditions, is highly anisotropic and in association with the morphology (high relief and steep
Landslides along Egnatia highway (Greece) slopes, it presents serious geotechnical problems in the construction of high cut slopes, tunnels and bridges connecting the different sections of the highway. The landslides are abundant along the road and occurred also at sites where the geometry of the discontinuities in the flysch are not favourable. The landslides present similar characteristics, making necessary an investigation regarding the common mechanical behaviour of the geological formations along the road. The geomechanical investigations and detailed studies, along with the field data and geological mapping are included in the research project entitled «Geological-Engineering Geological Research for the Egnatia Highway».

**GEOLOGICAL SETTINGS**

The study area is located in Northern Greece, in the Pindos mountain range. Two distinct geotectonic units dominate in the area, the Pindos zone nappe and the Pindos ophiolite nappe. Pindos zone represents the passive margin of the Neo-Tethyan ocean, composed of Mesozoic carbonate and siliciclastic rocks and the Tertiary Pindos flysch, which forms the main outcrops of the Pindos zone in the area. Pindos zone consists of a sequence of Tertiary thrusts including the Pindos nappe which over-thrusts towards WSW the flysch of Ionian and Gavrovo zones [10]. Three lithostratigraphic groups of flysch sediments have been distinguished in the study area. Politses group is very well exposed in the area, represents the nappe of the Pindos flysch and overthrusts the Zagori group sediments. The last one represents the younger sediments of the flysch of the Ionian zone. The Metsovon group appears as a tectonic window under the thrust-sheets of the Pindos Flysch nappe. Pindos flysch (Politses group) is divided into four formations, from base to top these are: the "red flysch", alternation of red shales, pelites and sandstones with maximum
thickness 100 m, the second formation comprises thin grey micaceous sandstones alternating with grey shales and marls with an average thickness 70 m, the third formation comprises thick massive sandstones and interbedded grey shales and marls with a maximum thickness 350 m and the last one characterized as "wild flysch" composed of strongly tectonized grey siltstones and sandstones.

Beneath the Pindos nappe, along the thrust front appears a "tectonic formation" consisting a melange of strongly tectonized rocks, pelites, sandstones and blocks of limestones [11].

The Pindos ophiolite complex represents fragments of the Neo-Tethyan oceanic lithosphere which was emplaced initially on the western margin of the Pelagonian zone (Cimmerian micro-continent) during Late Jurassic-Early Cretaceous and subsequently over the Pindos flysch during Tertiary [1, 12].

Pindos ophiolite consists of mafic and ultra-mafic rocks (upper mantle peridotites partly serpentinitised, gabbros, mafic and ultra-mafic cumulates, sheeted dikes, massive lavas, pillow lavas and basic breccias), metamorphic rocks parts of the sole (amphibolites, schists and meat-sediments) as well as deep sea sediments and turbidites (pelagic limestones, sandstones, calcarenites and micro-breccias, siltstones, green and red ribbon and nodular radiolarites) [1, 5, 9].

A tectonic formation containing blocks of all the above mentioned lithologies occurs along the tectonic contact between the Pindos ophiolite nappe and the Pindos flysch [11, 9]. In the northern part of the study area, molassic type sediments of the Meso-Hellenic Trough, were deposited during Oligocene-Early Miocene over the ophiolites and the Pindos zone sediments.

The general attitude of the contact between the Pindos ophiolite nappe and the Pindos flysch seems to be horizontal to slightly eastward dipping, as the large number of tectonic windows appearing in the study area, including the large semi-window of Malakasi confirms.

**TECTONICS**

Although several studies have been carried out and different explanations have been given on the emplacement of the Pindos ophiolites over the Pindos flysch, we believe that it took place during an important early Oligocene extensional tectonic event that caused a re-deformation of the tectonic melange along the ophiolite-flysch contact. The tectonic evolution of the area is complicated. Structural analysis carried out in the area [9] show that several tectonic events took place. Successive tectonic events arise from the structural analysis in the area. The sense of movement was established by using shear criteria and kinematic indicators. Using the methods of quantitative analysis it was possible to provide a quantitative interpretation in terms of strain from the striations observed on the fault planes [10].
Tertiary evolution started in Late Eocene times with a $D_0$ compressional event (maximum stress $\sigma_1$ axes ENE-WSW) which caused detachment, folding and thrusting of the Pindos flysch before the emplacement of the ophiolite over the flysch.

$D_0$ compressional event caused NW-SE to NNW-SSE trending inverse faults which are the dominant tectonic features in the area and bound the tectonic slices with a movement direction towards SW. Strike slip faults with remarkable displacements of the deformational front of the Pindos nappe along them, are closely related with the above mentioned compressional features. These faults are either dextral or sinistral The largest exists along Metsovitikos river. It is a major transverse fracture zone, known as Kas-taniotikos fault [8] that interrupts the continuation of the Pindos zone.

$D_0$ event was followed by an important $D_1$ extensional event (minimum $\sigma_3$ axes ENE-WSW) in Early Oligocene times, which caused a semi-ductile to brittle deformation in the area and the emplacement of the ophiolites over the Pindos flysch.

Two younger successive compressional events $D_2$ and $D_3$ are responsible for the refolding, imbrication and final shape of the Pindos nappe, with the maximum stress axes trending E-W and N-S respectively, took place during the Middle-Late Miocene (the second probably evolutionary to the first).
THE TECTONIC FORMATIONS

The Tectonic formation between Pindos and Ionian flysch (to the east of Motsovo tunnel, Fig. 2)

Beneath the Pindos nappe, along the thrust front appears a "tectonic formation" consisting a melange of strongly tectonized rocks, pelites, sandstones and blocks of limestones [11]. Different thrusting planes have been distinguished along the thrust front of the Pindos nappe, within the tectonic formation. This formation is widely extended throughout the study area. It concerns a tectonic melange having a "chaos" structure and an appearance that reminds a "wild-flysch" formation.

The matrix of the melange is mainly grey shales and sandstones in most cases completely sheared. Detached blocks of limestones and deep sea sediments such as thin bedded pelagic limestones, radiolarian cherts, and Late Cretaceous neritic limestones with dimensions from several centimetres up to several hundred meters, are observed within the matrix. The blocks are particularly tectonized and generally fault bounded.
Landslides along Egnatia highway (Greece)

The tectonic formation between the ophiolites and the flysch (to the west of Metsovo tunnel, Fig. 3)

A tectonic formation containing blocks of all the above mentioned lithologies occurs along the tectonic contact between the Pindos ophiolite nappe and the Pindos flysch [11, 9]. This formation resembles a tectonic melange which presents a "chaotic" structure. The matrix of the melange consists mainly of multicoloured shales, siltstone and fine grained sandstones and appears completely sheared. Detached blocks of serpentinites, basic volcanics, cherts, pelagic limestones and deep sea sediments derived from the ophiolite complex can be observed within the matrix. These blocks are strongly tectonized and fault bounded.

This tectonic formation was initially created during the Jurassic subduction-accretion evolution [5] and probably re-deformed during the tertiary emplacement of the ophiolites over the Pindos flysch [9].

GEOMECHANICAL INVESTIGATION

The region to the west of Metsovo tunnel

The more important landslides occurring in the area are not only due to the geometry of the discontinuities of the flysch, in relation to the cut slopes directions, but mainly to the nature of the specific geological formation in which landslides are determined.

After our investigation, the more important geological formation considered to be responsible for landslides creation is the "tectonic formation" that lies under the Pindos nappe overthrusting the Ionian flysch; it can be observed in many places along its front [11]. The formation has a significant thickness of 20 to nearly 80 m, depending on the site, and extends under Pindos flysch, creating important foundation problems. The particle size distribution of the matrix of the tectonic formation is given in Fig. 4.
Mechanically the material behaves differently in dry and in wet conditions. In dry conditions it behaves like a rock, having a dry density of 2.56 gr/cm³ and unaxial strength of 350 Kg/cm². In wet conditions it loses rapidly its cohesion and its original structure and behaves like a saturated soil. It is a fine grained material of intermediate plasticity. The small plastic range between plastic (PL) and liquid limits (LL), given in Table 1 determine the ability of the material to change rapidly from the semi-solid to the liquid state, improving the significant decrease of the cohesion, angle of internal friction and bearing capacity after raining [7]. The Group Index ($I_G$), given in Table 1, is rather high determining poor foundation conditions.

### Table 1. Physical characteristics of three representative samples from the tectonic formation.

<table>
<thead>
<tr>
<th>Property</th>
<th>TF1</th>
<th>TF2</th>
<th>TF3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid limit (LL, %)</td>
<td>36</td>
<td>39</td>
<td>38</td>
</tr>
<tr>
<td>Plastic limit (PL, %)</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Plasticity index (PI, %)</td>
<td>11</td>
<td>14</td>
<td>13</td>
</tr>
<tr>
<td>Pass No 200 sieve (%)</td>
<td>58</td>
<td>78</td>
<td>73</td>
</tr>
<tr>
<td>Group Index ($I_G$)</td>
<td>5</td>
<td>11</td>
<td>9</td>
</tr>
</tbody>
</table>

One other important parameter which was investigated, was the change of the shear strength in relation to the moisture content. For this purpose three representative samples from the area were investigated using a desk top fall cone penetrometer [6, 2]. The shear strength was measured for 10 artificially different moisture contents. The water contents in our tests covered almost the whole range of moisture, from the plastic limit to the liquid limit percentage. According to the correlation diagram of Fig. 5, an exponential relationship can express the changes of the above properties confirming that a small quantity of water can cause a significant decrease of the shear strength.

![Figure Σχάλμα! Άγνωστη παράμετρος αλλαγής. Correlation diagram between the shear strength and the moisture. Samples were collected from the tectonic formation (between Pondos and Ionian flysch) and moisture changes was made artificially.](image-url)
Landslides along Egnatia highway (Greece)

This observation can be related to our previous observation, that a small quantity of water can change rapidly this material from the semi-solid to the liquid state, improving that in the humid conditions of Pindos mountain chain a light rain can easily create landslides on the hill-slopes.

As the material is fine grained and so present low permeability, the above described change of the mechanical behaviour could not influence the stability of the formation at significant depth without the presence of important faults and closely spaced multiple open join sets, which drive the rain water dipper, in the mass of this tectonic formation.

The region to the east of Metsovo tunnel

Having already the experience of the western side (already described), the geomechanical and general stability problems in this area, should arise mainly from the presence of the tectonic formation (lying between the ophiolites and the flysch). Furthermore the existence of large scale strike-slip and normal faults, local rock mass wedging and sliding as well as possible combinations of these features, strengthen the instability phenomena along the road.

Table 2. Physical and mechanical properties of the tectonic formation.

<table>
<thead>
<tr>
<th>Description</th>
<th>Moist. content m (%)</th>
<th>Uniform. coef. U</th>
<th>Permeab. coef. K (m/sec)</th>
<th>LL (%)</th>
<th>PL (%)</th>
<th>Plastic. index</th>
<th>Group index</th>
<th>Compres. index</th>
<th>Bulk density (t/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clayey sand (SC-CH)</td>
<td>28</td>
<td>&gt;50</td>
<td>10⁻⁷</td>
<td>60</td>
<td>35</td>
<td>25</td>
<td>13</td>
<td>0,45</td>
<td>1,94</td>
</tr>
</tbody>
</table>

The tectonic formation has a significant horizontal extension under the ophiolitic complex and a varying thickness which in most cases lies between 10 to 20 meters. The thickness decreases from the west to the east.

The particle size distribution of the matrix of the tectonic formation is presented in Fig. 6 while its physical and mechanical properties are included in Table 2.

The plasticity and compression index values show that the material presents high risk for settlement and sliding [6,
In addition the correlation of its shear strength and moisture content presented in Fig. 7, shows a very rapid decrease in shear strength with the increase of moisture content [2]. This formation and its mechanical properties are similar with the analogous tectonic formation along the thrust front of the Pindos tectonic nappe (west of Metsovo tunnel, [3, 4]).

The poor mechanical properties of the tectonic formation can lead to a series of stability problems depending on the position of the formation in relation to the road design and the location of the construction (Fig. 8). In some cases the road slopes cut mainly through the ophiolitic formations, leaving the tectonic formation 15-20 m deeper from the road level. The existence of large scale normal and strike-slip faults, however,
Landslides along Egnatia highway (Greece) changes the position of the tectonic formation, bringing it to the road level and in some cases, to the level of major constructions like tunnels and bridges.

Another category of similar stability problems, mainly landslides and strongly tectonized mass movements, were encountered in cases where large scale fault zones cut through the road design. The large scale landslides activated at the slopes during the construction of the road consisted of very strongly tectonized material resembling soil formations.
The zones of this material present a general E-W orientation and our investigations have shown that they are actually large scale fault zones created by the E-W strike-slip faults (Fig. 9).

Combined stability problems are also related to important E-W faults, cutting the tectonic formation and collapsing probably the constructing works (tunels etc., Fig.10).

Concerning the geometry of the discontinuities, the sizes of the rock wedges in the most critical parts of the road were studied in detail and their safety factors were calculated. These calculations show that the formation of such rock wedges can create serious construction problems and they should be taken into account in the road design.

CONCLUSIONS

According to our investigation the more important landslides along the under construction Egnatia highway are mainly related:
1. to the nature of the tectonic formation that lies under the Pindos nappes overthrusting the Ionian flysch (on the west of Metsovo tunnel),
2. to the nature of the tectonic formation that lies under the ophiolites overlying the Pindos flysch (on the East of Metsovo tunnel).

These “tectonic formations” consist of shailes and pelites, containing detached blocks of limestones and deep sea sediments. Mechanically the above materials behave differently in dry and in wet conditions. In dry conditions they behave like a rock, while in wet conditions they loose rapidly their cohesion and their original structure behaving like a sutured soil causing landslides along an important part of the road.

Furthermore, important E-W strike slip faults either menace to collapse tunnels and other constructing works or create wide tectonic zones (>100 m width), in which the rock-mass is totally broken, behaving like a soil. These zones are usually perpendicular to the road axis, causing unstable high cut-slopes.

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