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Development of comprehensive earthquake loss scenarios for a Greek and a Turkish city: seismic hazard, geotechnical and lifeline aspects

Kyriazis D. Pitilakis*, Anastasios I. Anastasiadis, Kalliopi G. Kakderi, Maria V. Manakou, Dimitra K. Manou, Maria N. Alexoudi, Stavroula D. Fotopoulou, Sotiris A. Argyroudis and Kostas G. Senetakis

Aristotle University, Department of Civil Engineering, Research Unit of Geotechnical Earthquake Engineering and Soil Dynamics, 54124, Thessaloniki, Greece

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Abstract. The development of reliable earthquake mitigation plans and seismic risk management procedures can only be based on the establishment of comprehensive earthquake hazard and loss scenarios. Two cities, Grevena (Greece) and Düzce (Turkey), were used as case studies in order to apply a comprehensive methodology for the vulnerability and loss assessment of lifelines. The methodology has the following distinctive phases: detailed inventory, identification of the typology of each component and system, evaluation of the probabilistic seismic hazard, geotechnical zonation, ground response analysis and estimation of the spatial distribution of seismic motion for different seismic scenarios, vulnerability analysis of the exposed elements at risk. Estimating adequate earthquake scenarios for different mean return periods, and selecting appropriate vulnerability functions, expected damages of the water and waste water systems in Düzce and of the roadway network and waste water system of Grevena are estimated and discussed; comparisons with observed earthquake damages are also made in the case of Düzce, proving the reliability and the efficiency of the proposed methodology. The results of the present study constitute a sound basis for the development of efficient loss scenarios for lifelines and infrastructure facilities in seismic prone areas. The first part of this paper, concerning the estimation of the seismic ground motions, has been utilized in the companion paper by Kappos *et al*. (2010) in the same journal.

Keywords: site effects; seismic scenarios; microzonation; lifelines; infrastructures; vulnerability; Grevena; Düzce.

1. Introduction

Seismic vulnerability assessment is used to quantify potential losses in a given region or to a particular portfolio of lifelines and critical facilities, due to future earthquakes. The existence of preparedness plans based on the assessment of the impact of earthquakes and the minimization of their consequences are the most important tasks of civil protection. To fulfill these tasks, comprehensive earthquake loss scenarios have to be developed, in order to reduce the expected losses and improve the recovery actions. In the present paper, we selected two cities, one in Greece

* Corresponding author, Professor, E-mail: kpitilak@civil.auth.gr

Fig. 1 Location of the two cities: Grevena (Greece) and Düzce (Turkey)

(Grevena) and one in Turkey (Düzce) (Fig. 1) in order to describe a comprehensive earthquake loss scenarios methodology for lifelines and critical facilities. We present herein the main results of the methodology to estimate the site-specific seismic hazard for the two cities and the lifeline losses. The vulnerability assessment of the building stock, using the site-specific ground motion scenarios presented herein, has been presented in a previous companion paper (Kappos *et al*. 2010).

Düzce, characterized by very high seismicity, is located very close to the North Anatolian Fault (NAF), one of the most seismogenic faults in the world. The latest event occurred in 1999 ($M_s = 7.2$), following the even larger Kocaeli earthquake ($M_s = 7.8$), less than one hundred kilometers away, always along the North Anatolian Fault. The Kocaeli earthquake ($M_s = 7.8$), affected residential parts and several cities, including Düzce. Many buildings were completely destroyed in the residential districts, the Istanbul-Ankara expressway and the railway were seriously damaged, and communications were perturbed for several days. The death toll of this earthquake was very high (15,851), while the reported injuries were 43,953. The total number of house units collapsed and heavily damaged was 66,403, while the total economic losses are estimated, according to the United Nations, to 25 Billion USD (Ural 1999) equal to 12% of the Turkish GNP (1999). In November 12, the Düzce earthquake ($M_s = 7.2$), devastated the two towns of Kaynasli and Düzce, already affected by the previous Kocaeli earthquake, and killed about 1000 people. Extensive damages were observed in the water and waste water systems of Düzce.

Grevena, a small town in Northern Greece, was supposed to be of low seismicity. Unexpectedly in 1995 was struck by a strong earthquake ($M = 6.5$), which resulted to serious damages and important economic losses, but fortunately no fatalities. The maximum observed macroseismic intensity was IX + of the Modified Mercalli scale (Papanastassiou *et al*. 1998). Thousands of people remained homeless and the social infrastructure was severely affected. More than 1,000 houses of different typologies, (mostly 1-2 story masonry buildings of poor quality), collapsed in the affected area, and more than 10,000 buildings were damaged beyond repair. No major damages are reported in the water and waste water system.

Taking into account the serious consequences from the earthquakes, the spatial distribution of ground motion and the complexity and variability of lifeline components, a serious challenge for modern societies is to reduce the impact of earthquakes in lifelines, either by taking pre-earthquake strengthening measures, or by establishing efficient post- mitigation strategies. Comprehensive earthquake loss scenarios can only accomplish all these.

The aim of this paper is two-fold: (a) to describe a comprehensive site-specific probabilistic hazard assessment methodology adequate to the vulnerability and loss assessment for lifelines and critical facilities; (b) to apply the methodology in two cities in Turkey and Greece, recently affected by strong earthquakes. Results and assumptions in every step of the proposed methodology are discussed in order to highlight the applicability and the efficiency in other seismic prone areas. Moreover the site specific hazard assessment has been used in a companion paper by Kappos *et al.* (2010) for the loss assessment of buildings.

2. Methodology

The general framework of the methodology developed for the vulnerability assessment and risk management at a city or regional level, concerning buildings, utility networks (potable water, waste-water, gas, electric power, telecommunication, fire-fighting), transportation systems (roadway, railway, airport, port) and critical facilities, is illustrated in Fig. 2. Loss estimates including direct and indirect losses, depend on the existing inventory and typology classification of the elements at risk, the vulnerability models and the existing interactions between lifeline components. The level of seismic input motion, (in terms of efficient intensity measure parameters), is defined on the basis of probabilistic hazard scenarios and site-specific ground response analyses. Finally, the related uncertainties due to inventory data, seismic hazard analysis and vulnerability should be taken into consideration.

Inventory is an essential step to identify, characterize and classify all types of lifeline elements according to their specific typology and their distinctive geometric, structural and functional features. Geographical information systems (GIS) offer the powerful platform to implement any inventory inquires. Within this context, earthquake damage is directly related to structural properties and geometry of lifeline elements. Typology is thus a fundamental descriptor of a system, derived from the inventory of each element at risk. Seismic hazard provides in probabilistic terms the

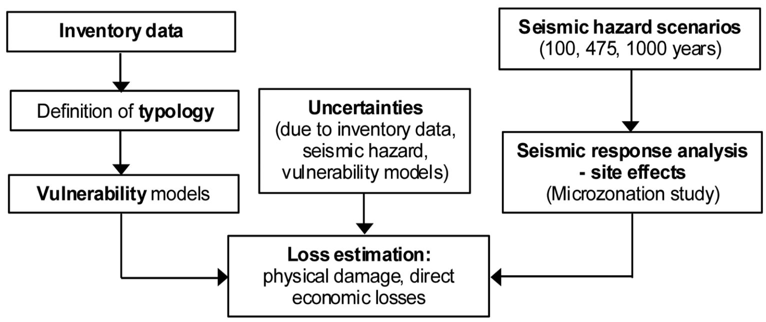


Fig. 2 Methodology for earthquake loss assessment

seismic load imposed to lifelines, utilities and infrastructures. It should be specified according to the particular lifeline components and networks and is essential input for the vulnerability analysis of the elements at risk. Taking into account the spatial extent of lifeline systems and the variability of ground motion, the influence of local soil conditions is of great importance (Pitilakis *et al*. 2006). Specific geotechnical and surface geology information is required; site specific ground response studies should be performed to estimate the necessary ground shaking parameters, in terms of seismic scenarios with different mean return periods. These studies were traditionally referred as “microzonation studies”, and this terminology will be used in the present paper, together with the more focused one described as site specific analysis, considering the vulnerability and loss assessment needs for every lifeline system and other assets exposed. Adequate models and fragility relationships (deterministic, statistical or probabilistic) that correlate component’s damage states, functionality, economic losses etc, with an appropriate measure of the intensity of the earthquake hazard, are used to describe vulnerability. The assessment of the seismic performance of a system is based on the estimation of the vulnerability of the components and the possible damages related to the level of seismic hazard intensity and the typology of each component and system.

Besides the great inherent uncertainties, the key assumption in the vulnerability assessment of lifeline and utility systems is that structures having similar structural characteristics, being in similar geotechnical conditions, are expected to perform in the same way for a given seismic loading. The spatial variability of the ground motion, which is one of the major causes of lifeline damages, is due mainly to the differential site amplification characteristics inherent to the local site conditions. Basin edge and azimuth effects may be also considered through appropriate 2D or/and 3D modeling of ground motion, which may modify the final ground motion for the vulnerability assessment (Pitilakis *et al*. 2001, Pitilakis *et al*. 2010, Paolucci and Pitilakis 2007). Thus, the respective fragility functions are defined on the basis of the typological characteristics of the elements at risk, taking also into consideration specific construction practices and distinctive features affecting their seismic behavior.

3. Seismic scenarios - site specific ground response analysis

Site-specific ground response analysis has been performed for the two cities, for different earthquake scenarios, based on one hand on the available geological, seismological and geotechnical data, and on the other hand on specific geotechnical and geophysical surveys performed for the purposes of this study.

3.1 Geological and morphological setting

Grevena

The morphological unit of Grevena presents a relatively smooth relief with characteristic planation surfaces developed either over the molassic formations of the Meso-Hellenic Trench, or the Plio-Pleistocene sediments. The area is situated in the western margin of the Pelagonian geotectonic zone and partly to the eastern part of the Subpelagonian zone. The basement of the area consists of pre-Alpine and Alpine rocks of Paleozoic, Mesozoic and Tertiary age. The geological bedrock can be classified into four units, which from the bottom to the top consist of a) crystalline rocks of the Pelagonian zone (gneisses, amphibolites, mica-shists, meta-granites), b) Triassic-Jurassic recrystallized limestones, c) thrust ophiolites and deep-sea sediments of the Subpelagonian zone, and d) Cretaceous pelagic limestones and Tertiary flyschs (Brunn 1956, Pavlides and Mountrakis 1987). The major part of the area of the city is covered by fluvial and lacustrine deposits, which overlie un-conformably the molassic sediments or the Alpine basement. While in general the lithological character of the deposits varies, it is reasonably accepted that it mainly consists of unconsolidated conglomerates, gravels, sands and silty sands with sandstone intercalations and silty lenses (Pavlides and Mountrakis 1987).

Düzce

Düzce is situated in a tectonic basin filled over time with river and lake sediments fluvial, stream and lacustrine deposits, which vary rapidly in vertical and horizontal direction, from one site to another. The alpine bedrock that is outcropping at the southern part of the basin, near the Beykoy village, consists of metagranites and granodiorites of Paleozoic and Precambrian age. To the north the basement consists of shale, sandstone and siltstone alternations of Devonian age. The bedrock is un-conformably overlain to the east by the Cretaceous Akveren formation which consists of conglomerate, sandstone, clayey limestone and marly alternations. To the southwest part andesites, spilites and agglomerates are located. The sediments thickness of the basin is about 200-250 m.

The Tertiary Kusuri formation observed to the north, northwest of the city comprises sandstones-mudstones, agglomerates and pyroclastics. The aforementioned units are covered by the Quaternary aged Orencik formation which are composed of loosely cemented, rounded and well sorted pebble-sands and silts. The Quaternary alluvial deposits according to Simsek and Dalgic (1997) consist of: (a) river alluviums (northern and southern parts of Düzce city) composed of sand-pebbles, limestone and magmatic rock blocks, (b) lacustrine deposits (north-eastern and eastern parts of the city) composed mainly by clayey-silty sand and sand pebbles and (c) lacustrine deposits (south-western part of the city), composed of clay, silty clay, clayey silt and sandy silt layers, with a significant amount of shell fragments.

3.2 Seismicity and tectonics

Grevena

The southeast part of the Grevena basin is dominated by large-scale neotectonic faults of NE–SW to ENE–WSW directions. The most impressive and typical fault zone is the Aliakmon River valley fault, which comprises three en-echelon fault segments. Two of them, Sarakina and Servia faults, are linked to form a nearly straight fault zone, whereas the Deskati fault merges with them forming a horsetail structure. The NE trending Sarakina fault with length of 25 km has been activated during the 1995 (13/05/1995, M6.6) earthquake (Mountrakis 1995, Pavlides *et al.* 1995).

Düzce

The region of Düzce is one of the more active seismic areas worldwide, as is located very close to the North Anatolian Fault (NAF). Both Kocaeli (August 17, 1999, Epicenter: 40.639N, 29.830E, $M = 7.8$) and Düzce (November 12, 1999, Epicenter: 40.768N, 31.148E, $M = 7.2$) earthquakes occurred in a region dominated by the North Anatolian Fault. The right lateral strike-slip Düzce fault, activated by the 12/11/1999 earthquake, extends eastwards about 70km from the main branch of the North Anatolian Fault, near Akyazi. The faulting on this mega tectonic entity has a segmental character with a characteristic earthquake $M_w > 7.0$.

Although the past activity of NAF was well known, specific information was very limited until late 1980s when detailed survey of recent ruptures including exploratory trenches is introduced to Turkey. At the same time, historic documents were so sparse that only a few events of 1668 A.D. (Ambraseys and Finkel 1987) and of 1784 A.D. (Barka 1992) and a few periods of higher activity have been inferred. Only in the last century, a detailed list of the earthquakes that occurred was described (Alsan *et al*. 1976, Sahin and Tari 2000) with many uncertainties in the epicenters.

3.3 Geotechnical zonation and dynamic soil characteristics

Reliable modeling and evaluation of site effects is the key factor in seismic microzonation, vulnerability and risk assessment studies, especially in high seismicity areas, with complex geology and soil conditions. The lack of sufficiently dense information of soil properties is a major problem for a reliable geotechnical zonation, which is the first and most important step for a reliable site specific and spatially distributed ground motion estimate, for any given seismic hazard scenario. The geotechnical zonation is based on the compilation of all available geotechnical and geological data and the performance of a complementary program of geotechnical and geophysical surveys and tests. The nature and the extent of these surveys depend on the area under study and the quantity and quality of the available data. All basic soil formations, and their dynamic properties (i.e. *Vs*, *G-γ-D* curves) must be identified. The construction of numerous detailed 2D soil geological and geotechnical cross sections, will determine the main geotechnical zones of the area and will permit the construction of representative 1D soil profiles (generally in a quadrangular grid 250 m to 1000 m) to be used for the ground response analysis.

Grevena

In the case of the city of Grevena, the primary source of geotechnical information comprises 37 boreholes, with conventional in situ and laboratory tests (SPT, classification and strength parameters); these data led to a preliminary soil and site classification and definition of the main soil formations covering the city. The depth of rock basement, and the shear wave velocity profiles and average values for all soil categories in Grevena have been estimated with a detailed geophysical survey based on ambient noise measurements. The geometry of the geological formations has been accordingly estimated using traditional geological survey. Based on the geology of the site and the available geotechnical information, a restrained number of 11 noise measurements, well distributed along the city, was enough for a complete description of the required information. The tests were performed using the Spatial Autocorrelation Coefficient method (SPAC) introduced by Aki (1957). The results depict the presence of rather stiff geological formations, covering practically the whole city with the exception of a narrow region around the river. Vs noise measurements, available geotechnical borehole data and local geology have been used to determine the soil stratigraphy (Fig. 3(a)). The Pliocene-Pleistocene layer (V_s = 800-900 m/s) expanding up to 200m depths is considered as the seismic bedrock.

The synthesis of all available information, lead to representative 2D cross sections (Pitilakis *et al*. 2008). The one given in Fig. 3(b) indicates that the NNW part of the city is covered by stiff soil layers, with shear wave velocities greater than 400m/sec, and the surface, low velocity layer is practically absent, contrary to the areas close to the small river crossing the city. In general the soil formations in Grevena may be classified as stiff (class B according to EC8). Locally along the riverbeds the soil could be classified as C, always according to EC8.

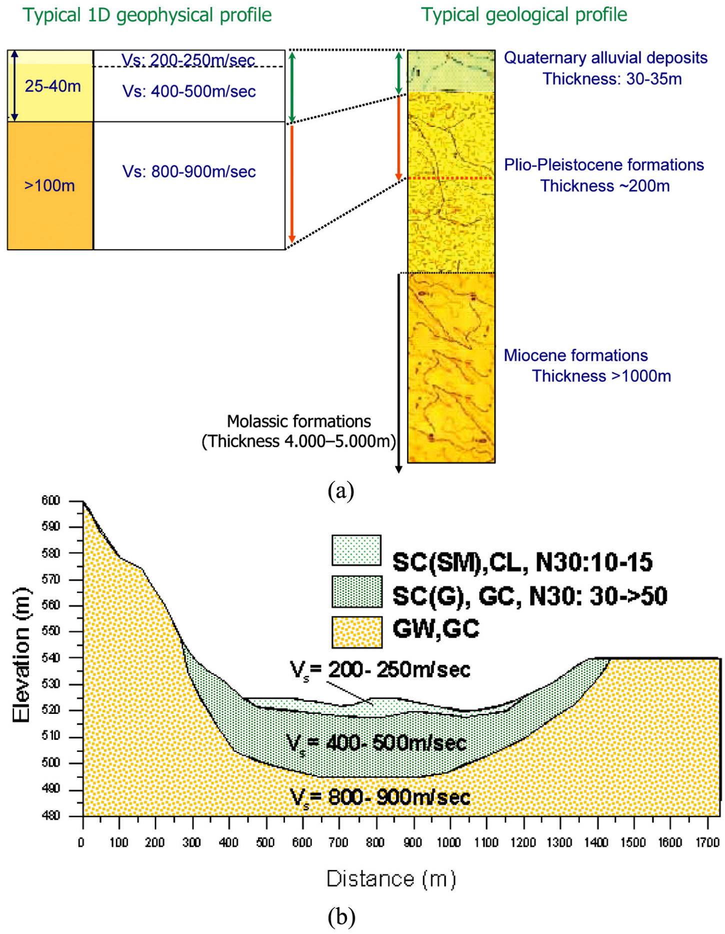
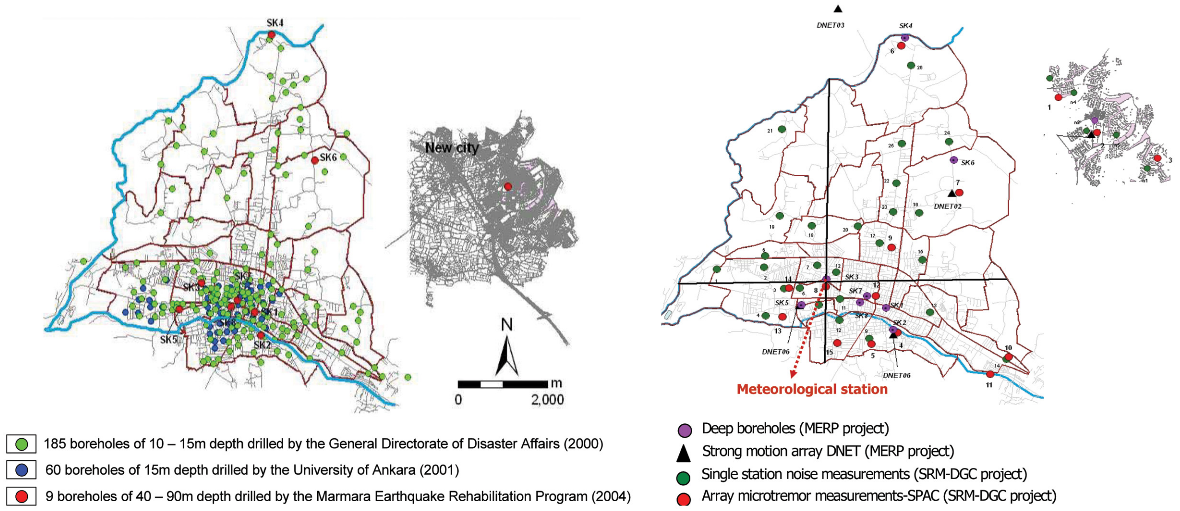


Fig. 3 (a) Correlation between geophysical and geotechnical data for the city of Grevena and (b) typical 2D soil profile at the Grevena region (Pitilakis *et al*. 2008)

Düzce

In contrast to the case of Grevena, in the city of Düzce, which is a much larger and extended city, we disposed, prior to this study, a relatively large number of sampling boreholes (in total 245), unfortunately all of shallow depth (10 to 15 m depth) with limited geotechnical information (Fig. 4(a)) (Kayabali *et al*. 2001). Few years after the Düzce earthquake several researchers have conducted noise measurements in few sites along the city (Kudo *et al*. 2002, Kayabali *et al*. 2001, Rosenblad *et al*. 2001, Yamanaka *et al*. 2002, Tromans 2004). These surveys allowed better design of our survey's program in 2004, comprising nine (9) boreholes of 40 to 90 m deep, and numerous microtremor measurements (MERP 2006). In particular we performed 15 array microtremor measurements using the Spatial Autocorrelation Coefficient - SPAC method (Aki 1957), and 31 single station ambient noise measurements using the Horizontal to Vertical Spectral Ratio - HVSR method (Nakamura 1989) (Fig. 4(b)).

Shear wave velocity (V_s) profiles were measured in fourteen (14) representative sites. The results show a rather regular distribution of V_s with depth. In the northern part of the city we found stiff soil formations with average $V_s = 400$ m/s. These formations are deepening at the southern part - the



(a) (b)

Fig. 4 (a) Map of Düzce with the locations of all the available geotechnical boreholes in the city (MERP 2006), (b) location of the new field measurements conducted in Düzce by AUTH- SDGEE

city centre - around the river. This area is characterized at the first 10 to 15 m depth with low velocity silty-clay, silty sands ($12 < V_s < 210$ m/s); then we found a medium velocity layer ($285 < V_s < 420$ m/sec), with varying thickness from site to site, overlying a stiffer soil formation with velocity V_s ranging from 490 to 620 m/sec and average thickness of 140 m; this layer covers another layer with velocity values around 780 m/sec, which is considered as the seismic bedrock. The real crystalline rock is much deeper. The dynamic properties of all these soil layers have been estimated through appropriate resonant column tests, conducted in the Laboratory of geotechnical earthquake Engineering and Soil Dynamics of Aristotle University (Pitilakis *et al*., SRM-DGC Final Report, Part B 2009).

3.4 Seismic hazard

Grevena

The seismotectonic and source model for Greece (Papaioannou and Papazachos 2000, Papazachos *et al*. 2001), was used for the probabilistic seismic hazard assessment applying Frisk88M (Cornell 1968), and an appropriate ground motion prediction equation proposed by Theodulidis and Papazachos (1992). Peak ground acceleration (PGA), velocity (PGV) and spectral acceleration (PSA) are estimated for various mean return periods, from 10 to 2000 years, and for two site conditions (rock and intermediate stiff soil). Based on the deaggregation of seismic hazard, the most likely earthquake magnitude and source-site distance for three mean return periods ($T_m = 100$, 475 and 1000 years), and two soil conditions (B and C according to EC8) were estimated (Pitilakis *et al*., SRM-DGC Final Report, Part A 2009). For example, the 475 years scenario corresponds to a 6.3 earthquake with $R = 14$ km for soil type B and $R = 13$ km for soil type C.

Düzce

Düzce is affected by two of the fourteen seismic sources (zones 1 and 2) for Turkey, as described by Erdik *et al*. (1985), Yaltirak *et al*. (1998) and Kayabali and Akin (2002). Seismic hazard analysis of Düzce has been conducted applying a poissonian probabilistic approach, using CRISIS 99 code (Ordaz 1999), for mean return periods of 100, 475 and 1000 years in a grid of 1 km × 1 km for the city of Düzce (Alexoudi 2005). The main assumption for the seismic source used is that earthquakes occur only along faults (Kayabali and Akin 2002). Three different Ground Motion Prediction Equations (GMPE) proposed by Ambraseys (1996), Sadigh *et al*. (1997) and Ozbey (2004) have been used to derive the distribution of PGA values for rock conditions and for return periods of 100, 475 and 1000 years. For the 1000 years scenario the PGA values derived from the use of different GMPE vary from 0.80 g (Ozbey 2004) to 0.93 g (Ambraseys 1996). For the 475 years scenario, which corresponds to the Düzce 1999 earthquake, the GMPE by Ozbey (2004) gives comparable results (PGA = 0.55 g) with the actual records, and consequently has been finally adopted herein.

3.5 Site response analysis

The site response analysis is based on the performance of numerous one dimensional (1D) equivalent linear (EQL) ground response analyses in representative sites, corresponding to the geotechnical zones and sub-zones derived earlier. A grid of 250 × 250 m or 500 × 500 m is usually selected, in order to detail in each zone the geotechnical conditions and the seismic rock basement geometry. Geological discontinuities and geotechnical particularities may also affect the grid selection. The final selection of the representative 1D soil models is also based on correlations in terms of fundamental period and amplification, obtained at selected sites from microtremor measurements, as well as empirical transfer functions from noise measurements.

The EQL site response analysis is performed in both sites applying the code EERA (Bardet *et al*. 2000), which is similar to the well-known SHAKE (Schnabel *et al*. 1972, Idriss and Sun 1992). It uses a multiple reflection theory, and the nonlinearity of soil behavior is considered through an equivalent linear approach. The hysteresis damping is taken into account through a complex shear modulus. Among the several advantages of this code is the way that it computes the deconvolution functions at various depths, using multiple reflection theory in frequency domain. Although the equivalent linear analysis usually overestimates the calculated shear stresses and underestimates amplifications in the high frequency range, in general it is considered quite reliable at medium strain levels.

Grevena

In the case of Grevena, the above procedure led to the development of 19 representative 1D dynamic soil profiles with varying depth from 15 to 40 m. Fig. 5 illustrates the grid of the study area (size of element of the grid 250 × 250 m), with the sites of the 1D representative soil profiles, along with a typical 1D dynamic profile.

1D-EQL soil response analyses are conducted at the 19 sites using as input motion real acceleration time histories carefully selected; the six earthquake records cover satisfactorily the intensity and frequency content of the bedrock motion in the area for the given earthquake scenario. The recorded input motions (Table 1) were scaled properly according to the results of the seismic hazard assessment, estimated to 0.14 g, 0.24 g and 0.30 g for rock soil conditions and for mean return period T_m = 100, 475 and 1000 years, respectively. Fig. 6 presents the elastic response acceleration spectra of the input motions for the 475 years seismic scenario and the mean elastic

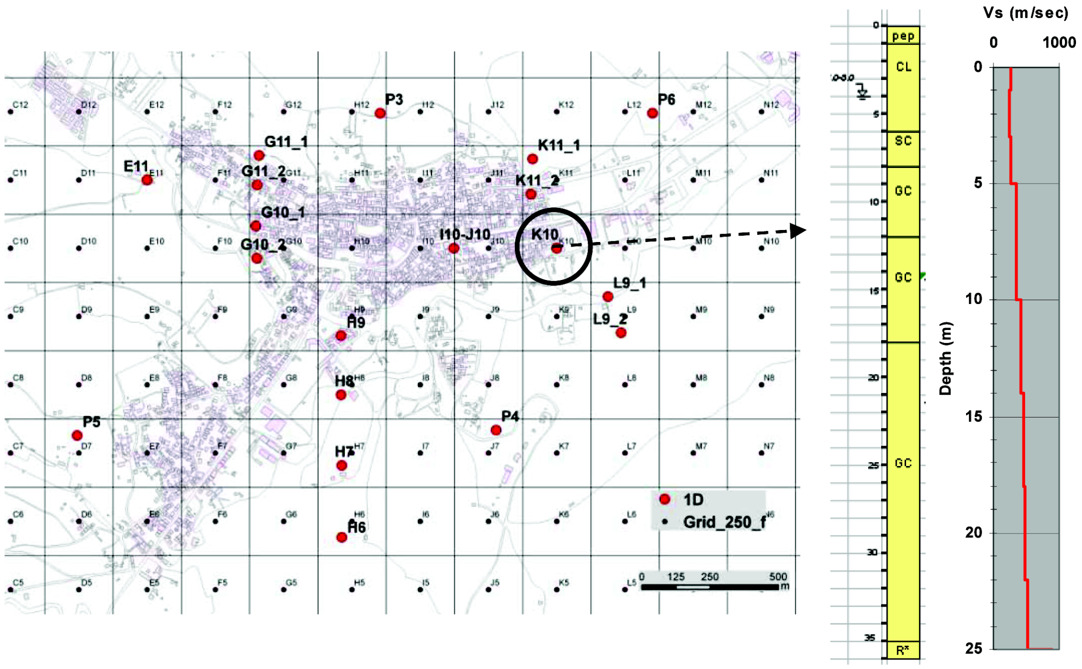


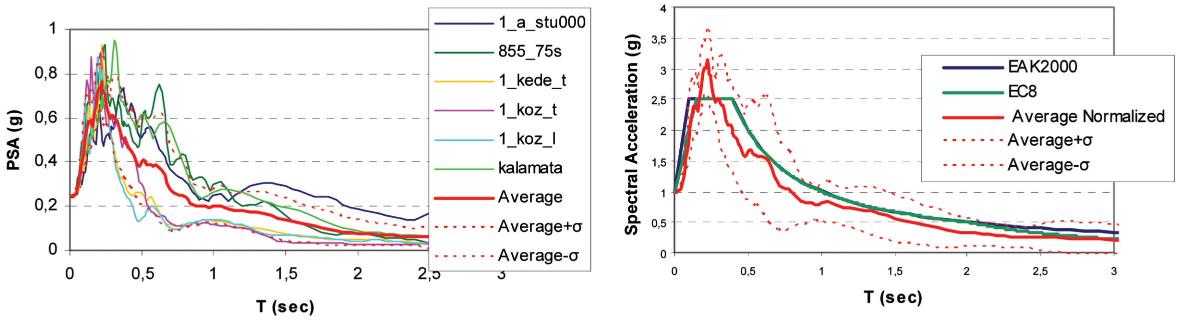
Fig. 5 Grid of the study area in Grevena. Sites of 1D representative soil profiles and typical dynamic cross section

Table 1 Seismic input motion at the bedrock for the city of Grevena

Code name	Earthquake (Station)	Date	M_w	Epicentral Distance R (km)	Focal depth (km)
KED99d	Athens, Greece (ATH_03)	07/09/1999	5.9	16.0	11.0
KOZ95-L	Kozani, Greece (Prefecture)	13/05/195	6.6	17.0	12.6
KOZ95-T	Kozani, Greece (Prefecture)				
855-Y	Umbria-Marche, Italy (Cubbio-Piene)	08/04/1998	4.8	18.0	10.0
KAL_86_D	Kalamata, Greece (OTE Building)	13/09/1986	5.9	11.0	1.0
STU80	Irpinia, Italy (ENEL-Sturno)	23/11/1980	6.9	30.0	9.5

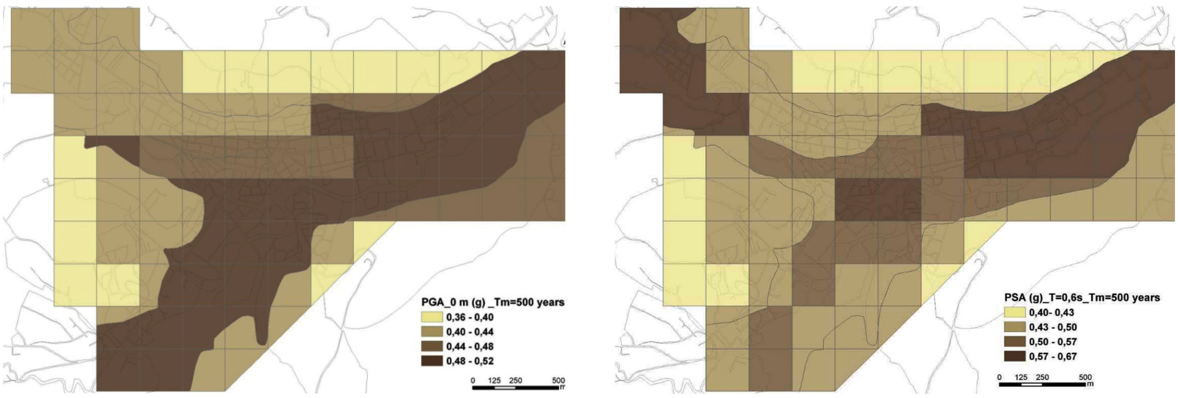
spectra in comparison with the proposed elastic spectrum for soil type A (rock) according to the Greek seismic code (EAK 2000) and EC8.

The computed ground responses for the set of six input motions were then compiled in order to estimate average acceleration and velocity response spectra, average spectral amplification ratios, variation of amplification ratios with frequency, variation of peak ground acceleration and maximum shear strain with depth, peak ground acceleration, velocity and displacement, at the ground surface and a depth of 3.0 m; the later is needed for the vulnerability assessment of utility systems like water and waste water systems, which are generally at this depth. The results are presented in tables, diagrams and maps in GIS format that present the spatial distribution of the strong ground motion parameters. For example Fig. 7 illustrates the spatial distribution of PGA and mean PSA values at $T = 0.6$ s, at the free surface, for the 475 years scenario. Relatively high PGA values are computed due to the presence of soil formations of small thickness; on the contrary, peak ground



(a) (b)

Fig. 6 (a) Elastic response acceleration spectra of the input motions for the city of Grevena and for the 475 years scenario, (b) mean elastic spectra in comparison with the proposed elastic spectrum for soil type A (rock) according to the Greek seismic code (EAK2000) and EC8



(a) (b)

Fig. 7 Grevena: spatial distribution of (a) peak ground acceleration PGA and (b) mean peak spectral acceleration PSA at $T = 0.6$ s at the ground surface ($T_m = 475$ years)

velocity values at the -3 m are relatively low.

Based on the synthesis of the ground motion analysis and the geological-geotechnical mapping, the city of Grevena was finally divided into five regions of "rather uniform" seismic response. The normalized mean elastic response acceleration spectra for the five zones are illustrated in Fig. 8. In the same figure we present the comparison with the elastic spectra of the Greek seismic code and EC8.

Grevena is actually a city developed in the bottom of a junction of two relatively deep and narrow valleys with steep slopes. Consequently the landslide risk during a strong earthquake may be quite important. From engineering point of view the best way to evaluate this type of risk is in terms of permanent ground displacements. So we computed for the three seismic scenarios the expected permanent ground displacements, applying the methodology proposed in HAZUS 2004 (NIBS 2004). The methodology is based on the classical Newmark's approach (Newmark 1965), and the involved parameters are the slope angle, the strength parameters of the local soil conditions (angle φ and cohesion) and the calculated *critical acceleration* (ranging from 0.10 g to 0.30 g for slope angles between 5-90°). Fig. 9 presents the spatial distribution of the upper and lower bound of the

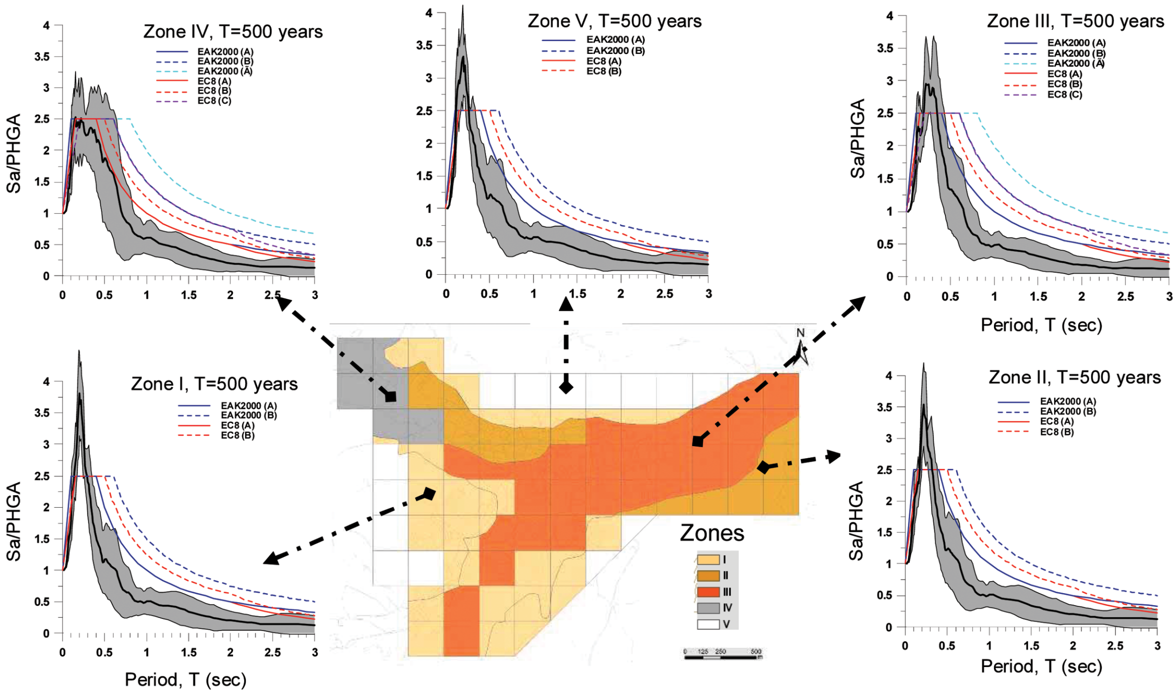
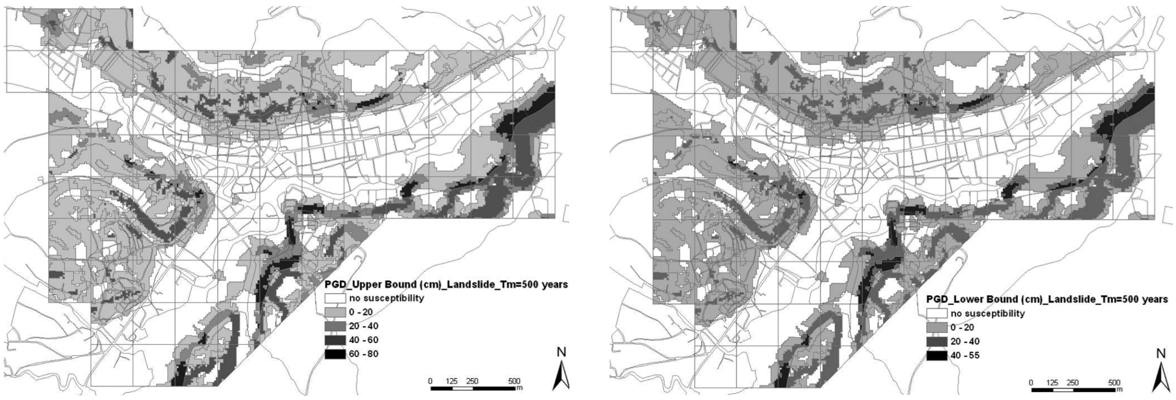


Fig. 8 Zonation of Grevena: normalized mean elastic response acceleration spectra for the five zones and corresponding elastic spectra of the Greek seismic code and EC8



(a) (b)

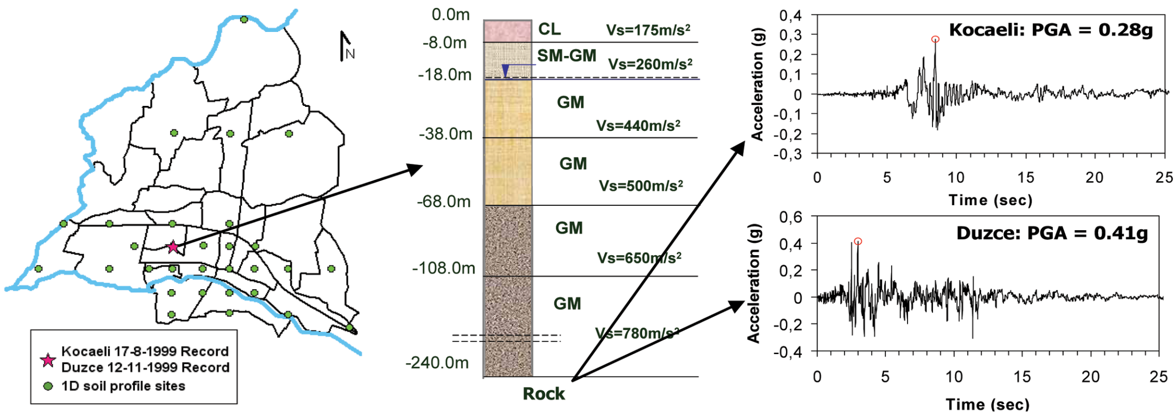
Fig. 9 Grevena: spatial distribution of (a) the upper and (b) lower bound of permanent ground displacement for landslide ($T_m = 475$ years)

computed permanent ground displacement (PGD) for the seismic scenario of 475 years, which in the worst case may reach 90 cm.

Düzce

In the case of Düzce, we selected thirty (30) representative soil profiles (Fig. 10(a)). The dynamic soil properties and the V_s (m/sec) profiles were derived from the synthesis of previously mentioned surveys and studies. Contrary to Grevena where we didn't have any record from the 1999 earthquake, in Düzce we have a set of good records from both Kocaeli and Düzce 1999 earthquakes recorded in the centre of the city at the Meteorological station. The deconvolution of these records at the seismic bedrock estimated previously could be used as an ideal input motion for the site response analysis. So we decided to make a detailed geotechnical study in this particular site comprising deep borehole drilling (100 m), SPT, down-hole measurements, array microtremor measurements and all necessary conventional and dynamic laboratory tests. The derived geotechnical profile is given in Fig. 10(b). Based on this soil profile we deconvoluted the available records from the ground surface down to the seismic bedrock, in order to get the input motion at the seismic rock basement at -240 m (Fig. 10(c)). In this way, we were able to estimate with acceptable approximation, the 12-11-1999 acceleration time history at the surface of the seismic bedrock below the city of Düzce. In particular, values of $PGA_{EW} = 0.41$ g and $PGA_{NS} = 0.23$ g were estimated for the two horizontal components of the ground motion recorded during the 1999 event.

As in the case of Grevena, besides the deconvoluted time histories of the Düzce earthquake record, four more real seismic motions recorded at "outcropping rock" conditions, were also selected; the Gebze record of the 17-8-1999 Kocaeli earthquake, two records from the 1994 Northridge earthquake (Pacoima Dam and Wonderland records) and the Sturno record of the 1980



(a) (b) (c)

Fig. 10 (a) Location of 1D site response analyses in Düzce, (b) V_s (m/sec) profile at the Meteorological Station and (c) deconvoluted time histories of the Kocaeli and Düzce records at the Meteorological station, to be used as input motions for the 1D EQL analyses

Table 2 Düzce: selected input motions at the rock basement

Code name	Earthquake (Station)	Date	M_w	Epicentral distance R (km)	Focal depth (km)
GBZ99	Kocaeli, Turkey (Tubitak Marmara Arastir)	17/08/1999	7.4	48	17.0
STR80	Campano Lucano, Italy (Sturno)	23/11/1980	6.6	32	16.0
PAC94	Northridge, U.S.A. (Pacoima Dam, CA)	17/1/1994	6.7	-	17.5
WOND94	Northridge, U.S.A. Los Angeles, CA, Wonderland Ave Elem. Sch.	17/1/1994	6.7	-	17.5

Campano Lucano earthquake in Italy (Table 2). All input motions were scaled properly to the PGA values proposed for the three seismic scenarios. In Fig. 11 we present the selected design response spectra at bedrock conditions, for the scenario of 475 years.

Fig. 12 illustrates an indicative example of the computed response spectra for the six different input motions for one representative site at the southern part of the city. In the same figure we present the mean and standard deviation curves compared to the Turkish seismic code (Z3) and EC8 soil C (CEN 2004). Similar results are produced for all representative sites. The synthesis of all, led finally to the proposition of two normalized acceleration response spectra; one for the north part of Düzce, where the soil formations are stiffer, and one for the south part of the city, where there are mainly deep soft alluvial deposits (Fig. 13). The calculated normalized average acceleration response spectra (S_a/PHGA), are compared for the north part with the design response spectra of seismic zone Z2 (Turkish Seismic Code) and soil class B (EC8), while for the south part with the corresponding design response spectra of seismic zone Z3 of the Turkish Seismic Code and soil class C of EC8.

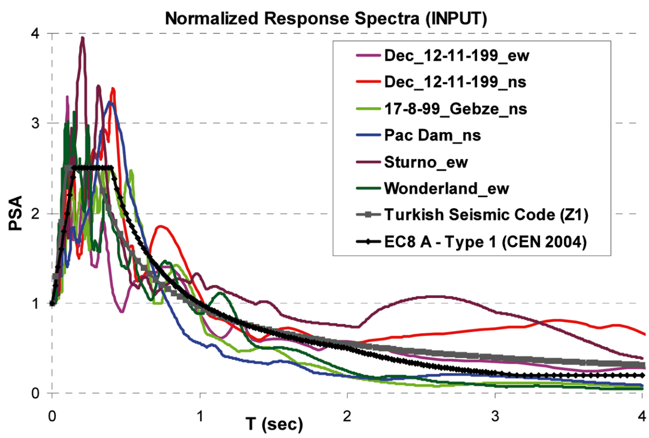
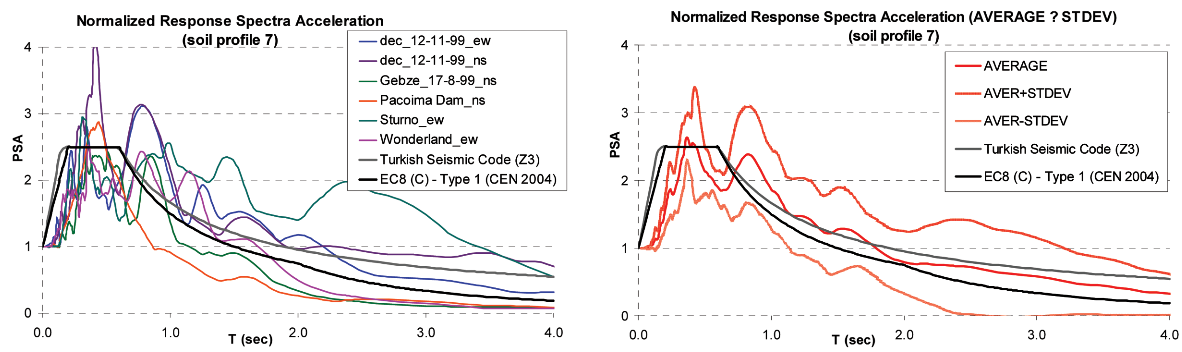


Fig. 11 Acceleration response spectra of the six input motions used in Düzce as input motion, compared with the design response spectra acceleration of the Turkish Seismic Code (Z1) and EC8 A - Type 1



(a) (b)

Fig. 12 (a) Normalized response spectra acceleration, (b) mean ± *sd* values at a representative soil profile, compared with the design response spectra acceleration of the Turkish seismic code (Z3) and EC8 C - Type 1

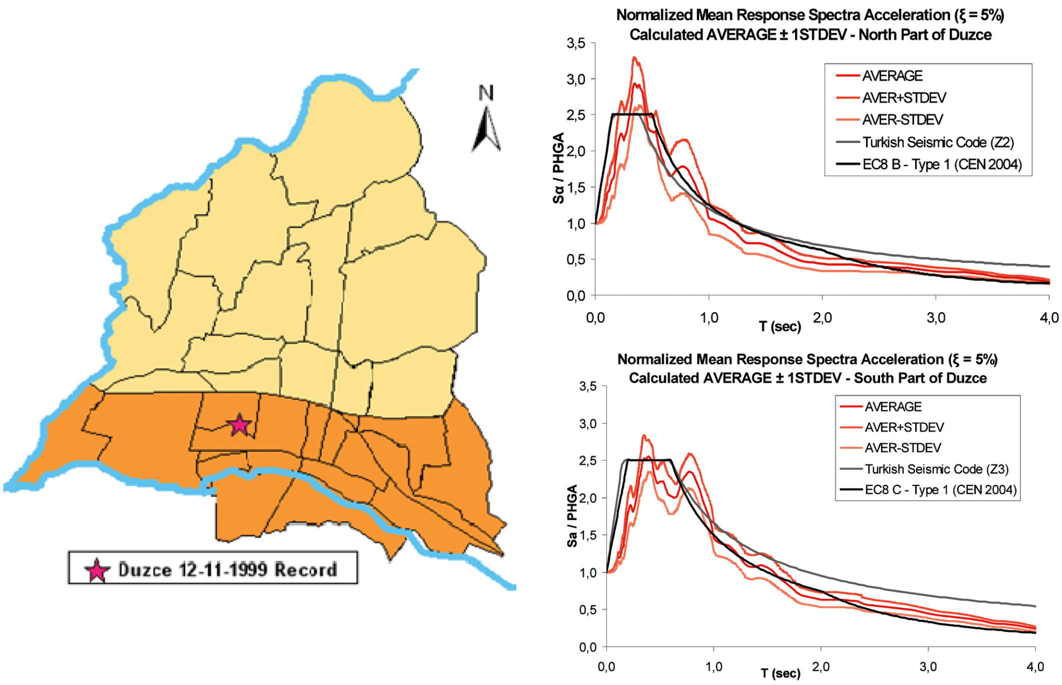


Fig. 13 Zonation of Düzce. Computed normalized response spectra acceleration (Sa/PHGA) in the north and south part of Düzce, compared to the Turkish seismic code and EC8

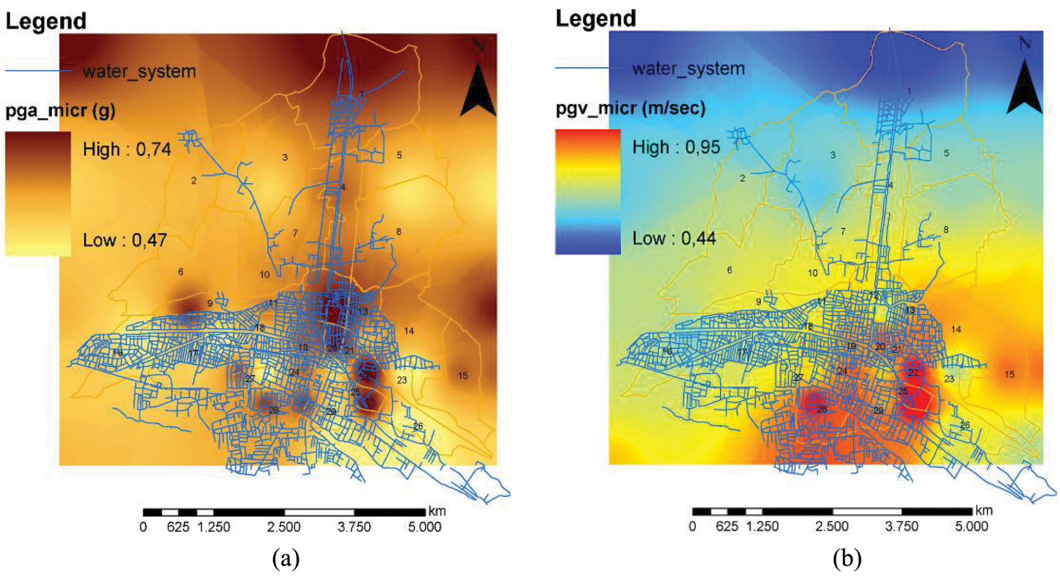
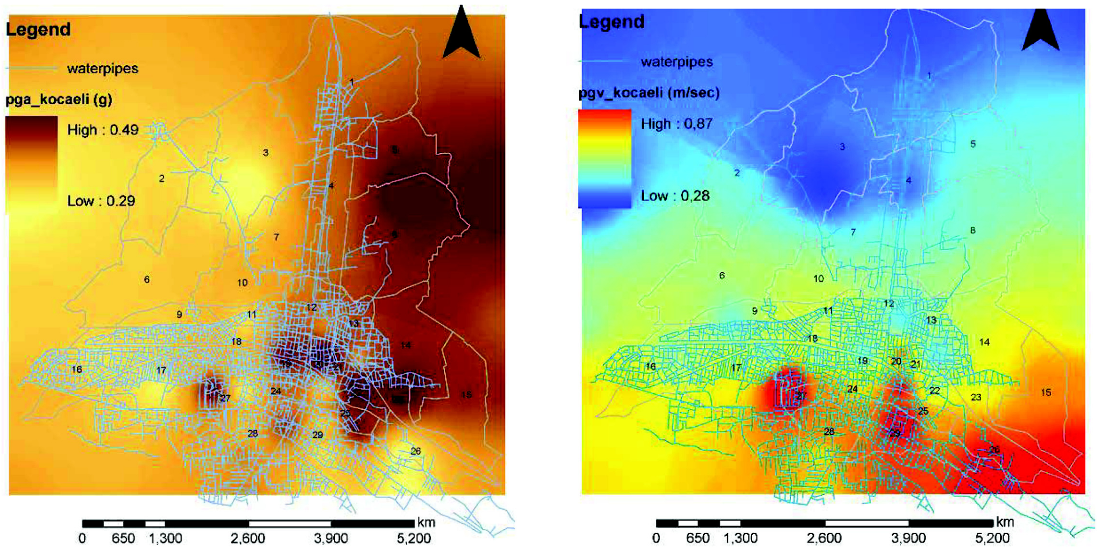


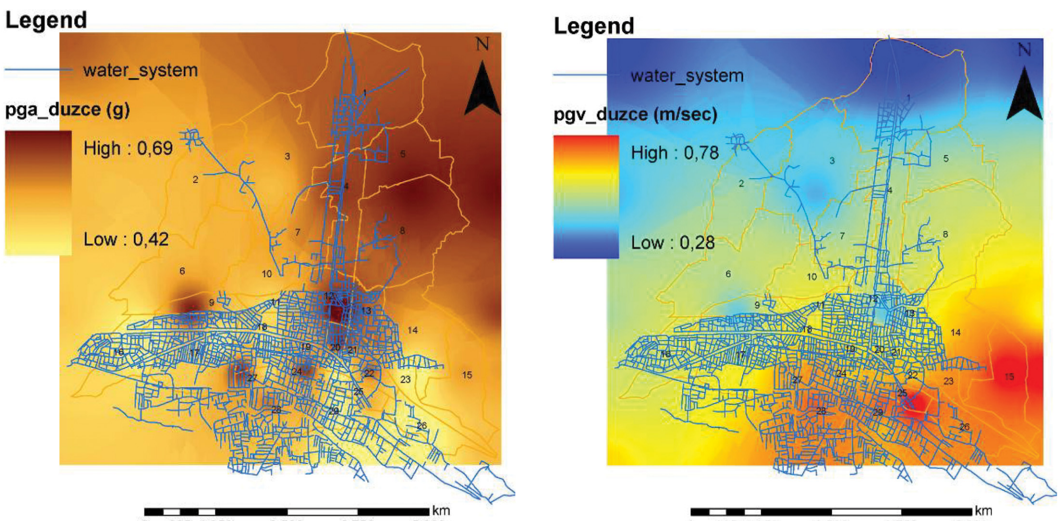
Fig. 14 Spatial distribution of (a) average PGA (g) and (b) average PGV (cm/sec) values in Düzce

The spatial distribution of the average Peak Ground Acceleration (PGA) and Velocity (PGV) values are presented in Fig. 14. Figs. 15 and 16 present separately the spatial distribution of PGA and PGV for the deconvoluted ground motions in the Meteorological Station of Düzce for Kocaeli



(a) (b)

Fig. 15 Spatial distribution of (a) PGA (g) and (b) PGV (cm/sec) values in Düzce for the deconvoluted Kocaeli 1999 record in the Meteorological Station in Düzce



(a) (b)

Fig. 16 Spatial distribution of (a) PGA (g) and (b) PGV (cm/sec) values in Düzce for the deconvoluted record of the Düzce 1999 earthquake

and Düzce 1999 earthquakes.

The combination of the results given in Figs. 13 and 14 offer a complete description of the necessary input motion for the vulnerability and risk assessment.

4. Vulnerability assessment and loss scenarios

Using the result of the site-specific seismic hazard analysis, we proceed then to the vulnerability and loss assessment of the utility systems and transportation infrastructures in the two cities. In particular we made the vulnerability assessment for the waste water and roadway system in Grevena, and for the potable and waste water system in Düzce. To this end appropriate inventory has been performed and appropriate fragility curves have been selected (Pitilakis *et al*. 2006, Alexoudi 2005, NIBS 2004).

4.1 Description of the utility systems

The waste water system of Grevena is a gravity network comprising 32 km of pipes; the construction was completed in 2006. The current inventory database includes several attributes, such as location, diameter, material, age, type, depth and length. The treatment plant is located 4 km away from the city, connected to a small river receiving the treated sewage.

The waste water system in Düzce is also a gravity network that dates back to the 1940's, while several parts of the system are dating back to the early 1900's. The pre-existing network is about 350 km in length; no specific maps exist to confirm this. Both networks were in use at the time of Kocaeli and Düzce earthquakes. With the support of local engineers the principle network of 54 km was digitized. 50.6 km are pipes-conduits with circular shape, while the rest 3.4 km has different shapes (rectangular, oval, and orthogonal). The main material used for the pipes-conduits is lightly reinforced concrete, which is considered as brittle material (Alexoudi 2005, Alexoudi *et al*. 2008). Detailed information about the dimension, the shapes and the material for the rest of the network is not available, so our study is limited to the principle network.

The water system in Düzce is about 500 km long and the great percentage dates back to 1940s (Tadday and Sahin 2001). The network consists mainly of cast iron (CI) and asbestos cement (AC) pipes, which could be classified as brittle pipes. A 600 mm diameter AC pipe conveys raw water from the main source, the River Ugur, to the water treatment plant at the south of the town. A 100 cm diameter steel pipe then carries the treated water to the distribution network, joining the town in the Azmimilli District. Twin CI pipes, of diameter 125 mm, transport water from a well field and reservoir to supplement the main river water supply; these pipes join the town in the north east district. The digitized pipeline network, with a total length of 298 km, is a mixed system, comprising both old and recently constructed parts.

The vulnerability assessment of the waste water and water supply networks of the two cities is based on the estimation of the expected Repair Rate per pipe km (RR/km). Expected damages (leaks and/or breaks) caused by wave propagation are estimated using O'Rourke and Ayala (1993) fragility relation proposed by HAZUS (NIBS 2004), where the seismic loading is described in terms of peak ground velocity (PGV). According to HAZUS (NIBS 2004) in case of wave propagation, 20% of failures are assumed as breaks and 80% as leaks. The anticipated damages due to ground failure (ground settlements or permanent ground displacements due to seismically induced landslides), are assessed using the American Lifeline Alliance fragility relation (ALA 2002). Prior to their application, these empirical vulnerability functions have been validated with recorded damages in Düzce 1999 earthquake and in Lefkas- Greece 2003 earthquake (Alexoudi 2005, Pitilakis *et al*. 2005). Appropriate fragility curves for large diameter conduits (pipes with diameter larger than 900 mm) are also used (Argyroudis *et al*. 2006), taking into consideration local soil

Table 3 Computed water pipe failures in the water network of Düzce due to ground shaking for the Düzce and Kocaeli earthquakes (Alexoudi *et al*. 2010)

Fragility curves/ Earthquake	Düzce	Kocaeli
O' Rourke and Ayala (1993)	147	116
Isoyama *et al*. (1998)	80	66
Eidinger and Avila (1999)	104	84
ALA (2001)	28	25
Recorded	164	200

conditions. For the vulnerability assessment of the waste water treatment plant, fragility curves recently developed in AUTH for small/medium waste water treatment plants with anchored components are used.

In order to validate the available fragility curves for water pipes, different vulnerability functions were used to estimate the expected damages in the water network of Düzce, (about 300 km long), which were compared with the observed damages after Düzce and Kocaeli earthquakes. Table 3 presents the computed water pipe failures in these 300 km long network due to ground shaking, applying four different fragility expressions and two input motions describing the consecutive Kocaeli and Düzce events (Alexoudi *et al*. 2010). Recorded damages, according to our field inspection in Düzce and reported failures from Tromans (2004), are well compared with the fragility curve proposed by O'Rourke and Ayala (1983). This relation is finally adopted in our paper for both water and waste-water systems having a similar construction practice.

It is also worth to notice that despite the fact that PGV is higher for the Kocaeli earthquake the reported failures during the Düzce earthquake are larger. This can be attributed to the larger duration of the Düzce earthquake, with an Arias Intensity almost two times larger than the Kocaeli one, indicating greater damage potential (Tromans 2004).

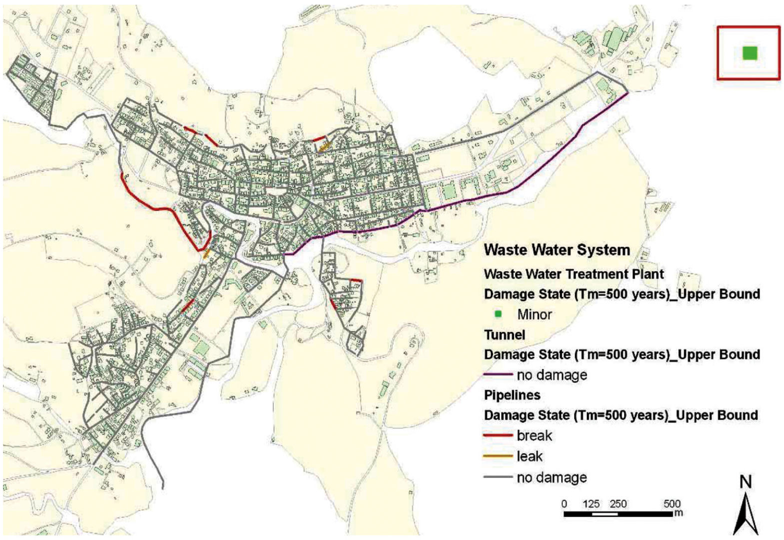
4.2 Estimation of damages

Grevena

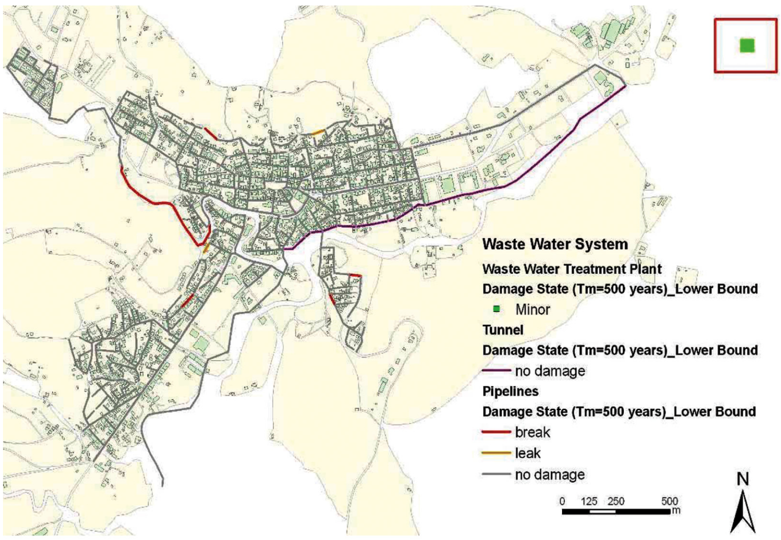
Fig. 17 presents the spatial distribution and the intensity of the estimated damages of the waste water network in Grevena for the 475 years scenario. For each seismic scenario the number, intensity and location of the damages are related to the site-specific ground motion and the characteristics of the pipes. Due to the stiff soil conditions, the estimated PGV values are very low, and hence we estimated a relatively low number of failures for ground shaking. Most of the expected damages are due to permanent ground displacements in landslide prone areas along the city (Table 4). If a segment of the network presents one or more failure the whole segment is considered to be out of service and gets the appropriate colour.

Düzce

The estimated damages due to ground shaking for the waste water network in Düzce are presented in Table 5. We calculated the number of repairs separately for the average design input motions (microzonation study), and the deconvoluted input motions recorded at the ground surface for the Kocaeli and Düzce earthquakes. Finally, Fig. 18 illustrates the spatial distribution of the estimated damages for the microzonation study. Most of the damages are expected in the southern



(a)



(b)

Fig. 17 Vulnerability assessment of the waste water system of Grevena due to ground shaking and landslide: (a) upper and (b) lower bound of estimated PGD values ($T_m = 475$ years)

Table 4 Estimated damages due to ground shaking and permanent ground displacements for the waste water pipelines of Grevena

Seismic scenario	Number of repairs		Number of breaks		Number of leaks	
	Upper bound	Lower bound	Upper bound	Lower bound	Upper bound	Lower bound
100 years	5	4	4	3	1	1
475 years	11	9	9	7	2	2
1000 years	14	12	11	10	3	2

Table 5 Ground shaking damages for the waste water pipes in Düzce

Seismic scenario	Total number of repairs	Number of breaks	Number of leaks
Average (475 years)	86	17	69
Kocaeli 1999 earthquake	44	9	35
Düzce 1999 earthquake	52	10	42

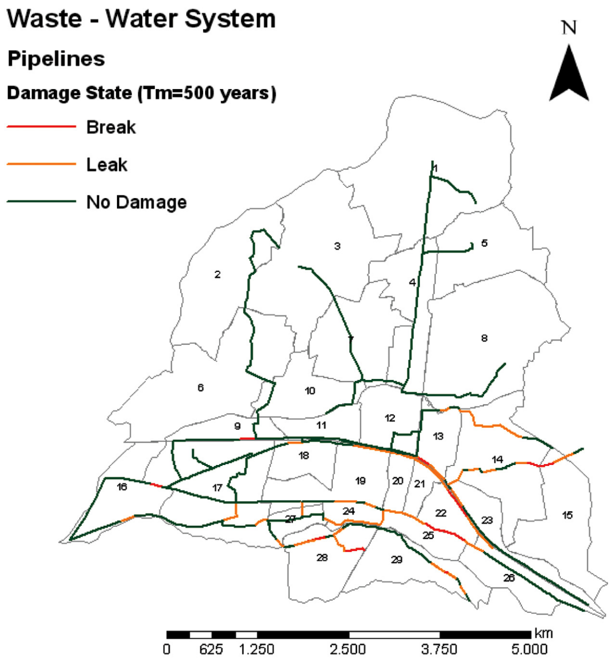


Fig. 18 Vulnerability assessment of the waste water system in Düzce for the microzonation study ($T_m = 475$ years)

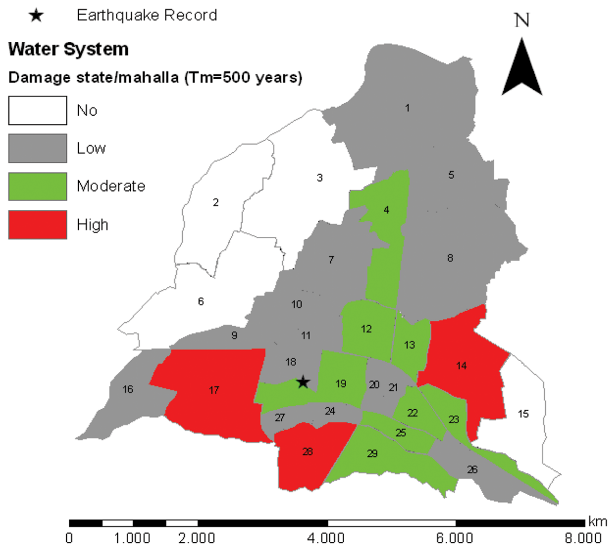


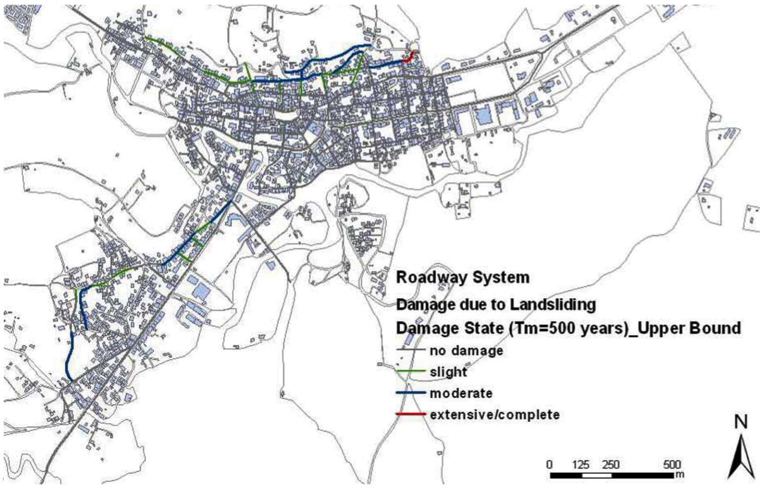
Fig. 19 Estimated water pipe damages per district (machala) in Düzce

part of the city, where soft soils dominates the surface soil conditions.

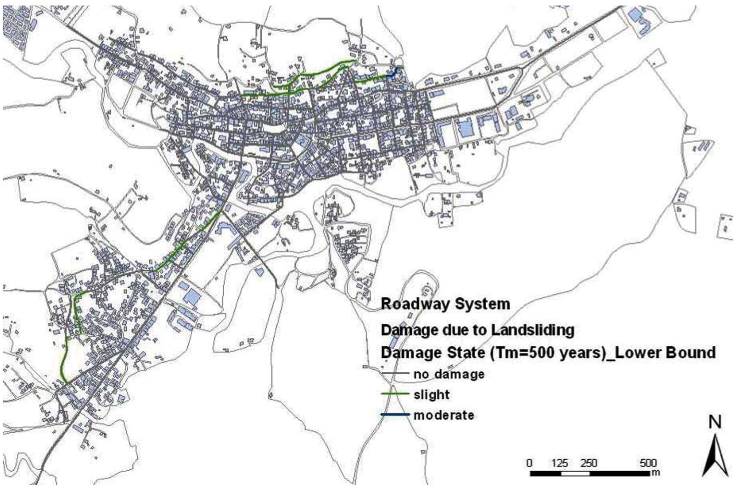
Table 6 presents the total number of damages for the water supply system in Düzce. The percentage of the pipelines of the network that are expected to have some type of damage for the Kocaeli and Düzce earthquakes, as well as average values evaluated in the microzonation study, is

Table 6 Ground shaking damages for the water pipes in Düzce

Seismic scenario	Total number of repairs	Number of breaks	Number of leaks
Average (475 years)	245	49	196
Kocaeli 1999 earthquake	116	23	93
Düzce 1999 earthquake	147	29	118



(a)



(b)

Fig. 20 Vulnerability assessment of the roadway system of Grevena due to seismically induced landslides for (a) the upper and (b) lower bound of the estimated PGD values ($T_m = 475$ years)

7%, 9% and 13% respectively.

The majority of damages are expected at the southern and eastern part of the city, which is well compared with the recorded damage distribution during the sequence of Kocaeli and Düzce earthquakes (Manou *et al*. 2007).

4.3 Damages to the transportation system of Grevena

The inventory and classification of the road network in Grevena is based on their functionality, frequency of use, land uses of serviced areas and available escape routes. For the vulnerability assessment we used the fragility curves proposed in HAZUS (NIBS 2004) for permanent ground displacements due to landslides. Fig. 20 illustrates the anticipated damages for the 475 years scenario. As expected the damages are observed in the steep slope regions of the city. For the 1000 years scenario the rate of damages is increased and more road segments suffer important damages.

To estimate the functionality of the city roads just after the main shock, we used a model developed by Argyroudis *et al*. (2008). The model is based on the estimation of the debris of heavily damaged or collapsed buildings that will close the roads. A Gaussian distribution describes the variation of the debris width, which is a function of the angle (ϕ) of the debris and the building volume reduction (kv). The model describes the probability of exceedance of certain road function levels. The collapse probability for the buildings in Grevena is estimated in Kappos *et al*. (2010). The risk assessment depends on the building typology, their density and high, the length and width of the road segments and the intensity of seismic loading for each seismic scenario.

Fig. 21 illustrates the probability of closure (>50% of road width) of the main roads for the 475

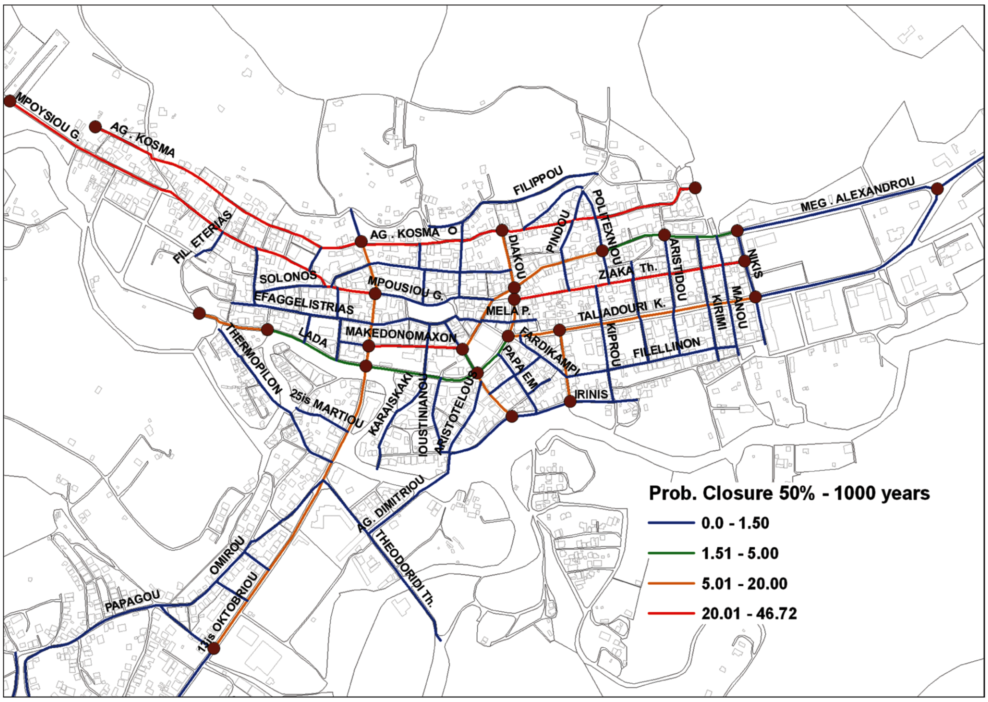


Fig. 21 Road closure probabilities (>50% of road width) in Grevena for the 475 years seismic scenario

years scenario. Due to the existence of narrow roads, we observe a quite important percentage of roads presenting high probability of closure for the estimated building collapses.

5. Conclusions

We presented a general modular methodology for constructing comprehensive earthquake-loss scenarios, and we applied it in the cities of Grevena in Greece and Düzce in Turkey for the estimation of the spatial distribution, intensity and frequency content of the ground motion for three scenarios, and the loss assessment of utility and transportation systems. Seismic loss scenarios take into consideration the inventory, typology and vulnerability characteristics of different elements at risk, as well as the seismic hazard, geotechnical characterization and site response of the main soil formations for different seismic scenarios. Thus, vulnerability and loss estimates for utilities and transportation systems are evaluated on the basis of site-specific seismic hazard analysis, using available inventory data and adequate fragility curves.

The construction of such comprehensive earthquake loss scenarios for urban areas in high seismicity regions constitutes the basis for the elaboration of effective pre-earthquake mitigation actions, post earthquake restoration efforts and efficient disaster management plans.

Acknowledgements

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References

Aki, K. (1957), "Space and time spectra of stationary stochastic waves, with special reference to microtremors", *Bull. Earthq. Res. Inst. Tokyo Univ.*, **25**, 415-457.

Alexoudi, M. (2005), *Contribution to seismic assessment of lifelines in urban areas. Development of a holistic methodology for seismic risk*, PhD Thesis, Civil Engineering Department, Aristotle University of Thessaloniki. (in Greek)

Alexoudi, M., Manou, D. and Pitilakis, K. (2008), "Seismic vulnerability analysis of waste-water system. Methodology and application for Düzce and Kocaeli earthquakes", *Proceedings of the 14th WCEE*, Beijing, October.

Alexoudi, M., Manou, D. and Pitilakis, K. (2010), "The role local soil condition and vulnerability relations in the seismic behavor of water system. Application in Düzce", *Proceedings of the 6th National Conference on Geotechnical and Environmental Engineering.* (in Greek)

Alsan, E., Tezucan, L. and Bath, M. (1976), "An earthquake catalogue for Turkey for the interval 1913-1970", *Tectonophysics*, **31**, 13-20.

Ambraseys, N.N. (1996), "The prediction of earthquake peak ground acceleration in Europe", *Earthq. Eng. Struct. Dyn.*, **24**, 467-490.

Ambraseys, N.N. and Finkel, C.F. (1987), "Seismicity of Turkey and neighbouring regions, 1899-1915", *Ann. Geophysicae*, **5**, 701-725.

American Lifeline Alliance (ALA) (2002), *Development of guidelines to define natural hazards performance*

objectives for water systems, Vol. I, 138 pp.
American Lifelines Alliance (ALA) (2001a), *Seismic fragility formulations for water systems, Part 1 – Guideline*, ASCE-FEMA, 104 pp.
American Lifelines Alliance (ALA) (2001b), *Seismic fragility formulations for water systems, Part 2 – Appendices*, ASCE-FEMA, 239 pp.
Argyroudis, S., Billis, Th., Deri, A. and Pitilakis, K. (2006), "Seismic fragility of shallow tunnels in alluvial deposits", *Proceedings of 5th National Conference on Geotechnical and Geoenvironmental Engineering*, Xanthi, May-June. (in Greek)
Argyroudis, S., Pitilakis, K. and Chatzigogos, Th. (2008), "Seismic risk assessment of thessaloniki's roadway network", *Proceedings of 3rd National Conference on Earthquake Engineering and Engineering Seismology*, Athens, November. (in Greek)
Bardet, J.P., Ichii, K. and Lin, C.H. (2000), *EERA, A computer program for equivalent-linear earthquake site response analysis of layered soil deposits*, University of Southern California, Department of Civil Engineering.
Barka, A.A. (1992), "The North Anatolian fault zone", *Ann. Tectonicae*, **6**, 164-195.
Brunn, J. (1956), "Contribution a L'Etude Geologique du Pinde Septentrional et Dune Partie de la Macedoine occidentale", *Ann Geol. Pays. Hellen.*, **7**, 1-358.
CEN European Committee for Standardization (2004), *Eurocode 8: Design of structures for earthquake resistance–Part 1: General rules, seismic actions and rules for buildings.*
Cornell, C.A. (1968), "Engineering seismic risk analysis", *B. Seismol. Soc. Am*., **58**, 1583-1606.
EAK2000 (2000), *Greek seismic code*, Organization of Seismic Planning and Protection.
Eidinger, J. and Avila, E. (1999), "Guidelines for the seismic upgrade of water transmission facilities", *Monograph No. 15*, TCLEE/ ASCE.
Erdik, M., Doyuran, V., Gulkan, P. and Akkas, N. (1985), "A probabilistic assessment of the seismic hazard in Turkey", *Tectonophysics*, **117**, 295-344.
Eurocode 8, *Design provisions for earthquake resistance of structures - Part 1-1: General rules - seismic actions and general requirements for structures*, European Pre-standard, ENV 1998-1-1, Oct.1994, CEN-European Committee for Standardization.
FRisk88M (1996), *User's manual*, ver. 1.70., Risk Engineering Inc., Boulder CO., 69pp, 2 Appendixes.
Idriss, I.M. and Sun, J.I. (1992), *User's manual for SHAKE91*, A computer Program for Conducting Equivalent Linear Seismic Response Analyses of Horizontally Layered Soil Deposits Program Modified based on the Original SHAKE Program Published in December 1972 by Schnabel, Lysmer and Seed.
Isoyama, R., Ishida, E., Yune, K. and Shirozu T. (1998), "Seismic damage estimation procedure for water supply pipelines", *Proceedings, Water & Earthquake '98 Tokyo, IWSA International Workshop, Anti-Seismic Measures on Water Supply, International Water Services Association and Japan Water Works Association*, Tokyo, Japan.
Kappos, A.J., Panagopoulos, G., Sextos, A.G., Papanikolaou, V.K. and Stylianidis, K.C. (2010), "Development of comprehensive earthquake loss scenarios for a Greek and a Turkish city - structural aspects", *Earthq. Struct*. **1**(2), 197-214.
Kayabali, K. and Akin, M. (2002), "Modeling of seismic hazard for Turkey using the recent neotectonic data", *Eng. Geology*, **63**, 221-232.
Kayabali, K., Ulugergerli, E. and Tokgoz, E. (2001), *Geological-geophysical-geotechnical survey report of 246 hectare area in provincial centre of Düzce based on municipal plan*, Dep. of Geology and Geophysical Engineering, Faculty of Science, Ankara University, vol.1.
Kudo, K., Kanno, T., Okada, H., Ozel, O., Erdik, M., Sasatani, T., Higashi, S., Takahashi, M. and Yoshida, K. (2002), "Site-specific issues for strong ground motions during the Kocaeli, Turkey, earthquake of 17 August 1999, as inferred from array observations of microtremors and aftershocks", *B. Seismol. Soc. Am*., **92**, 448-465.
Manou, D., Alexoudi, M., Raptakis, D. and Pitilakis, K. (2007), "Düzce (M7.2, 1999) earthquake: damage correlation with the microzonation study and vulnerability assessment of the water system in Düzce, Turkey", *Proceeding of the 4th International Conference on Earthquake Geotechnical Engineering*, Thessaloniki, June.
Marmara earthquake rehabilitation project-MERP, Final Scientific Project Report (2006), "An Integrated Intervention for the Rehabilitation of Düzce", Laboratory of Soil Mechanics, Foundations & Geotechnical Earthquake Engineering, Department of Civil Engineering, Aristotle University of Thessaloniki.

Mountrakis, D. (1995), *Geotectonic evolution of the broader Hellenic region*, Geology Department, School of Science, University of Thessaloniki. (in Greek)

Nakamura, Y. (1989), "A method for dynamic characteristics estimation of subsurface using microtremors on the ground surface", *QR Railway Tech. Res. Inst.*, **30**, 25-33.

National Institute of Building Sciences (NIBS) (2004), *Earthquake loss estimation methodology HAZUS 2004, technical manual*, FEMA, Washington DC.

Newmark, M.N. (1965), "Effects of earthquakes on dams and embankments", *Geotechnique*, **15**, 139-160.

Ordaz, M. (1999), *CRISIS99: A computer program to compute seismic hazard*, University of Mexico (UNAM).

O'Rourke, M.J. and Ayala, G. (1993), "Pipeline damage due to wave propagation", *J. Geotech. Eng. - ASCE*, **119**, 1490-1498.

Ozbey, C. (2004), *Empirical peak horizontal acceleration relationship for northwestern Turkey*, MSc Thesis, Bogazici University, Istanbul.

Paolucci, R. and Pitilakis K. (2007), "Seismic risk assessment of underground structures under transient ground deformations", Pitilakis K. (Ed.), *Earthquake Geotechnical Engineering*, Chap. **18**, 433-459, Springer.

Papaioannou, Ch.A. and Papazachos, B.C. (2000), "Time-independent and time-dependent seismic hazard in Greece based on seismogenic sources", *B. Seismol. Soc. Am.*, **90**, 22-33.

Papanastassiou, D., Drakatos, G., Voulgaris, N. and Stavrakakis, G. (1998), "The May 13, 1995, Kozani-Grevena (NW) Greece earthquake: source study and its tectonic implications", *J. Geodynamics*, **26**, 233-244.

Papazachos, B.C., Mountrakis, D.M., Papazachos, C.B., Tranos, M.D., Karakaisis, G.F. and Savvaidis A.S. (2001), "The faults which have caused the known major earthquakes in Greece and surrounding region between the 5th century BC and today", *Proc. 2nd Greek conf. Earthq. Eng. & Eng. Seismol.*, Thessaloniki, November.

Pavlides, S. and Mountrakis, D. (1987), "Extensional tectonics of northwestern Macedonia, Greece, since the late Miocene", *J. Struct. Geol.*, **9**, 385-392.

Pavlides, S., Zouros, N.C., Chatzipetros, A.A., Kostopoulos, D.S. and Mountrakis, D.M. (1995), "The 13 May 1995 western Macedonia, Greece (Kozani Grevena) earthquake; preliminary results", *Terra Nova*, **7**, 544-549.

Pitilakis *et al*. (2009), "SRM-DGC (Development and proposition for implementation of an efficient methodology and appropriate local instruments for the management, prevention and reduction of seismic risk in Düzce -Turkey, Grevena - Greece and Catania – Italy) Final Report, Part A (2009)", *Final report for the city of Grevena (WP: 1-5)*, Laboratory of Soil Mechanics, Foundations & Geotechnical Earthquake Engineering, Department of Civil Engineering, Aristotle University of Thessaloniki.

Pitilakis *et al*. (2009). "SRM-DGC (Development and proposition for implementation of an efficient methodology and appropriate local instruments for the management, prevention and reduction of seismic risk in Düzce - Turkey, Grevena - Greece and Catania - Italy) Final Report, Part B (2009)", *Final report for the city of Düzce (WP: 1-5)*, Laboratory of Soil Mechanics, Foundations & Geotechnical Earthquake Engineering, Department of Civil Engineering, Aristotle University of Thessaloniki.

Pitilakis, K., Alexoudi, A., Argyroudis, S., Monge, O. and Martin, C. (2006), "Chapter 9: Vulnerability assessment of lifelines", C.S. Oliveira, A. Roca and X. Goula ed., *Assessing and Managing Earthquake Risk. Geo-Scientific and Engineering Knowledge for Earthquake Risk mitigation: Developments, Tools and Techniques*, Springer Publ.

Pitilakis, K., Alexoudi, M., Kakderi, K., Manou, D., Batum, E. and Raptakis, D. (2005), "Vulnerability analysis of water systems in strong earthquakes. The case of Lefkas (Greece) and Düzce (Turkey)", *Proceedings of the International Symposium on the Geodynamics of Eastern Mediterranean: Active Tectonics of the Aegean*, Istanbul, June.

Pitilakis, K., Anastasiadis, A., Manakou, M., Apostolidis, P., Messini, A., Senetakis, K. and Fotopoulou, S. (2008), "Theoretical and empirical site response studies in the city of Grevena", *Proceedings of 3rd National Conference on Earthquake Engineering and Engineering Seismology*, Athens, November. (in Greek)

Pitilakis, K., Makra, K. and Raptakis, D. (2001), "2D vs 1D site effects with potential applications to seismic norms: the cases of EURO-SEISTEST and Thessaloniki", *Invited lecture in XVth International Conference on Soil Mechanics & Geotechnical Engineering*, 123-133, Istanbul - Turkey.

Pitilakis, K., Raptakis, D., Makra, K., Manakou, M. and Chávez-García, F.J. (2010), "EUROSEISTEST 3D array for the study of complex site effects", Akkar, D. Sinan; Gülkan, Polat; Eck, Torild van (Eds.), Earthquake

Data in Engineering Seismology, Predictive Models, Data Management and Networks. Series: Geotechnical, Geological, and Earthquake Engineering, Vol. 14.

Rosenblad, B.L., Rathje, E.M. and Stokoe, K.H. (2001), *Shear wave velocity profiling by SASW method at selected strong-motion stations from the 1999 Turkey earthquakes*, Final Report to Pacific Earthquake Engineering Research Center, September.

Sadigh, K., Chang, C.Y., Egan, J.A., Makdisi, F. and Youngs, R.R. (1997), "Attenuation relationships for shallow crustal earthquakes based on California strong motion data", S*eism. Res. Lett.*, **68**, 180-189.

Sahin, M. and Tari, E. (2000), "The August 17 Kocaeli and the November 12 Düzce earthquakes in Turkey", *Earth Planets Space*, **52**, 753-757.

Schnabel, P.B., Lysmer, J. and Seed, H.B. (1972). "SHAKE: a computer program for earthquake response analysis of horizontally layered sites", *Report No. EERC72-12*, University of California, Berkeley.

Simsek, O. and Dalgic, S. (1997), "Consolidation properties of the clays at Düzce plain and their relationship with geological evolution", *Geol. Bull. Turkey*, **40**, 29-38.

SRM-DGC (2006-2008), *Development and proposition for implementation of an efficient methodology and appropriate local instruments for the management, prevention and reduction of seismic risk in Düzce -Turkey, Grevena - Greece and Catania – Italy*, Research project, Interreg III B Archimed, Code Number. A.1.010.

Tadday, K. and Sahin, M., (2001), "Situation analysis and recommendations related to improvement measures for drinking water supply system in Düzce", *Proceedings of the Symposium on Water Supply Situation in Earthquake Affected Region*, Düzce, April.

Theodulidis, N. and Papazachos, B. (1992), "Dependence of strong ground motion on magnitude-distance, site geology and macroseismic intensity for shallow earthquakes in Greece: I, Peak horizontal acceleration, velocity and displacement", *Soil Dyn. Earth. Eng.,* **11**, 387-402.

Tromans, J. (2004), *Behaviour of buried water supply pipelines in earthquake zones*, PhD Thesis, Imperial College of Science, Department of Civil and Environmental Engineering, University of London.

Ural, O. (1999), "What Went Wrong?", *ITU-IAHS International Conference on the Kocaeli Earthquake*, Scientific Assessments and Recommendations for Re-building, Istanbul, December.

Yaltirak, C., Alpar, B. and Yuce, H. (1998), "Tectonic elements controlling the evolution of the Gulf of Saros (Northeastern Aegean Sea, Turkey)", *Tectonophysics*, **300**, 227-248.

Yamanaka, H., Kato, M., Hashimoto, M., Gulerce, U., Iyisan, R. and Ansal, A.M. (2002), *Assessment of seismic local-site effects at plural test sites*, Final Report to the Ministry of Education, Science, Sports and Culture, Research Grant No.11694134.

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