Terrain stability mapping of the Pindos flysh formation, NW Greece

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Abstract: The purpose of the study is to investigate the engineering geology and relative slope stability of an area covering about 140km^2, located on the western mountainous part of Grevena prefecture, NW Greece. The area consists of Pindos flysh formation, a complex lithological sequence with chaotic structure. Extensive landslides affect a significant part of the study area that has been characterized by an urban growth, due to the vicinity to Vassilitsa mountain ski-center. Landslides cause damage to roads but also to some new buildings, houses and hostels. Engineering geological investigations of the relative slope stability may serve as an essential tool in the evaluation of landslide hazards and help authorities in land-use planning, decision making and development.

Three distinct lithological and geotechnical units of the Pindos flysh formation are specified and mapped at 1:25.000 scale.1) Sandstone unit, with thin intercalations of siltstone. 2) Limestone unit, consisting of thin bedded limestones and sandstones in varying amounts and 3) Silty-clayey chaotic unit, with many olistostromes. Mixed units and many other lithophases including conglomerates are locally present, but they are not significant. The first two units are relatively coherent with minor slope instabilities, while the last one, which covers more than 50% of the area, hosts about 95% of recorded landslides.

The results of the study are thematic maps displaying the distribution of the above units as well as areas of active and previously active landslides. Attempt is made to define the essential characteristics and parameters, for each geotectonical unit, which mostly affects the stability of the natural slope. A relative stability map was created with three zones, as follows: a) moving ground, b) potentially unstable ground and c) stable ground. The study included a list of recommendations concerning future development and the possible stability conditions that may be encountered under physical or anthropogenic conditions.

Résume: La recherche se réfère a la géologie d'ingénieur et la stabilité de côtes d'une région montagneuse, de 140 km^2 de surface, à l'ouest de la préfecture de Grévéna, au NW de la Grèce. La région est couverte par de formations du flysch. Il s'agit d' une séquence lithologique complexe, caractérisé d'une structure chaotique. Nombreux glissements de terrain affectent une grande partie de la région, qui présente récemment une évolution urbaine très importante, à cause du voisinage du centre sportif du mont Vassilitsa. Les glissements ont causé de dégâts au réseau routier, mais aussi à de bâtiments nouveaux, maisons où hôtels. La recherche géotechnique de stabilité de côtes est un outil indispensable a l' évaluation des risques liés au glissements de terrain et d'autre part, aide les autorités locaux à prendre des décisions pour l'aménagement du territoire et au développement.

Trois unités lithologiques et géotechniques sont distinguées et cartographiées dans le flysch, a l'échelle 1:25.000. a) Unité de grés avec intercalations de silts b) Unité de calcaires. Il s'agit d'alternances de couches de grés et de calcaires d'épaisseur diverse et c) Unité chaotique de silts argileux avec d'olistostromes. Des unités intermédiaires et/où de lithologie différente, comme les conglomérats, affleurent localement. Les deux premières unités sont relativement stables, avec de glissements de moindre importance. La troisième, qui couvre le 50% de la surface du flysch, présente le 90% des glissements de terrain.

Les résultats de la recherche sont des cartes thématiques avec la distribution des unités du flysch et des zones avec glissements de terrain actifs où possiblement actifs. D'effort a été fait enfin de définir les principaux caractéristiques et paramètres de chaque unité géotechnique et principalement ceux qui interviennent a la stabilité de côtes. Une carte relative à la stabilité est crée avec trois zones, celles de terrains a) instables b) possiblement instables et c) stables. La recherche est complète avec des recommandations concernantes au développement future et les conditions possibles de stabilité comme se déterminent par les conditions physiques ou humaines.

Keywords: landslides, engineering geology maps, foundations, loading, laboratory tests, geographic information systems,

INTRODUCTION

The study area is located at a distance of 25-35km west of the town of Grevena, NW Greece (Fig.1). It comprises the eastern part of North Pindos Mountains and covers 140km^2 of predominantly mountainous and forested land between 800m and 1850m altitude.

Because of the unfavourable morphological and climatic conditions but also the lack of basic infrastructures until 15 years ago, there was no important human activity within the area for the greater part of the year. Except, that during the summer shepherds from the plain of Thessaly moved their sheep there and stayed for three or four months living in small villages comprised of single story houses of light construction.

However, continuing development was occurred in the area during the last two decades, which is mainly due to the operation of the nearby ski centre of Vasilitsa Mountain. The construction of the ski centre was accompanied by important improvements to the local road network. In parallel, new concrete houses have been built in the place of the old ones, as well as many big hotels. In the broad area of study are located the villages of Samarina (altitude 1550m), Filippaioi (1250m), Aetia (1100m), Smixi (1250m), Polyneri (970m), Panorama (1040m) and Lavdas (1050m) (Fig1). The total population of the above settlements during the summer reaches 6.000-8.000 residents, while many people visit the area during the rest of the year. At the present time, there is an increasing interest in the acquisition of seasonal residences not only near the existing villages but also within the wider region, preferably close to the main road that leads to the mountain of Vasilitsa.

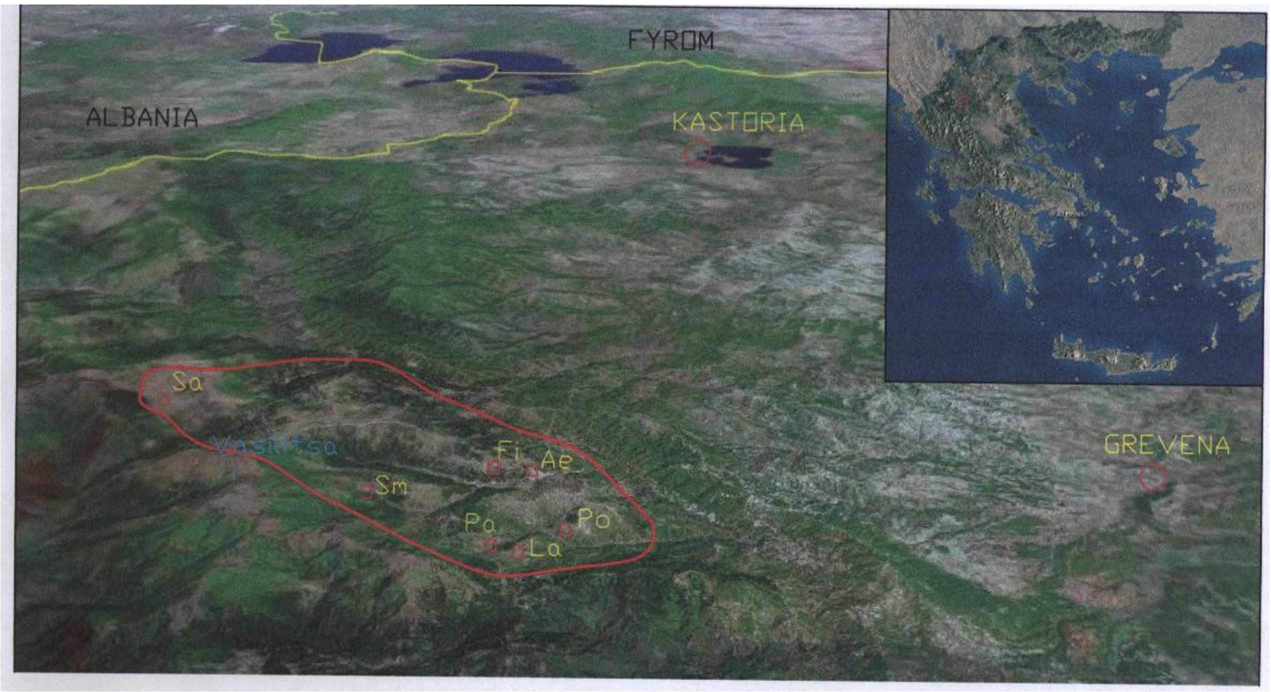

Figure 1. General view of the area of study, in which the position of seven villages is shown: Sa) Samarina, Fi) Filippeoi, Ae) Aetia, Po) Polineri, Pa) Panorama, La) Lavdas and Sm) Smixi.

The urban growth of the area along with the development of corresponding infrastructure, was made without taking into consideration the particular geotechnical characteristics of the ground. Indeed, the waste area is characterised by the frequent activation of landslides. Because many of these landslides are ancient, the danger has been often underestimated. Their morphology, which is flat around the foot area, gives a false impression to people that it is the most suitable ground on which to build. Thus, modern buildings are sometimes constructed in areas of old landslides, without any protective structures.

Intensive damage such as cracks in buildings, roads and retaining walls, caused by the landslides are observed in almost every one of the above seven settlements. The recent case of a landslide at the eastern part of the village of Smixi, resulted in the destruction of a hostel while still under construction. Moreover, the continuous need to improvement roads is resulting in excavation works for their widening and new cuttings in sensitive slopes without sufficient regard to stability and the provision of protection measures.

The above phenomena demonstrate the short memory of natural hazards that is held not only by the local population, but also by public bodies committed to land use and planning management. Generally, the low rate of displacement of the local landslides has rarely constituted a real danger to human lives, even though severe traffc accidents happen from time to time, due to destruction of sections of the road system.

Currently, there has been no systematic engineering geological research of the area concerning the landslide mapping or their monitoring. Also, the geological suitability of the foundation conditions in the region of the seven settlements has yet be documented.

The purpose of this study is to investigate the engineering geology of the area and to create a relative slope stability map. Geological, geomorphological, hydrogeological and engineering geological conditions of the territory were evaluated and presented cartographically at a scale of 1:25000.

GEOLOGICAL FRAMEWORK

The Pindos Zone of the Hellenides comprises a deep-water succession of late Triassic/Jurassic to Paleocene age, exposed within several westward-verging alpine thrust sheets. The flysch of the Pindos Zone in the North Pindos Mountains reaches from the Paleocene to the Upper Oligocene. During the Miocene, high-angle extensional faulting and westward thrusting of the Pindos Zone over the Ionian Zone caused detachments and many repetitions of successive thrust sheets.

Thus, the area is dominated by NW-SE trending tectonic structures, which may have been formed over a major frontal ramp as the Pindos ophiolite “rose” over the thick Pindos flysch wedge during the Tertiary thrusting.

To the west of the area, the flysch formation is tectonically overlain by massive, thick units of the Northern Pindos ophiolite complex (Vasilitsa and Smolikas mountains). A NW/SE trending ophiolite thrust sheet several km long constitutes the eastern boundary of the flysch formation. To the South, flysch goes underneath the Molasse formation of the Messoellenic Trench southeast of Perivolaki village, while to the North it continues to the prefecture of Kastoria.

GEOTECHNICAL UNITS OF THE FLYSCH FORMATION

In the regional, 1:50.000 scale geological map of the area made by Brunn (1952), the Pindos flysch formation appears undivided. It consists of rhythmic alterations of clastic sediments that are associated with orogenesis. The clastic material derives from erosion of the previously formed neighbouring mountain ridge. The clastic sediments may contain sandstone layers, conglomerate beds and fine grained layers, usually siltstone, silty shale or clayey shale. The flysch formation is generally very thick (up to 1000 metres) although locally it may be reduced considerably by erosion or by thrusting.

In general, the flysch formation has the following mass characteristics, which are significant for its mechanical properties: a) High heterogeneity, since it consists of successive alternations of competent and incompetent layers or bodies, .b) intense tectonic discontinuities, usually resulting in a soil-type material and c) presence of clay minerals.

The present detailed investigation indicated considerable regional differences in the composition of the Pindos flysch within the area of study. Three distinct flysch units can be recognised and mapped, each of which has a distinct lithological composition and structure, which is reflected in their geotechnical behaviour. Moreover, it was noted that the occurrence of landslide phenomena is directly related to the mapped units. The contact between the units is not tectonic, but reveals a progressive stratigraphic change from one unit to the other. The three mapped flysch units are as follows:

Lime-rich unit

Consists of layered light grey limestone, with thin intercalations of fine grain sandstone, siltstone and conglomerate (Fig 2-1). The proportion of limestone in the unit is generally high, ranging from 30% - 80%. It overlies the rest of the flysch units and, in general, covers the top hills higher than 1200 - 1300m altitude. The thickness of the unit ranges from a few metres up to 350m. The main system of discontinuities is bedding, which is characterised by tight folding while multiple joint systems cut the rock mass and consequent normal faulting results in the local degradation of the flysch unit.

In regions of smooth morphological relief, reddish to dark brown soil covers the underlying bedrock, with a maximum thickness of 0.5m. This material consists mainly of fine grain sand/shale and clay material and suffers extensive erosion, particularly in areas of poor vegetation cover (Fig. 2-5).

The lime-rich unit of the flysch covers roughly 25% of total extent of the area of study. It is characterized by increased permeability and good mechanical properties, due to the high competence of the constituent rocks, especially the limestone. The unit is characterized by an almost complete absence of landslide phenomena. Rare rock falls of limited scale occur in places with high slope angles. Although this unit has comparatively good geotechnical properties, it is not favourable for settlement, because it forms areas of high altitude, which face problems due to extreme climatic conditions (snowfalls, strong winds). However, roads that cross this unit show remarkable stability, with limited requirements for maintenance work.

Chaotic unit

This unit consists of disturbed silty or clayed shale, with many olistostromes forming a chaotic structure, equivalent to that of an ophiolitic melange (Fig.1-2). It contains micaceous sandstones and shales, typical of the Pindos flysch, as well as shaly, calcareous, mud matrix supported debris flows containing clasts of lithologies such as red and grey mudstones and shales, dark grey and pale grey shales and limestones, red or green bedded cherts, serpentinite blocks merging locally with debris flows. Slumped and boudinated units less than 20m in thickness, or extensive olistostromes masses are included in the chaotic unit. Olistostromes originate partly from the margin of the Gavrovo ridge to the West, and partly from the edge of the Pelagonian Platform to the east. The presence of thick, muddy sequences indicate deposition from large muddy turbiditic currents.

The internal structure of the chaotic unit of flysch formation contains a large variety of soft-sediment deformation structures. Some units of the red/grey lime-mudstones and shales show the effects of a pervasive stretching deformation with resulting boudinage of micritic beds. Slump folds occur both in deformed bedded sequences and as isolated hinges in debris-flow units.

Locally coherent sequences appear to merge laterally with slumped horizons. Coherent sediment blocks generally rest on and are draped by slumped or debris-flow units or thicker olistostrome units. The crude sedimentary fabric of slumped and olistostrome units and the bedding orientation of many of the large coherent blocks is frequently sub-parallel to thrust contacts, while many of the large coherent sediments probably represent slide blocks. Local early high-angle faults cut later thrust-related shear zones. The matrix of many of the debris flows and olistostrome units is often pervasively sheared, especially near thrust contacts. Thrusting and consequent normal faulting, results in considerable degradation of the geotechnical quality of the chaotic flysch unit. This unit shows normal sedimentary contacts with the surrounding flysch layers, as well as to the overlying lime-rich unit (Fig 2-2).

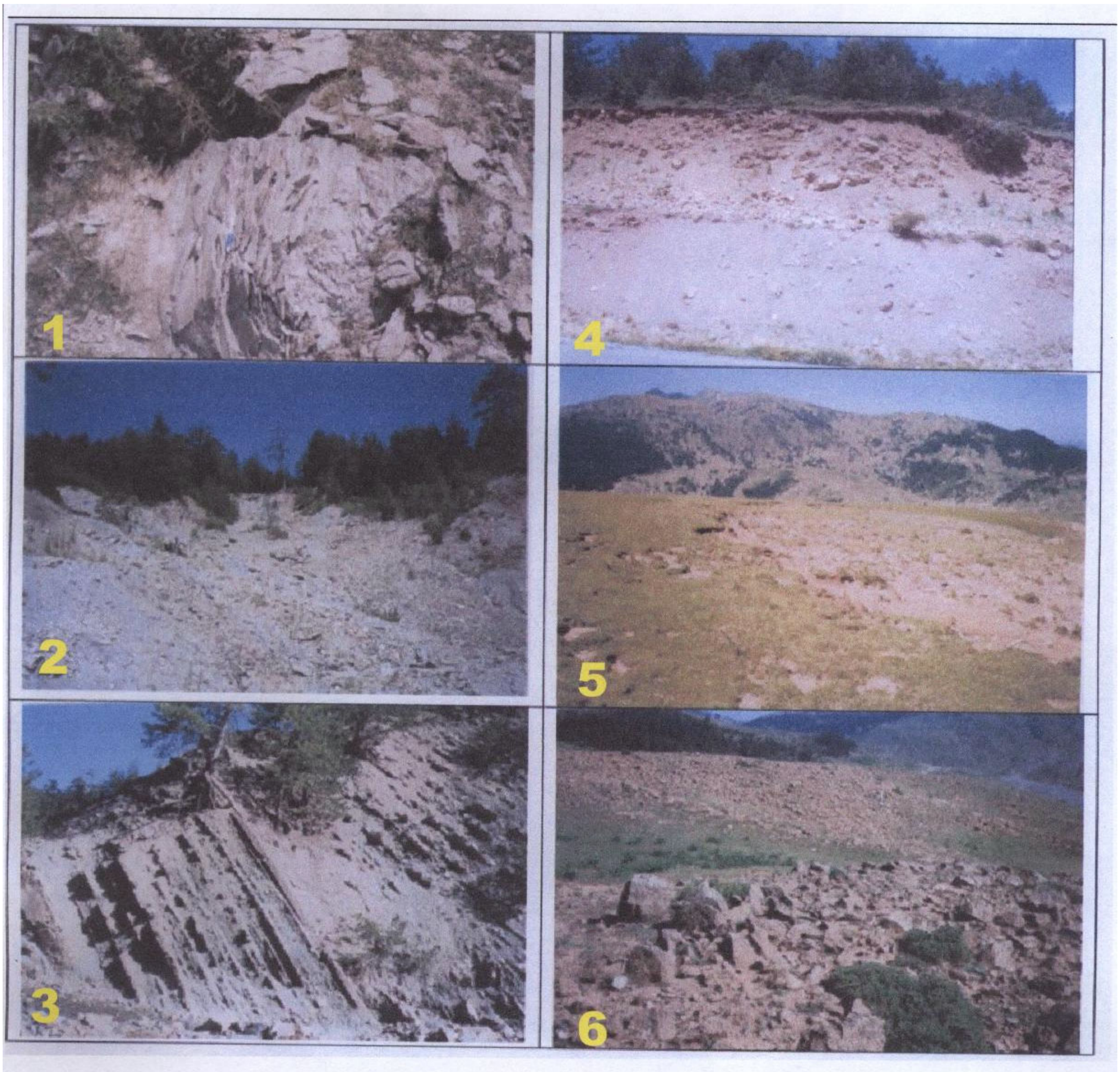

Figure 2. Typical form of the mapped geotechnical units: 1) lime-rich flysch unit, 2) chaotic unit, 3) sandstone unit, 4) contact of lime-rich and chaotic units, 5) erosion of the top soil of lime-rich unit and 6) Glacial moraines formation..

Laboratory geothechnical tests conducted on 22 samples of the matrix material of the chaotic unit taken from exploratory pits, gave the following results (Table 1):

Table 1. Summary of geotechnical parameters of the matrix material of <chaotic flysch unit>

Parameter	Range
Grain size analysis (%)	gravel:0-18 sand:9-43 silt:29-81 clay: 1-15 (soil type: CL)
Moisture content (w %)	19 - 21
Dry density (Mg/m^3)	1.63-1.96
Atterberg Limits (%)	LL: 31.9-49.8 PL: 15.7-22.3
Cohesive strength c (kPa)	54-101
Friction angle (φ°)	8-20

The chaotic unit constitutes about 60% of the Pindos flysch formation. Its characteristic chaotic structure appears to be a primitive sedimentary feature, affecting the whole thickness of the unit, which exceeds 400 metres in the area of the study. The permeability of the chaotic flysch masses is generally low and, because of the presence of clay minerals, the unit mass may be weakened to a significant degree where free drainage is not present. Within the surface layers pervasive infiltration of water occurs during the wet period of the year. The estimated depth to which water infiltration occurs is 3 to 5 metres. Except from direct rainfall, a continuous supply of water to the uppermost unit occurs from the overlying lime-rich unit, which has a higher permeability and is capped by a thick snow mass in winter, which melts slowly.

The composition and structure of the unit as well as the presence of infiltrated water are the main causes of extensive landslides at many scales. More than 95% of the mapped landslides are located within the chaotic unit of flysch. Thus it is remarkable that the villages of Polyneri, Panorama, Aetia, Filippaioi as well as the eastern part of Smixi, are founded in the “chaotic unit.”

Sandstone unit:

The deeper horizons of the Pindos flysch consists of a sandstone unit, which is similar in appearance to the relative unit of the Molasse formation. It underlies the chaotic unit and constitutes the lowest topographic parts of the area, roughly bellow the height of 1000m. It consists of rhythmical alternations of sandstone layers 2-30cm thick, with fine silty layers and clayey schists, with local conglomerate intercalations. The percentage of sandstone as well as the thickness of layers varies widely from place to place, but in general it does not exceed 50%. Bedding is the dominant discontinuity of the unit. Its orientation is quite constant over distances of tens of metres, with local fluctuations due to folding and subsequent fault structures. Bedding surfaces are generally smooth, with a small friction angle due to the presence of thin silty/clayey interbedding, tectonic fatigue of the formation and weathering, which appears to be more intense in the fine members of the unit.

The joint systems observed in sandstone are usually discontinuous, with rough surfaces of limited length. Thrusting surfaces are limited to the weak pelitic layers, while sandstone rich sequences appear intact, between the major fault systems. The infiltration and movement of underground water is favoured by joint system discontinuities, but the presence of fine-grain horizons blocks deep infiltration.

The sandstone unit has good geotechnical characteristics with respect to the maintaining slope stability. In steep slopes exposures occur, uncovered by vegetation, extensive weathering and erosion processes, causing detachment of rock fragments which move downwards by heavy rain. In areas of low relief , covered by vegetation, a cover of thick sandy soil is developed. This unstable material has a thickness of 1-5 metres and may produce instabilities under physical (erosion of slope foot) or anthropogenic conditions (road cut excavations). About 3 to 4% of the known landslides in the studied area were movements of soil masses under similar conditions.

Although, this unit generally exhibits good geotechnical characteritics, similar to the lime-rich flysch unit, the fact that it occurs at low levels with steep slopes, exposed to stream flooding, thus it is difficult to recommend these areas for future settlement development. The village of Lavdas is the only one founded on the sandstone unit and it has landslide problems.

Other units of flysch formation

Apart from the above main flysch units, big fragments of olistostromes or thrust sheets consisting of limestone, conglomerate, chert, ophiolite or schist formations, are distinguished and mapped as separate units in the regional engineering geological map.

Quaternary formations

The above described flysch formations constitutes 95% of the studied area, and the remaining 5% is covered by Quaternary materials, that comprise the following formations:

Accumulations of morainic detritus: Three main occurrences of old typical glacial deposits, were mapped in the western part of the studied area, along the contact of the flysch formation with the Pindos ophiolite complex. They consist mainly of coarse, semi-loose ophiolitic cobbles and rubble, locally covered by reddish clayey material. The village of Samarina is completely founded on morainic deposites, as well as the western part of Smixi. The thickness of the formation ranges from a few metres up to 25m. It is often remobilized along slopes, commonly along its contact to the underlying chaotic unit of Pindos flysch. This slow movement is the main reason of the observed damage in Samarina structures.

Scree and talus cones: Loose to semi-loose material occur along steep slopes of the western flysch boundary.

Alluvial deposits: Mainly gravely-sandy stream deposits of limited exposure, they consist of semi-loose materials reaching a height of 30m south of the village of Aetia.

LANDSLIDES MECHANISMS

Engineering geological mapping of the area shows that 30% of the hill and mountain territory is subject to landsliding. Most landslides are quite large and appear to be the result of low to medium deep-seated creep. This slow movement is not obvious by direct observation and can only be recorded instrumentally. In many cases phase of large-scale landslide creep is followed by sliding and subsequent earth-flow phenomena. In the evolution of many landslides these three phases are transitory depending on the amount of pore water available at the time of movement. About 95% of mapped landslides occur within the chaotic unit of the flysch formation. This process has a long history and in most cases old landslides are reactivated. The basic mechanism includes slow creep originating at the maximum depth of water infiltration, which is estimated to be about 3 to 5m below the ground’s surface. Very deep-seated creep does not generally appear to take place. Shallow creeping is followed by sliding, which occurs when the shear strength of the material is overcome. Earth flows occur, when the amount of water is enough to reach a visco-fluid physical state, as happens in the area during late-winter and spring time due to snow melting. The displacement rates are then in the order of a few tens of metres per day or greater. A number of active landslides in the area (15) have an overall length of 500-1300m, while the accumulated material reaches a thickness of 10 to15m (Fig.3-1,2).

Apart from the above mechanism that is involved in the majority of the 208 landslides that were mapped within the studied area, a small number of other mechanisms are present including rockfalls and block sliding. Sliding movement in the morainic formation is facilitated by the saturated contact surface of clayey/silty material, with the underlying chaotic unit.

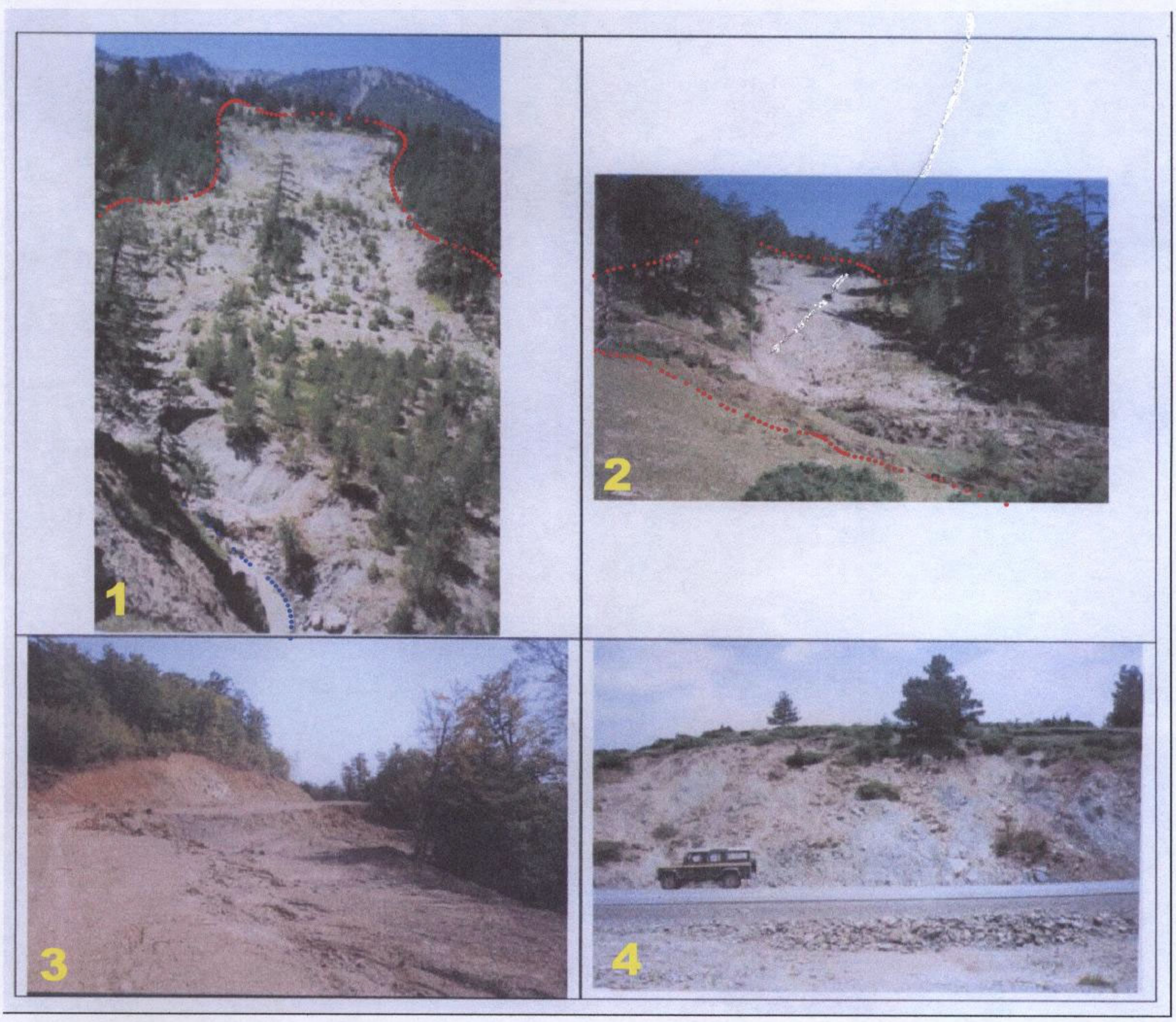

Figure 3. Typical landslides within the studied area: 1, 2) Large landslides in natural slopes 3,4) Small scale landslides in road cuts.

LANDSLIDE CONTROLLING FACTORS

The main factors controlling slope instability and landslide phenomena within the studied area are:

Geological structure plays the most important role in the observed slope instability of the studied area. The extensive occurrence of the chaotic flysch unit with its characteristic lithological and tectonic structure and the subsequent very low geotechnical properties is the main factor of instability.

Slope Gradient and Elevation: Weight is the main driving force for movement of a particle on the steep slope surface. This force is divided to two components, the component perpendicular to the slope's surface maintains the object stable on the steep surface, but the component tangential to the slope's surface increases the object's instability. By increasing steepness and elevation, the driving force also increase, due to the following factors: a). Increment of elevation after earth filling b) Decrement of elevation after soil removal c) Erosion or making a platform in the foothills. All these processes are in active within the area studied.

Climatic conditions: a) Continuous and intense rain and snowfalls re the main climatological factors fpr landsliding. Even in seasons with low rainfall, groundwater flow from within the ground takes place through joints, faults and layering. Water absorption into the upper beds leads to the saturation of material that become unstable. b) Winter snowfall and spring melting causes soil creep on steep slopes. c) River activity in seasonal flooding, caused instability of valley sides d) Daily and seasonal temperature changes are high in the areaand cyclic changes cause increased rates of mechanicalweathering. Thus weathering due to climatic changes, leads to rock fragmentation and soil generation making rock slopes less stable..

Groundwater: also facilitates slope movements. Raising soil moisture content increases the weight of the soil and its apparent density. Groundwater could decrease resistant force and increase driving forces along the surface of rupture. Increases in Pore fluid pressure decreases shear strength. Even small amounts of water within rock and soil fractures can significantly increase the driving force.

Vegetation: Generally, plant roots act as reinforcement to soil strength that protects soil from movement. The observation on the studied area, which has large slopes covered by thick forest, confirms the positive role of plants in slope stabilization. Plants also prevent slope erosion and control water supply to slopes after raining and decrease groundwater level of upper parts of soil. Root networks makes the superficial soil layers like a sponge which increases their ventilation and the evaporation of water from them. Also after roots decay, organic content is increased in the soil, increasing its capability for water storage. This process limits water infiltration to deeper layers that would promote slope instability.

Seismicity is secondary factor for instability in the studied area, since this area has no known seismically active faults. Even the big earthquake of Grevena in 1995 with a magnitude of the 6.6R did not result in an increase in landsliding events.

Anthropogenic activity makes a significant contribution to the intensity of landsliding, because the assessment of foundation conditions do not consider the effect of the above critical instability factors.

CONCLUSIONS

Intense landslide phenomena occur within the Pindos flysh formation, of NW Greece, where several developing urban areas are located. Geological, geomorphological, hydrogeological and engineering geological conditions of the territory were evaluated and presented cartographically at a scale of 1:25000.

Three distinct flysch units were mapping, each of which was characterized by individual lithological stratigraphical and geotechnical features: 1) Lime-rich unit, consisting of layered light grey limestone, with thin intercalations of fine grain sandstone, siltstone and conglomerate. This unit is quite stable and does not favourite landslide phenomena, with the exception of small scale rockfalls. 2) Chaotic unit, consisting of disturbed silty or clayed shale, with many olistostromes forming a chaotic structure, similar to an ophiolitic melange. Thrusting and consequent normal faulting, results in considerable degradation of the geotechnical quality of the chaotic flysch unit. The composition and structure of the unit as well as the presence of infiltrated water are the main causes of extensive landslides of many scales. More than 95% of the mapped landslides are located within the chaotic unit of flysch. 3) Sandstone unit, consisting by rhythmical alternations of sandstone layers 2to 30cm thick, with fine silty layers and clayey schists, with local conglomerate intercalations. The sandstone unit has good geotechnical behaviour in respect to the landslide phenomena and only a few small scale landslides occur, in the thick soil cover of the unit. Glacial deposits of accumulations of morainic detritus cause significant problems for foundations in the villages of Samarina and Smixi. This formation overlies the chaotic unit of flysch and moves slowly eastwards.

Engineering geological mapping of the area showed that 30% of the hill and mountain territory is subject to landslides, while about 95% of the mapped landslides occur within the chaotic unit of flysch formation. Most of these landslides formed in extreme climatic conditions that occurred hundreds of years ago. Therefore, if the distribution of the old landslide bodies is known, almost all instabilities can be reduced or prevented.

In respect to the landslide mechanism, the most common process is creep at low to medium depth. This slow movement is not obvious and can only be measured instrumentally. In some cases creeping, is followed by sliding and subsequent earth-flow.

The main causes of the landslide occurrence within the studied area are: a) the extensive occurrence of the chaotic flysch unit with its characteristic lithology and tectonic structure and the subsequent very poor geotechnical properties, b) the steepness and elevation of the morphology, c) the extreme climatic conditions, with heavy rain, snowfall and considerable seasonal changes in temperature, which favours extensive weathering of the flysch formations, d) the groundwater, which increases the weight of the soil facilitating slope movements and e) landslides occur more often in areas with poor vegetation cover.

Engineering geological mapping may be an effective tool for planning and assessment and for evaluation and planning suitable types of foundation and construction design, in order to prevent the onset of hazardous geological phenomena.

The probability of a landslide occurrence within a set period of time at the given area must be carefully analysed and estimated, with systematic monitoring if required.

The response of public authorities has frequently been to issue stricter, administratively more effective rules, but real hazard has not actually been assessed. Also people tend to underestimate the extent of landslides and their influence on their properties and even human lives.

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