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Engineering-geological conditions of the formations in the Western Thessaly basin, Greece

Research Article

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Abstract: An engineering-geological map of the Western Thessaly basin has been compiled, providing a valuable guide to both urban planning and industrial development of the wider area. This map contributes significantly to the optimization of land use and improved planning of technical work. Additionally, the engineering-geological conditions of the formations encountered in the Western Thessaly basin are examined. The formations are grouped into thirteen (13) engineering-geological entities, with regard to their geotechnical behaviour. This entire study was based on both in situ investigations and geotechnical information extracted from 1,039 boreholes.
Furthermore, a landslide inventory map of the Western Thessaly basin has been compiled. In addition, the surface subsidence ruptures, due to ground-water overexploitation, have been examined in the eastern part of the study area.

Keywords: Engineering-geological map • Engineering-geological entities • Geomechanical characteristics • Landslide inventory map • Land subsidence

1. Introduction

Engineering geology was developed in response to the increasing demands of various technical projects, which required a better understanding of the interaction between ground, foundations and constructions, in order to build more economically and safely [1]. The geological, geotechnical and hydrogeological conditions must be well known in order to provide the necessary information to the local authorities, engineers and constructors, in order to form the framework to plan such technical projects.

The need for engineering-geological mapping has been well established over the last 40 years. At the beginning of this period the international community recognized the importance of these maps regarding all kinds of civil works (roads, dams, tunnels, etc), infrastructure development, and urban and land planning [2–9].

Until approximately 20 years ago, in Greece, there has been a lack of regional engineering-geological maps giving basic engineering-geological information, useful for planning land use and technical projects or for the selection of the most appropriate types and methods of construction, or for improved environmental protection. Finally, one of the first important projects was the creation

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of an engineering-geological map of Greece at a scale of 1:500,000 [10]. In addition, several researchers compiled engineering-geological maps of the wider areas of Athens, Thessaloniki, Patras, Trikala, Karditsa and Nafplion city [11–22].

In many areas of Greece, the climatic and geological conditions are favourable for the development of landslides [23, 24]. In Western Thessaly basin, landslides occur very frequently. These natural catastrophic phenomena affect urban and cultivated areas, as well as technical infrastructure, various forms of transportation infrastructure, civil engineering work, etc., with disastrous socio-economic implications [25].

Furthermore, in the eastern part of the Western Thessaly basin, namely the area extending from Farsala to Stavros, land subsidence has been recorded since 1990, due to ground-water overexploitation. An excessive drawdown of the groundwater table (20 – 40 m) has been recorded in the various successive aquifers the last decades. The study area consists of terrestrial Pleistocene deposits containing sands and gravels interbedded with clayey silt to silty clay horizons. The overexploitation of groundwater activates the subsidence mechanism in the discharged aquifers and subsequently leads to the manifestation of the accompanying phenomena on the surface, apart from the land depression [26, 27].

The present work aims for a better understanding of the geotechnical conditions in the study area. So, an engineering-geological map of Western Thessaly basin with several lithological units was created. This map is a useful and basic tool for further research and for planning of various technical projects during their preliminary stages. This thematic map can provide significant information for urban planning, the design of future infrastructure, and even more for the prevention and mitigation of natural hazards.

2. Study area

The Province of Thessaly is located in Central Greece and it comprises the most extensive smooth-relief area in the Greece [28]. Thessaly is the most intensely cultivated and productive agricultural plain in Greece, mainly crossed by the Pinios River and surrounded by high mountains [29]. This plain is subdivided by a group of hills into two hydrogeological basins, the Western (Trikala-Karditsa plain) and the Eastern (Larisa plain) [28].

Considering the morphological conditions, the Western Thessaly basin (Figure 1), with an areal extent of 6,093.06 km^2, can be divided into two areas. These are the hilly-mountainous region, with an absolute altitude ranging from 200 m up to more than 2,000 m and the lowland region, with an absolute altitude up to 200 m. These areas occupy 62.12 % and 37.88 % of the overall area, respectively. The hydrographic network is well developed with a significant surface runoff [28, 29].

The Western Thessaly basin lies between the internal and external Hellenides (geotectonic zones), which, along with the recent tectonic activity explains the great variety within the prevailing geological formations (Figure 1). Rock formations that surround the basin are distributed between four geotectonic zones of the Alpine bedrock [25, 30–36]. The Pelagonian zone units consist of gneisses, crystalline schists, phylites, crystalline limestones, marbles and dolomites. The Sub-Pelagonian zone units consist of schists, schist-gneisses, sandstones, pelites, limestones, dolomites, ophiolites and flysch. The Ultra-Pindic sub-zone units consist of limestones, conglomerates, sandstones, pelites and flysch. The Pindos zone units consist of limestones, cherts, first flysch, transition beds and flysch.

Post-Alpine formations that also contribute to the geological structure of the basin are: (a) Molassic formations of the Mesohellenic trench (sands, clays, marls, sandstones and conglomerates), (b) Neogene sediments (clays, silts, marls, sands, sandstones, conglomerates, breccias, grits and marly limestones) and (c) Quaternary deposits (alluvial and fluvial deposits, fluvial terraces, screes and talus cones) [25, 33]. The major part of the Western Thessaly basin is comprised mainly of formations of Quaternary age (2,570.62 km^2, or 42.19%). Their thickness exceeds 550 m and there is a progressive transition from deposits formed within a lacustrine environment to the more recent fluvial deposits.

The Quaternary deposits contain the main aquifers of the study area. The aquifers constitute a system of unconfined shallow aquifers, extending through the upper layers, and successive confined-artesian aquifers developing in the deepper permeable layers [37, 38]. This system is supplied by water through the lateral infiltration from the karstic aquifers in the alpine carbonate formations, outcropping in the margins of the Western Thessaly basin, as well as from percolated surface water. The majority of the aquifers in the Thessaly plain are under a regime of overexploitation, resulting in a systematic drawdown of the ground water level [26, 27, 39, 40].

Referring to the tectonic evolution of the wider area, two extension events took place near the end of the final phase of Alpine-related folding; the one with NE–SW-directed extension(Miocene–Pliocene) and the other with N–S directed extension (Lower–Middle Pleistocene until now). The latter event is responsible for the significant seismic activity that exists in Thessaly [35, 36].

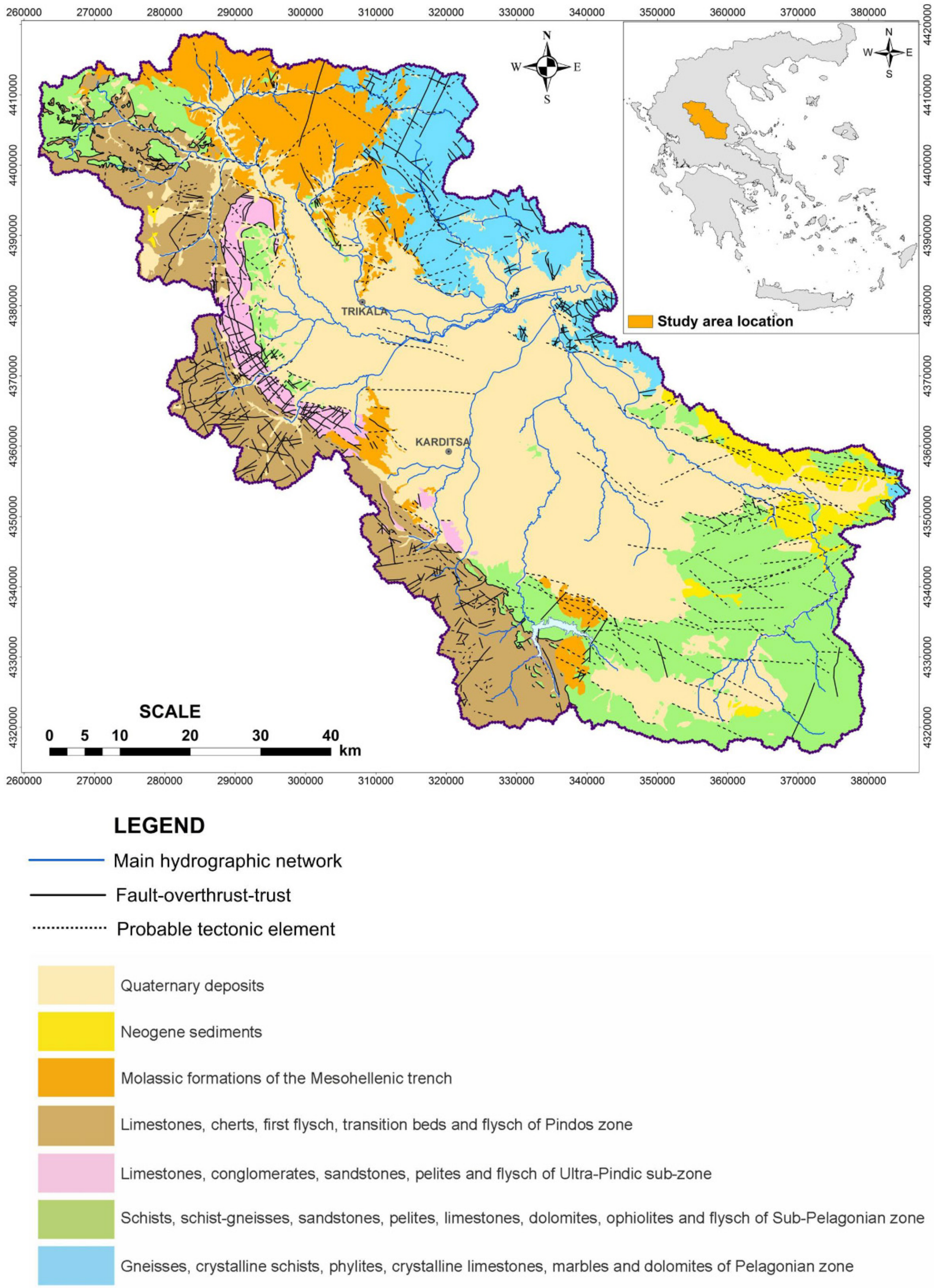

Figure 1. Simplified geological map of Western Thessaly basin.

Medium seismicity has occurred in the region of Western Thessaly over the last 100 years [41]. An extension-related generation mechanism is justified in the region by shallow earthquakes with up to 60 km focal depths. The extension is N-S directed and is related to the formation of E-W trending faults, which are dipping either in the North or South direction [42].

The climate of the wider study area is continental with cold winters, hot summers, and large temperature differences [34]. According to the hydro-meteorological data for the time-period of 37 years (1970–2007) obtained from 14 meteorological stations, the following results have been derived: (a) the rainy period begins in October and ends in May, (b) the mean annual precipitation is 885.8 mm, (c) a wide fluctuation of the annual values of rainfall exists between 541.7 and 1,592.0 mm, (d) an increase in rainfall from E to the W is evidenced, (e) the mean annual temperature value fluctuates between 5.0 and 26.6°C, and (f) the annual fluctuation pattern of temperature is exactly the opposite from that of the precipitation.

3. Data and methodology

The main types of datasets used in this study were the following:

- Nineteen (19) sheets of topographic maps from the Hellenic Military Geographical Service (HAGS) at a scale of 1:50,000.
- Nineteen (19) sheets of geological maps from the Hellenic Institute of Geology and Mineral Exploration (IGME) representing lithological and structural units at 1:50,000 scale.
- The engineering-geological map of Greece at a scale of 1:500,000 [10].
- The tectonic map of Thessaly at a scale of 1:200,000 [35].
- The Corine Land Cover map 2000 of the European Environment Agency [43].
- Hydro-meteorological data, covering a time-period of 37 years (1970 – 2007).
- Seismological data for the time-period from 1900 to 2012, from the Geophysical Laboratory of the University of Thessaloniki [41] and from the Geodynamic Institute of the National Observatory of Athens.
- Field data involving observations on engineering-geology mapping and natural hazards sites. Extended field investigation was carried out during the years 2006 and 2009.
- A large number of technical reports and studies obtained from IGME and other public or private sectors.
- Geotechnical data sets and studies concerning the landslide deposits.

The methodology followed by the current research comprises:

- Collection, evaluation, registration and process of all data, analogue or digital.
- Integration and evaluation of data.
- Statistical evaluation of data.
- Creation of thematic maps (engineering-geological, simplified-modified geological, landslide inventory map, etc) and databases, using Geographical Information System processing (ArcGIS Desktop 9.3.1 software environment). Data processing and final map preparation were performed digitally using GIS, so that it can be used as a complete and fully integrated database.

A Geotechnical Database, using Microsoft Access, was created. Data derived from 1,039 boreholes drilled in the plain of the Western Thessaly basin were evaluated (Figure 2). The aforementioned 1,039 boreholes can be separated into 571 exploratory boreholes with maximum depth 70.45 m, 157 trial pits with maximum depth 5.00 m and 311 water-boreholes with maximum depth 400.00 m. This database was designed to allow rapid retrieval and evaluation of the data in selected areas.

The engineering-geological map of the Western Thessaly basin was compiled by evaluating the above mentioned data. According to the international guidelines and recommendations, this map is characterized as a multipurpose, synoptic and large scale engineering-geological map [2–7, 44]. The map includes thirteen (13) engineering-geological units, based on their geological origin, relevant age, composition, physical state and geotechnical conditions (Figure 3). These units were divided by statistically determined values deriving from their physical properties and mechanical parameters. Special emphasis was given to the units located in urban and industrial areas.

In the Western Thessaly basin, landslides occur frequently. Consequently, serious social, economic and technical problems arise, whichaffect the technical projects

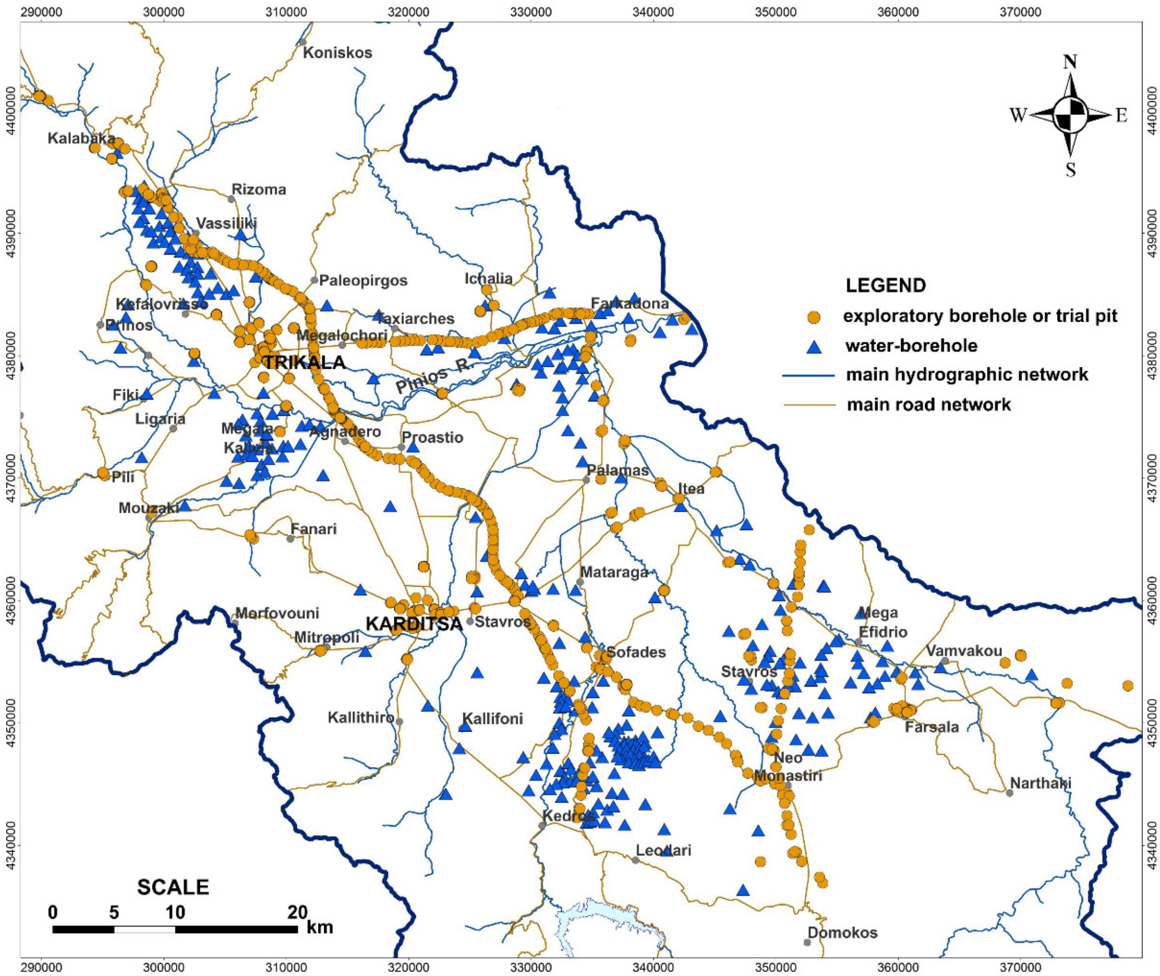

Figure 2. Location map of the 1,039 boreholes examined in the flat section of Western Thessaly basin.

(transportation network, extensive engineering works, etc) with immediate impacts on urban development. These phenomena mainly concern zones of older activation due to geological factors, but also recent ones due to anthropogenic activity and incidents of peak precipitation [21, 23–25].

Many technical reports and studies, which refer to landslide occurrences, mainly obtained from IGME, were used to analyse and record all the landslides of the study area, in a database (using Microsoft Access). The interplay between the database system and Geographical Information System was established with the defined coordinates of the locations of existing landslide occurrences. After modifications, 979 landslide occurrences, which occurred between 1952 and 2012, were recorded and digitally stored [21, 25, 33, 34, 45–49]. The spatial distribution of the recorded occurrences and the evaluation of the processed data led to the compilation of a landslide inventory map of Western Thessaly basin (Figure 4).

4. Engineering-geological map

The descriptions of the thirteen (13) engineering-geological units of the Western Thessaly basin map, as estimated by evaluating the above described data are given below and illustrated in Figure 3.

4.1. Quaternary deposits

Three (3) engineering-geological units were derived, namely:

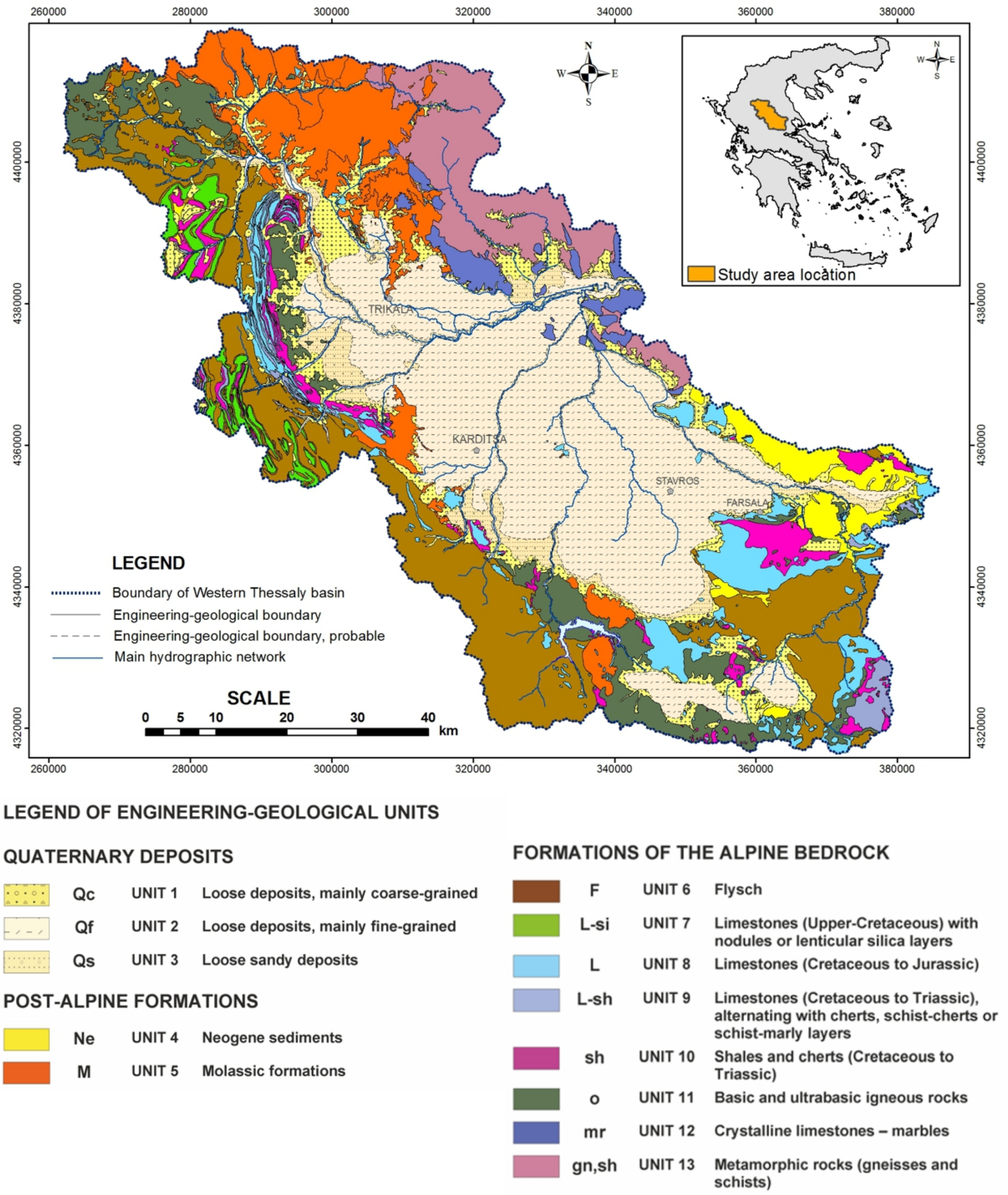

Figure 3. Engineering-geological map of Western Thessaly basin.

UNIT 1 (Qc): Loose deposits, mainly coarse-grained.

This unit consists of cobbles, pebbles, gravels of different origin and various sizes, grits and sands, usually with low proportions of clayey silts to sandy clays. Small fragments of limestone are found in places. These are loose deposits in alternate layers, with rapid lateral wedging out. They present satisfactory behaviour under static loading, especially in areas of gentle inclinations, but they are sensitive to dynamic loading. Their geomechanical behaviour is usually controlled by the characteristics and percentage of the fine material.

The range of values of the main physical properties and mechanical parameters of fines of the deposits of the unit 1 is presented in Table 1.

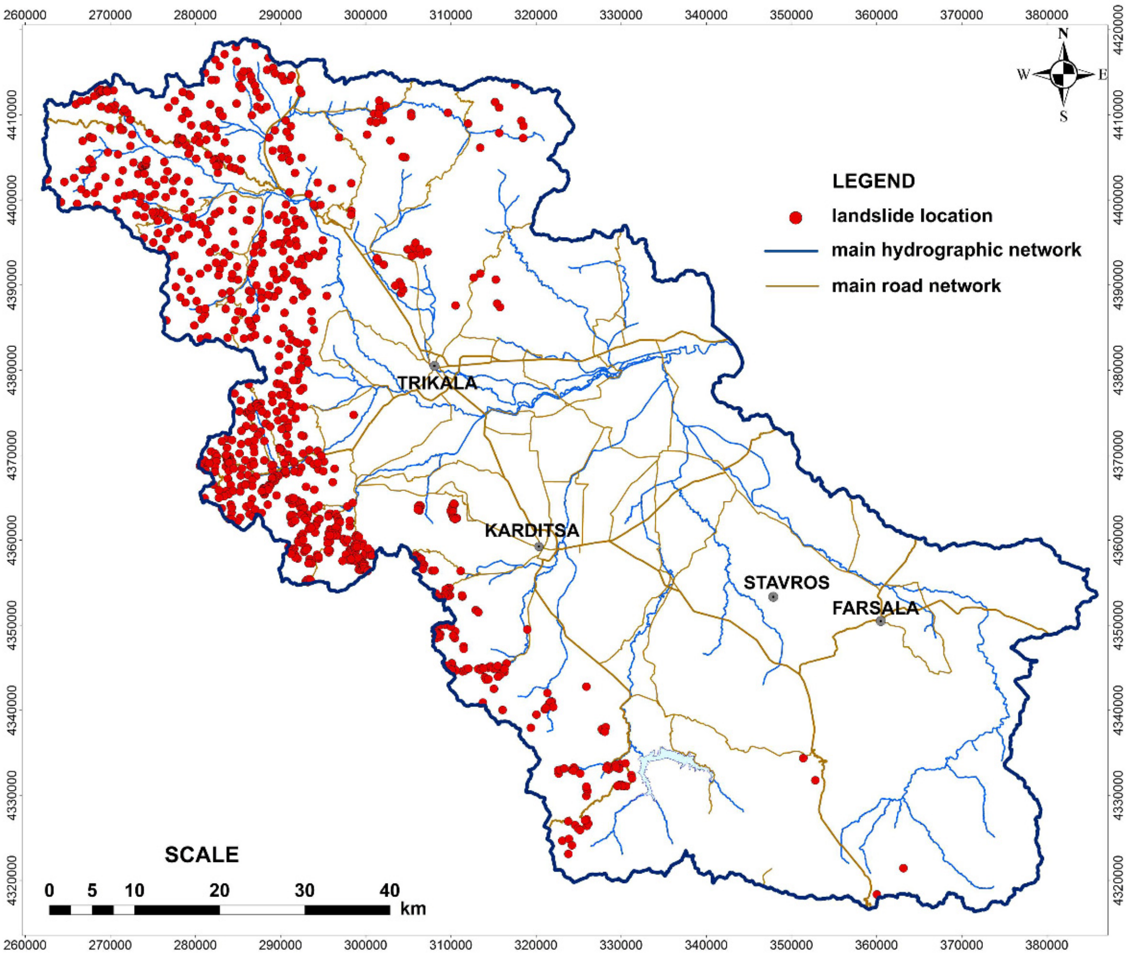

Figure 4. Landslide inventory map of Western Thessaly basin.

Table 1. The range of values of the main physical properties and mechanical parameters of fines of the deposits of unit 1.

LL (%)	PI (%)	w (%)	γ_b (kN/m^3)	γ_d (kN/m^3)	Gs	e
15.60 – 26.40	2.00 – 12.00	0.90 – 25.00	19.00 – 22.00	15.50 – 19.00	2.50 – 2.70	0.32 – 0.76
c_s (kPa)	**φ_s (°)**	**c_u (kPa)**	**φ_u (°)**	**c (kPa)**	**φ (°)**	
0.00 – 36.50	26.50 – 44.50	10.00 – 60.00	0.00 – 20.50	24.00 – 25.30	27.85 – 29.00	
c′ (kPa)	**φ' (°)**	**q_u (kPa)**	**Cc**	**e_o**		
10.70 – 17.85	32.00 – 35.00	18.0 – 166.0	0.040 – 0.150	0.268 – 0.800		

LL: liquid limit (%), PI: plasticity index (%), w: moisture content (%), γ_b: bulk unit weight (kN/m^3), γ_d: dry unit weight (kN/m^3), Gs: specific gravity, e: void ratio, n: porosity (%), c_s: cohesion (kPa) from direct shear tests, φ_s: angle of internal friction (°) from direct shear tests, c_u: undrained shear strength (kPa) from UU triaxial shear tests, φ_u: angle of internal friction (°) from UU triaxial shear tests, c: cohesion (kPa) from CUPP triaxial shear tests (total stress), φ: angle of internal friction (°) from CUPP triaxial shear tests (total stress), c′: effective cohesion (kPa) from CUPP triaxial shear tests (effective stress), φ': effective angle of internal friction (°) from CUPP triaxial shear tests (effective stress), q_u: unconfined compressive strength (kPa), Cc: compression index from consolidation tests, e_o: initial void ratio from consolidation tests.

UNIT 2 (Qf): Loose deposits, mainly fine-grained.

Unit 2 consists of horizons of clayey silts to silty clays, with ranging of sands, grits and gravels. They are characterized by frequent and rapid changes in their lithological composition and grain size distribution both horizontally and vertically. These fine deposits are characterized by alternations towards their lower boundary with the sandy horizons of unit 3. Because of their extended surface development (1,716.98 km^2, 28.18 % of the area) most of the construction, towns and villages are founded on them and so the knowledge of their geomechanical behaviour is very important. Their physical properties and mechanical parameters depend on the lithological composition and grain-size distribution, while their behaviour is controlled by their thickness, their lithological anisotropy and the inclination of the ground. They often present geotechnical problems due to settlements and ground movements. Table 2 presents the descriptive statistics for the main physical properties and mechanical parameters of fines of the deposits of unit 2.

UNIT 3 (Qs): Loose sandy deposits.

This unit consists of sands or sands with clay or silty clay, locally silty sands. Grits and gravels are also found, but less frequently. These loose deposits are characterized by alternations towards their vertical development with the fines horizons of the unit 2. Their geomechanical behaviour is controlled by the characteristics and percentage of the fine material. Table 3 presents the descriptive statistics for the main physical properties and mechanical parameters of fines of the deposits of the unit 3.

4.2. Post-Alpine sediments

Two (2) engineering-geological units were derived, namely:

UNITY 4 (Ne): Neogene sediments.

This unit consists of clays, silts, marls, clayey-marls, sands, sandstones, marly sandstones, conglomerates, breccias, grits and marly limestones, which mainly occur in thin layers. The heterogeneity, but mainly the lateral evolution and wedging out of the horizons, contributes to the non-uniform and anisotropic behaviour of the formation as a whole, and to the rapid change of the mechanical parameters in the different horizons, both vertically and laterally.

The range of values of the main mechanical parameters is presented in Table 4.

UNIT 5 (M): Molassic formations of the Mesohellenic trench.

This formation consists of sands, clays, marls, calcareous marls, sandstones and conglomerates in alternate layers, with rapid wedging out and lateral transitions. The heterogeneity of the phases results in a strong non-uniformity and anisotropy in the behaviour of the mixed formations, with mechanical parameters which differ significantly in the various horizons according to the lithological composition and physical state of the formation. Therefore, sandstones, marls and conglomerates usually present high values in both shear and compressive strength, while sands and clays present wide fluctuation in the values of their mechanical parameters. Landslide phenomena are limited in the weathered horizons of the fine-grained phase. Rockfalls can be observed in the cohesive conglomerates. The range of values of the main mechanical parameters is presented in Table 4.

4.3. Formations of the Alpine bedrock

Eight (8) engineering-geological units were derived:

UNIT 6 (F): Flysch.

This unit consists of shales, siltstones and sandstones in alternate layers. Locally, conglomerates, grits or marls also participate, while calcareous schists and limestones or marly limestones are even more rarely interbedded. This formation is intensely fractured and folded. Surface beds show a medium to strong weathering and a dense net of discontinuities, causing intense secondary looseness. In macro-scale, flysch is considered as an impermeable formation, allowing the occurrence of small springs, usually between the fragmentation zones or weathering mantle and bedrock.

Flysch is characterized by an obvious instability, which is usually connected with the numerous heterogeneous layer contacts and the steep bed inclinations, in conjunction with the strong relief and the action of water. Problems connected with foundation of technical projects, especially in road construction, are very common. In general, geotechnical behaviour presents a clear anisotropy and rapid changes, controlled by the degree of looseness, the orientation of discontinuities, the dip of slopes and the action of water. Landslide phenomena occur with an increased frequency, usually affecting the weathering mantle and the upper fragmentation zone. The range of values of the main mechanical parameters is presented in Table 5.

Table 2. Descriptive statistics for the main physical properties and mechanical parameters of fines of the deposits of unit 2.

	LL (%)	PI (%)	w (%)	γ_b (kN/m^3)	γ_d (kN/m^3)	Gs	e	n (%)
min	16.80	1.00	2.44	13.00	8.00	2.39	0.310	23.66
max	99.00	70.50	124.70	28.00	23.51	2.86	2.390	69.58
average	42.14	22.79	25.70	20.05	16.13	2.65	0.689	40.70
standard deviation	13.83	12.05	7.93	1.19	1.53	0.08	0.21	5.61
number of samples	3,324	3,324	2,544	2,204	1,632	524	1,522	931
	c_s (kPa)	φ_s (°)	c_u (kPa)	φ_u (°)	c (kPa)	φ (°)	c′ (kPa)	φ ′ (°)
min	0.00	2.00	7.00	0.00	3.00	1.20	0.00	1.20
max	183.20	41.33	414.00	50.50	117.00	35.00	121.00	39.00
average	33.68	24.69	78.99	8.03	46.29	20.13	39.23	23.33
standard deviation	29.70	8.30	61.20	7.20	20.20	7.30	23.20	7.90
number of samples	161	161	366	362	120	120	141	141
	q_u (kPa)	Cc	e_o					
min	4.50	0.060	0.229					
max	995.00	0.835	1.925					
average	177.88	0.196	0.731					
standard deviation	130.80	0.10	0.20					
number of samples	1,430	551	523					

Symbols as described in Table 1.

Table 3. Descriptive statistics for the main physical properties and mechanical parameters of fines of the deposits of unit 3.

	LL (%)	PI (%)	w (%)	γ_b (kN/m^3)	γ_d (kN/m^3)	Gs	e	n (%)
min	15.10	0.20	1.10	14.56	10.10	2.41	0.19	15.87
max	49.00	33.00	55.00	24.93	22.80	2.77	1.52	60.39
average	25.04	9.33	18.48	20.26	17.16	2.63	0.54	31.79
standard deviation	6.93	6.44	7.46	1.64	1.96	0.07	0.19	9.69
number of samples	268	268	292	206	165	119	110	26
	c_s (kPa)	φ_s (°)	c_u (kPa)	φ_u (°)	c (kPa)	φ (°)	c′ (kPa)	φ ′ (°)
min	0.00	11.00	10.00	0.00	17.00	25.00	0.00	29.00
max	128.00	47.00	245.60	48.00	25.30	29.00	25.00	40.00
average	27.64	30.62	77.72	16.22	22.43	27.33	13.55	34.00
standard deviation	27.10	8.48	72.77	13.23	4.71	2.08	10.28	4.55
number of samples	57	57	13	13	3	3	4	4
	q_u (kPa)	Cc	e_o					
min	18.00	0.040	0.278					
max	356.00	0.450	1.533					
average	118.75	0.119	0.623					
standard deviation	97.28	0.07	0.22					
number of samples	42	46	44					

Symbols as described in Table 1.

UNIT 7 (L-si): Limestones (Upper-Cretaceous) with nodules or lenticular silica layers.

This unit is composed of thin to medium-bedded limestones, often microbrecciated, with nodules or lenticular silica layers and locally thin intercalations of shales. The rockmass behaviour presents a characteristic anisotropy and non-uniformity and is controlled by the density of chert and schist interbeds. The increased density of discontinuities and the heterogeneous contacts reduce the shear strength and increase the instability on sleep slopes. Extended landslide phenomena have been observed in these formations. The range of values of the main mechanical parameters is presented in Table 5.

UNIT 8 (L): Limestones (Cretaceous to Jurassic).

This unit is composed of compact limestones, thin to thick-bedded or unbedded, locally brecciated or crystalline or marly, giving extended talus cones at places. The upper beds are usually fractured and strongly karstified. The intact rock is characterized by high values of strength pa-

Table 4. The range of values of the main mechanical parameters of the Post-Alpine sediments.

		c (MPa)	φ (°)	c_s (MPa)	φ_s (°)	q_u (MPa)	σ_c (MPa)	$I_{S(50)}$ (MPa)	E (GPa)
UNIT 4	(4a)	0.005-0.29	10-40	0.003-0.1	20-50	0.02-1.08	2.5-63	0.21-6.5	7-35
	(4b)	0.2-7.5	25-55						
UNIT 5	(5a)	0.02-0.29	10-40			0.02-2.50	12.9-135.14	0.36-6.04	1-20
	(5b)	0.3-8	17-55						13.53-21.25

(4a) Clays, silts, sandy silts, marls.
(4b) Sandstones, conglomerates, marly limestones.
(5a) Clayey-marls, marls.
(5b) Sandstones, conglomerates.

c: cohesion from triaxial compression tests (MPa), φ: angle of friction from triaxial compression tests (°), c_s: cohesion (MPa) from shear tests along discontinuities, φ_s: angle of friction (°) from shear tests along discontinuities, q_u: unconfined compressive strength (MPa), σ_c: unconfined compressive strength (MPa), $I_{S(50)}$: standard point load strength index (MPa) and E: modulus of elasticity or Young's modulus (GPa).

Table 5. The range of values of the main mechanical parameters of the formations of the Alpine bedrock.

		c (MPa)	φ (°)	σ_c (MPa)	$I_{S(50)}$ (MPa)	E (GPa)
UNIT 6	Shales-siltstones	0.6-10	20-35	5-40	1-3	3-14
	Sandstones	1-20	25-45	7.2-120	1-5	7-50
UNIT 7		10-30	30-45	6-170	1-7	2-100
	These values refer to intact rock. The behaviour of the rock as a whole is controlled by much lower values, mainly the shear strength ones (along discontinuities with clay filling and with a thickness up to 1cm): c_s =10-100 kPa, φ_s =13°-22°					
UNIT 8		0.5-10	29-45	6-135	2-7.5	2-92
	These values refer to intact rock					
UNIT 9	Limestones	10-30	25-45	30-120	2-7.5	2-92
	Cherts	20-35	30-48	20-190		8-40
	Schist-marly layers	1-3	28-35	7-40		
	These values characterize the intact rock. The behaviour of the rock as a whole is controlled by much lower values, mainly the shear strength ones (along discontinuities with secondary filling): c_s =25-750 kPa, φ_s =4°-30°					
UNIT 10	Cherts	20-35	25-38	10-190	0.91-6.93	5-40
	Shales-siltstones	0.5-2	30-35	7-15		3-14
UNIT 11		25-55	40-50	18.5-82	1.51-3.68	3.5- 44
UNIT 12		10-30	35-45	50-250	2-8.5	70-100
UNIT 13		4-40	28-48	10-180	1-7	4-25

Symbols as described in Table 4.

rameters, while the rockmass shows medium to high permeability and satisfactory geomechanical behaviour for the foundation of technical works. Failures are usually observed as rockfalls on steep slopes. The range of values of the main mechanical parameters is presented in Table 5.

UNIT 9 (L-sh): Limestones (Cretaceous to Triassic), alternating with cherts, schist-cherts or schist-marly layers.

This unit consists of limestones and thin alternations of cherts, shales, siltstones, marly limestones, marls or silica layers. They are intensively folded and fractured. The geotechnical behaviour of the rockmass is mainly determined by the physical condition of the formation and its lithological composition and to a smaller extend by the mechanical parameters of the various phases. The range of values of the main mechanical parameters is presented in Table 5.

UNIT 10 (sh): Shales and cherts (Cretaceous to Triassic).

This unit is composed of thin alternations of shales and cherts with scattered thin-bedded limestones, sandstones and siltstones. They are intensively fractured and folded. The mechanical behaviour of the rockmass on the slopes is

Table 6. Frequency and relative frequency distribution of landslides in relation to the engineering-geological units.

Unit	Area (km^2)	Area (%)	Landslide occurrences	Landslide frequency (%)	Landslide relative frequency (%)
1	588.21	9.65	13	1.33	0.91
2	1716.98	28.18	0	0.00	0.00
3	266.04	4.37	0	0.00	0.00
4	178.52	2.93	0	0.00	0.00
5	585.34	9.61	124	12.67	8.68
6	1083.10	17.78	572	58.43	21.64
7	93.16	1.53	53	5.41	23.31
8	343.71	5.64	19	1.94	2.27
9	79.24	1.30	39	3.98	20.17
10	181.23	2.97	59	6.03	13.34
11	452.27	7.42	87	8.89	7.88
12	114.36	1.88	2	0.20	0.72
13	410.66	6.74	11	1.12	1.10

characterized by low shear strength but, in gently inclined areas, the compression strength is satisfactory. Landslide phenomena mainly occur in the thick weathering mantle and the fractured zone. The range of values of the main mechanical parameters is presented in Table 5.

UNIT 11 (σ): Basic and ultrabasic igneous rocks.

This unit is composed of ophiolites, peridotites, serpentinized peridotites, pyroxenites, dunites, diabases, dolerites, basalts, diorites, gabbros, granites, etc. In the upper parts they are strongly altered and weathered, covered by thick mantle. They are impermeable, but the intensively fractured zones present increased permeability. The values of their mechanical parameters are definitely influenced by the natural state of the rockmass (degree of alteration-weathering and fracturing density). The range of values of the main mechanical parameters is presented in Table 5.

UNIT 12 (mr): Crystalline limestone–marble.

This unit consists of micro or coarse-crystalline limestone–marble, often of great thickness and extended surface development in the areas of metamorphic masses. These are compact, medium to thick-bedded rock, homogeneous and highly permeable. They present high strength parameters and good behaviour in the foundations of technical projects. The range of values of the main mechanical parameters is presented in Table 5.

UNIT 13 (gn,sh): Metamorphic rocks.

This formation consists of gneisses, mica-amphiboles and other schists, quartzites and amphibolites with frequent marble and cipolin interbeds. Locally, phyllites occur in alternating layers of schists, sandstones, quartzites and thin red limestones. They are impermeable formations with perfect schistosity and great thickness, characteristic homogeneity and satisfactory uniform behaviour in static and dynamic loadings. In the unweathered state, they present high strength parameters. The range of values of the main mechanical parameters is presented in Table 5.

5. Natural Hazards

5.1. Landslide movements

The west Thessaly region suffers from numerous landslide events. A simple statistical evaluation of the available recordings was applied for the estimation of the engineering geological data regarding lithology and geomechanical characteristics of the affected materials [50]. An extremely high landslide number of 979 recorded landslides (Figure 4) was evaluated leading to the following conclusions (Table 6):

- The highest landslide frequency (58.43%) is recorded for flysch (formations of unit 6). If the geographical area covered by each lithological type within the study area is also taken into account, it appears that the frequency of the landslides on flysch still remains dominant (area 1,083.10 km^2, 17.78%). In addition, the increased percentage (Table 6) of the landslide relative frequency (frequency normalized to the real area covered by each lithological type) on limestones with nodules or lentic-

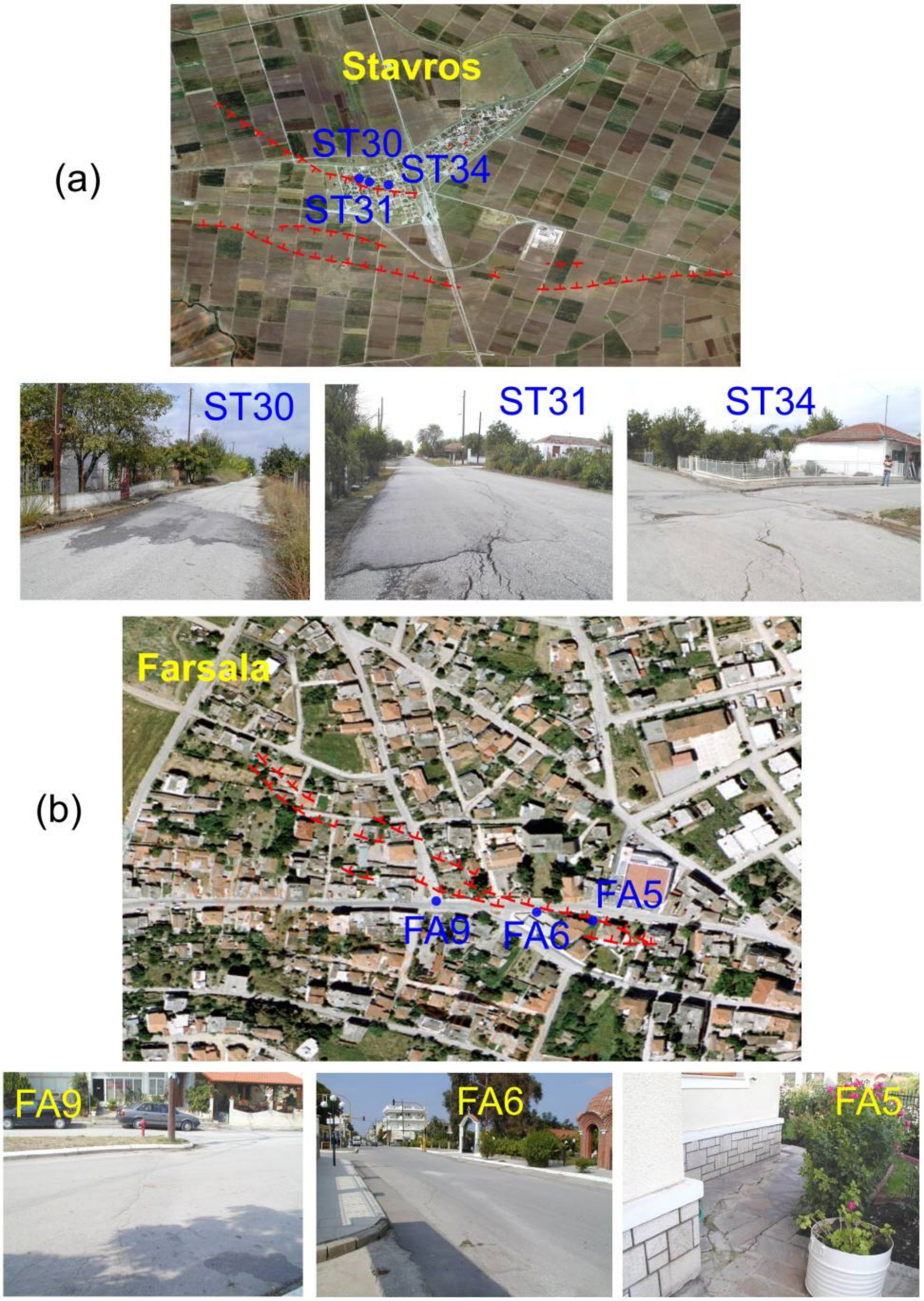

Figure 5. Satellite pictures pointing to the location of some surface ruptures near the towns of Stavros (a) and Farsala (b). Pictures ST30, ST31 and ST34 (a) and FA9, FA6 and FA5 (b) show some roads and buildings damaged by the surface ruptures.

ular silica layers (formations of unit 7) or on limestones, alternating with schist-cherts (formations of unit 9) is due mainly to their restricted extent of coverage in the study area (1.53% and 1.30% respectively). It should be noted that in the loose fine-grained deposits of unit 2 (area 1,716.98 km^2, percentage 28.18%) landslide phenomena are not recorded.

- Regarding the type of movement, the largest percentage (70.00%) is found to be rotational landslides in argillaceous sediments (flysch and molasses).

- The greatest percentage of landslides (47.01%) occurs on areas having an elevation between 600 and 1,000 m. If the spatial extent of elevation classes is taken into account, it is proved that a linear relationship between landslide frequency and elevation exists.

- Considering the frequency of the mean annual height of the rainfall, it is derived that for the 85.49 % of cases corresponds to a mean annual precipitation height greater than 800 mm, while it is largest, percentage occurs in the precipitation categories of 1,000 – 1,600 mm (49.64%) and 800 – 1,000 mm (35.24%). It should be noted that most landslides occur during the period of heavy rainfall, while during the rest of the year a significant decrease is observed both for the initial movement and for the reactivation.

- The greatest percentage of landslides (68.95%) is located in areas with surface slope between 15° and 45°. A percentage of 57.71% of this portion corresponds to areas with surface slope between 15° and 30°.

5.2. Land subsidence due to excessive ground-water pumping

In the centre of the town of Farsala (Figure 4), an area extending 50 m x 360 m (Figure 5b), was intensively damaged by land subsidence phenomena. The road pavements present multiple fractures, reactivated after any repairing work. Several buildings were affected by the ruptures and were intensively damaged, requiring expensive reconstruction work. Small ground ruptures have also been observed in the northern part of the town, in an area covering 180 m x 200 m. Beyond the south western limits of the town and at the west of the railway line, two more extensive ruptures were observed, with total length 1,000 m and 2,500 m respectively. The northern one has a mean azimuth of about 100° and shows a vertical displacement at a range of 20 to 50 cm. The southern rupture, with a mean azimuth of about 110°, presents a vertical displacement of 15 to 150 cm [26, 27].

In addition, in the town of Stavros (Figure 4), the main ground rupture was found to the west of the railway line. This tensile rupture has a total length of about 2,100 m, an azimuth of 105° and a vertical displacement 60 cm (Figure 5a). The trace of the rupture affects road pavements and numerous buildings. The buildings founded along the trace of the ruptures show a degree of damage, such as cracks in the stonework, distortions in doors, windows, stockyards and pavements. In addition, several ground ruptures are located in the south of the town, intersecting cultivated areas [26, 27]. The study of these phenomena is a useful tool for urban and regional planning [51].

6. Conclusions and discussion

From the above analysis, regarding the compilation of the engineering-geological map of the Western Thessaly basin, the following remarks can be made:

- For the preparation of the engineering-geological map, both extended fieldwork and an evaluation of 1,039 boreholes and investigations pits were used. Thirteen (13) engineering-geological units have been distinguished. Special attention was given to thoseunits which occur in inhabited zones, as well as in industrial areas, in terms of avoiding problems for the future development of the Western Thessaly basin. For every unit, the range of values of the main physical properties and mechanical parameters was examined and a general description of their geomechanical behaviour was given.

- The results of this study were evaluated for the determination of the ground foundation conditions of the Western Thessaly basin, this providing a useful guide for urban planning and for planning construction and technical projects. However, such maps cannot be considered a substitute for in situ geotechnical investigations at the microscale for every individual construction project.

References

[1] Rozos D., Apostolidis E., Xatzinakos I., Engineering-geological map of the wider Thessaloniki area, Greece. *Bull. Eng. Geol. Environ.*, 2004, 63, 103-108

[2] Geological Society of London, The Geological Society Engineering Group Working Party, The preparation of maps and plans in terms of Engineering Geology. *Q. J. Eng. Geol.*, 1972, 5, 293-381
[3] UNESCO/I.A.E.G., Engineering geological maps - A guide to their preparation. The UNESCO Press, Paris, 1976
[4] I.A.E.G., Commission of Engineering Geological mapping of the I.A.E.G., Part I., Rock and Soil materials, Classification of rocks and soils for engineering geological mapping. *Bulletin of International Association for Engineering Geology and the Environment*, 1979, 19, 364-371
[5] I.A.E.G., Commission of Engineering Geological mapping of the I.A.E.G., Rock and Soil description for engineering geological mapping. *Bulletin of International Association for Engineering Geology and the Environment*, 1981, 24
[6] Dearman W., Matula M., Environmental aspects of Engineering Geological Mapping. *Bulletin of International Association for Engineering Geology and the Environment*, 14, 141-146, 1976
[7] Matoula M., Hrasna H., Vleko J., Regional Engineering geological maps for land use planning documents. Proceedings of 5th International I.A.E.G. Congress, Buenos Aires, Balkema, Rotterdam, 1986, 1821-1827
[8] Bell F., Engineering properties of soils and rocks. Butterworth Co. Ltd., London, 1981
[9] Carter M., Geotechnical Engineering Handbook, London, 1983
[10] IGME, Engineering geological map of Greece (1:500,000 in scale), Athens, 1993
[11] Sabatakakis N., Engineering geological research of Athens Basin. PhD thesis, University of Patras - Department of Geology, Greece, 1991 (in Greek, with summary in English)
[12] Koukis G., Sabatakakis N., Engineering geological environment of Athens, Greece. *B. Eng. Geol. Environ.*, 2000, 59, 127 – 135
[13] Kynigalaki M., Nikolaou N., Karfakis J., Koutsouveli A., Poyiadji E., Pyrgiotis L., Konstantopoulou G., Bellas M., Apostolidis E., Loupasakis K., Spanou N., Sabatakakis N., Koukis G., Digital engineering geological map of the Athens Prefecture area and related Database Management System. *Bull. Geol. Soc. Greece*, 2010, 43, 1619-1626
[14] Rozos D., Xatzinakos I., Apostolidis E., Engineering geological mapping and related geotechnical problems in the wider industrial area of Thessaloniki, Greece. Proceedings of the 6th International Congress of Engineering Geology (I.A.E.G.), Amsterdam, 1990, 1, 127-134
[15] Hadzinakos I., Rozos D., Apostolidis E., Engineering geological mapping and related geotechnical problems in the wider industrial area of Thessaloniki, Greece. Proceedings of 6th International I.A.E.G. Congress, Balkema, Rotterdam, 1990, 127-134
[16] Rozos D., Koukis G., Sabatakakis N., Large-scale engineering map of the Patras city wider area, Greece. The Geological Society of London, I.A.E.G., 2006, 241
[17] Koukis G., Tsiambaos G., Sabatakakis N., Engineering geological-geotechnical conditions of Patras city, Greece. Bulletin of the Central Public Works Laboratory, Athens, 1994, 121-124, 3-23
[18] Koukis G., Rozos D., Sabatakakis N., Engineering geological map of Patras city wider area, Greece. *Bull. Geol. Soc. Greece*, 2001, 34, 1679-1687
[19] Tsiambaos G., Sabatakakis N., Koukis G., Engineering geological environment and urban planning of the city of Patras, Greece. Proceedings of the International Symposium on Engineering Geology and the Environment, I.A.E.G., 1997, 2, 1527-1534
[20] Koukis G., Rozos D., Apostolidis E., Engineering geological conditions of the formations in the wider area of the city of Trikala (Thessaly, Greece). Proceedings of the 3rd Hellenic Conference on geotechnical engineering, Patras, 1997, 1, 113-120
[21] Pyrgiotis L., Engineering geological conditions in Karditsa County - Landslides phenomena in flysch formations. PhD thesis, University of Patras - Department of Geology, Greece, 1997 (in Greek, with summary in English)
[22] Apostolidis E., Koutsouveli A., Engineering geological mapping in the urban and suburban region of Nafplion city (Argolis, Greece). Proceedings of the 12th International Congress, *Bull. Geol. Soc. Greece*, 2010, 53, 1418-1427
[23] Koukis G., Rozos D., Geotechnical conditions and landslide phenomena in Greek territory in relation with geological structure and geotectonic evolution. Oryctos Ploutos, 1982, 16, 53–69, Athens (in Greek, with summary in English)
[24] Koukis G., Slope deformation phenomena related to the engineering geological conditions in Greece. Proceedings of the 5th International Symposium on Landslides, Switzerland, 1988, 2, 1187-1192
[25] Rozos D., Pyrgiotis L., Skias S., Tsagaratos P., An implementation of rock engineering system for ranking the instability potential of natural slopes in Greek territory. An application in Karditsa County. *Landslides*, 2008, 5, 261-270
[26] Apostolidis E., Georgiou C., Engineering Geological of the surface ground ruptures in Thessaly basin sites - Recording and documentation. Institute of Geology

and Mineral Exploration (IGME), Athens, 2007, unpublished report (in Greek)

[27] Rozos D., Sideri D., Loupasakis C., Apostolidis E., Land subsidence due to excessive ground water withdrawal - A case study from Stavros-Farsala site, West Thessaly, Greece. Proceedings of the 12th International Congress, *Bull. Geol. Soc. Greece*, 2010, 43, 1850-1857

[28] Migiros G., Bathrellos G., Skilodimou H., Karamousalis T., Pinios (Peneus) River (Central Greece): Hydrological — Geomorphological elements and changes during the Quaternary. *Cent. Eur. J. Geosci.*, 2011, 3, 215–228

[29] Kamberis E., Bathrellos G., Kokinou E, Skilodimou H., Correlation between the structural pattern and the development of the hydrographic network in the area of Western Thessaly basin (Greece). *Cent. Eur. J. Geosci.*, 2012, 4, 416-424

[30] Aubouin J., Contribution a l'étude géologique de la Grčce septentrionale: le confins de l'Epire et de la Thessalie. *Ann. Geol. Pays Hellen.*, 1959, 10, 1-484

[31] Ferriere J., Reynaud J., Pavlopoulos A., Bonneau M., Migiros G., Proust J., Gardin S., Geological evolution and geodynamic controls of Tertiary intramontane piggyback Meso-Hellenic Basin, Greece. *Bull. Soc. Geol. Fr.*, 2004, 175, 361-381

[32] Ferriere J., Chanier F., Reynaud J., Pavlopoulos A., Ditbanjong P., Migiros G., Coutand I., Stais A., Bailleul J., Tectonic control of the Meteora conglomeratic formations (Mesohellenic basin, Greece). *Bull. Soc. Geol. Fr.*, 2011, 182, 437-450

[33] Bathrellos G., Geological, geomorphological and geographic study of urban areas in Trikala Prefecture – Western Thessaly, Ph.D. thesis, National and Kapodistrian University of Athens, Athens, Greece, 2005 (in Greek with extended English abstract)

[34] Bathrellos G., Gaki-Papanastassiou K., Skilodimou H., Skianis G., Chousianitis K., Assessment of rural community and agricultural development using geomorphological-geological factors and GIS in the Trikala prefecture (Central Greece). *Stoch. Env. Res. Risk A.*, 2013, 27, 573-588

[35] Caputo R., Geological and structural study of the recent and active brittle deformation of the Neogene–Quaternary basins of Thessaly (Central Greece). Ph.D. thesis, Aristotle University of Thessaloniki, 1990

[36] Caputo R., Pavlides S., Late Cainozoic geodynamic evolution of Thessaly and surroundings (central-northern Greece). *Tectonophysics*, 1993, 223, 339-362

[37] Marinos P., Thanos M., Perleros V., Kavadas M., Water dynamic of Thessaly basin and the consequences from its overexploitation. Proceedings of the 3rd Hydrogeological Congress, 1995, Heraklion, Crete (in Greek)

[38] Marinos P., Perleros V., Kavadas M., Deposited and karstic aquifers of Thessaly plain. New data for the status of their overexploitation. Proceedings of the 4th Hydrogeological Congress, 1997, Athens (in Greek)

[39] Kontogianni V., Pytharouli S., Stiros S., Ground subsidence, Quaternary faults and vulnerability of utilities and transportation networks in Thessaly, Greece. *Environ. Geol.*, 2007, 52, 1085-1095

[40] Vassilopoulou S., Sakkas V., Wegmuller U., Capes R., Long Term and Seasonal Ground Deformation Monitoring of Larissa Plain (Central Greece) by Persistent Scattering Interferometry. *Cent. Eur. J. Geosci.*, 2013, 5, 61-76

[41] Papazachos B., Comninakis P., Scordilis E., Karakaisis G., Papazachos, C., A catalogue of earthquakes in the Mediterranean and surrounding area for the period 1901–2010. Publication of the Geophysical Laboratory of the University of Thessaloniki, 2010, Thessaloniki.

[42] Papazachos B., Papazachou C., The earthquakes of Greece, Ziti Editions, Thessaloniki, 1997

[43] Bossard M., Feranec J., Otahel J., CORINE land cover technical guide-Addendum 2000. European Environment Agency, Copenhagen, 2000

[44] Ilia I., Rozos D., Perraki T., Tsangaratos P., Geotechnical and mineralogical properties of weak rocks from Central Greece. *Cent. Eur. J. Geosci.*, 2009, 1, 431-442

[45] Bathrellos G., Kalivas D., Skilodimou H., GIS-based landslide susceptibility mapping models applied to natural and urban planning in Trikala, Central Greece. *Estud. Geol.*, 2009, 65, 49–65

[46] Bathrellos G., Gaki-Papanastassiou K., Skilodimou H., Papanastassiou D., Chousianitis K., Potential suitability for urban planning and industry development by using natural hazard maps and geological-geomorphological parameters. *Environ. Earth Sci.*, 2012, 66, 537–548

[47] Rozos D., Bathrellos G., Skilodimou H., Comparison of the implementation of Rock Engineering System (RES) and Analytic Hierarchy Process (AHP) methods, based on landslide susceptibility maps, compiled in GIS environment. A case study from the Eastern Achaia County of Peloponnesus, Greece. *Environ. Earth Sci.*, 2011, 63, 49–63

[48] Rozos D., Skilodimou H., Loupasakis C., Bathrellos G., Application of the revised universal soil loss equation model on landslide prevention. An example from

N. Euboea (Evia) Island, Greece. *Environ. Earth Sci.*, 2013, DOI 10.1007/s12665-013-2390-3

[49] Kouli M., Loupasakis C., Soupios P., Vallianatos F., Landslide hazard zonation in high risk areas of Rethymno Prefecture, Crete Island, Greece. *Nat. Hazards*, 2010, 52, 599–621

[50] Koukis G., Sabatakakis N., Nikolaou N., Loupasakis C., Landslide hazard zonation in Greece. Proceedings of open symposium on landslide risk analysis and sustainable disaster management in the First General Assembly of International Consortium on landslides. Springer, Berlin, 2005, 37, 291–296

[51] Papadopoulou-Vrynioti K., Bathrellos G., Skilodimou H., Kaviris G., Makropoulos K., Karst collapse susceptibility mapping using seismic hazard in a rapid urban growing area. *Eng. Geol.*, 2013 158, 77-88, doi: 10.1016/j.enggeo. 2013.02.009