

## GEOTECHNICAL EARTHQUAKE HAZARD ASSESSMENT BASED ON A GIS PLATFORM

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### ABSTRACT

The present work explores the ability of a GIS platform based tool to estimate potential losses of geotechnical earthquake hazard. Phenomena, such as liquefaction, dynamic settlements, lateral spreading, landslides and permanent ground displacements are assessed in both qualitative and quantitative way, under a probabilistic hazard scenario that corresponds to the earthquake of 14<sup>th</sup> August 2003 that stroke the island of Lefkada. Post earthquake observations of geotechnical failures triggered by the above seismic event, meticulously registered in situ, are directly compared to theoretical scenarios of anticipated losses of geotechnical earthquake hazards, as depicted in relevant thematic maps. Theoretical results directly compared to observed geotechnical earthquake hazards are quite concluding in a considerable number of issues. However, a certain number of discrepancies that have been detected between calculations and observations are qualitatively explained, whilst perspectives for improvement of the computational GIS based approach are highlighted.

Keywords: GIS, landslides, hazard, slope stability, liquefaction, deformation, acceleration

### INTRODUCTION

At 8:15am on 14 August 2003 (05:15 GMT) an earthquake Mw=6.2 occurred at the NW Lefkada coast at the Ionian Sea. The main shock was strongly felt throughout Lefkada island and the other Ionian islands (from Corfu to Zakynthos) and in an extensive area of the western mainland of Greece. The shock was also felt as far as Athens, almost 280 km away. At the town of Lefkada island a low-resolution tri-axial strong motion instrument, recorded the main shock. The strong ground motion triggered seven more accelerographic stations of the permanent network of IESEE, located at the islands of Cephalonia and Zakynthos, as well as in the western mainland of Greece. Peak ground acceleration values of the recordings varied from 0.02 to 0.41g.

The island of Lefkada has been affected several times by strong seismic events causing structural and non-structural damage, injuries and human losses. During the last century the area of Lefkada was hit by the earthquakes of 27th November 1914 (Mw=6.3), of 22nd April 1948 (Mw=6.4) and of 30th June 1948 (Mw=6.4). Those seismic events of magnitude Mw>6.0 caused severe damage (Papazachos and Papazachou, 2003) such as: landslides, rockfalls, permanent ground displacements, lateral spreading, dynamic settlements, liquefaction, failures in harbors, houses, monuments, churches, lifelines etc, similar to the damage and failures observed at the recent earthquake of 14th August 2003 (Figure 1). In this work, results from a comprehensive, earthquake geotechnical loss

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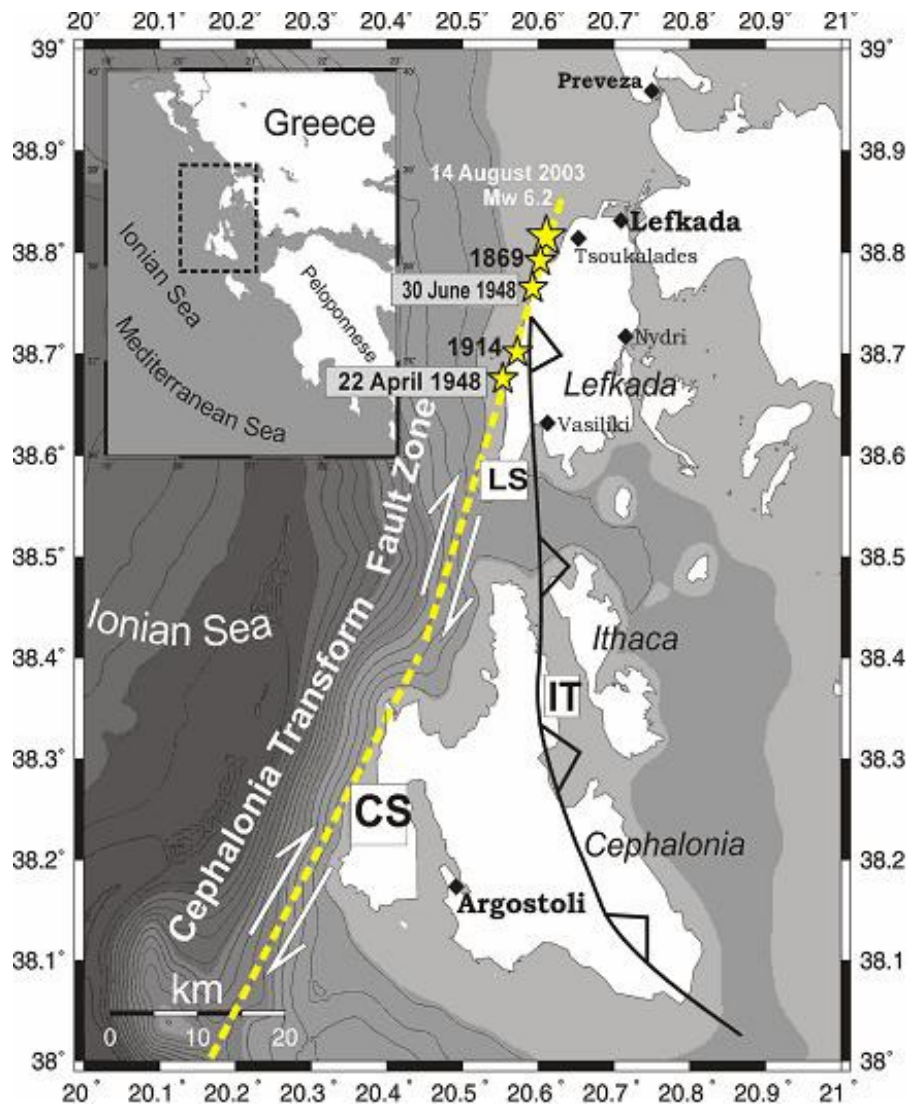
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scenario, based on the  $M_w=6.2$  earthquake of 13 August 2003, are critically presented and adequately compared to geotechnical damages as registered after the above seismic event at a regional scale covering the entity of Lefkada island.

### SEISMOLOGICAL AND STRONG GROUND MOTION DATA

The earthquake of August 14th 2003,  $M_w=6.2$ , occurred at the northern part of CTFZ, in the northern segment (LS) and is characterized by a dextral strike-slip motion with a thrust component, striking in a NNE direction and dipping in a SSE direction. The island of Lefkada is located at the most seismically active area of Greece. Karakostas et al. (2004), determined the properties of this seismic sequence, and using a great number of aftershock foci proposed a NNE-SSE seismic band which is in a good agreement with the strike of the main shock nodal planes in accordance to Harvard CTM solution (strike= $18^\circ$ , dip= $60^\circ$ , slip= $-175^\circ$ ). Determination of the seismic source mechanism of the Lefkada earthquake (2003), was carried out by Zahradnik et al. (2005), using a moment tensor inversion for a multiple point source extended to full waveform data at regional / local distances. Their model concludes two main events, which dominated the rupture process, the first (including 3 different sub-events) at Lefkada island and the second (one sub-event) at Cephallonian area.



**Figure 1** The Cephalonia Transform Fault Zone (CTFZ), showing the Cephalonian (CS) and Lefkada (LS) segments. The epicentre of the earthquake under study along with the epicentres of past strong earthquakes in the same area, are shown with asterisks (Benetatos et al., 2005)

Benetatos et al. (2005), using teleseismic long period digital data to determine the source parameters and regional broadband waveforms to study the focal mechanisms of the aftershocks of the sequence, defined the earthquake as a multiple source event.

The strong earthquake ground motion of the main shock was recorded by accelerometers located at the cities of Lefkada (LEF1), Preveza (PRE1), Amfilochia (AML1), Agrinio (AGR1), Argostoli (ARG1), Zakynthos (ZAK1) and Vartholomio (VAR2) (Margaris et al., 2003). Some of those sites (Lefkada, Preveza, and Argostoli) are presented in Figure 1. A peak horizontal ground acceleration of 0.42g was recorded at the station located at the city of Lefkada. The 5%-pseudoacceleration spectral values of the main record recorded at the Lefkada city, exhibit amplitudes  $S_a > 0.9g$  for a period range of 0.2 to 0.7sec revealing a spectral peak value of about 1.7g around 0.5 sec. For the same station, a fundamental period of the soil column was estimated around 0.5sec utilizing strong motion excitation (Dimitriou et al., 1999).

## METHODOLOGICAL APPROACH AND IMPLEMENTATION

HAZUS methodology was selected due to its sound scientific background, its flexibility and reliability. HAZUS is a multidisciplinary, modular based tool that local and state authorities can use for earthquake-hazard mitigation, development of seismic risk and loss scenario, emergency preparedness and any kind of disaster response planning (NIBS 1999). In this particular project, attention is specifically drawn on PESH module where geotechnical implications are described upon a user-provided probabilistic seismic hazard map based on local source and path seismological characteristics, as well as local site conditions.

The main goal of this work is to evaluate the possibility of using FEMA's loss estimation methodology incorporated in HAZUS software at an area outside USA. Lefkada island has been selected as a case study, since a serious number of geotechnical damage was registered as a consequence of the severe seismic event of the 14th of August 2003.

A straightforward comparison of results provided by the methodology, using an earthquake scenario equivalent to the 14/08/2003 earthquake ( $M_w=6.2$ ), with the actual damage induced by the aforementioned earthquake, consist the base of a critical evaluation of HAZUS methodology. Application of the methodology avoiding direct use of HAZUS software, involved the use of Arc GIS v8.3 software, the characterization of the earthquake hazard input using area specific geologic, geotechnical and seismological data and the creation of new geo-databases. Loss calculations were performed using a fairly dense grid of about 0.5 x 0.5km, leading to relatively dense geotechnical damage estimation.

Evaluation of HAZUS methodology in this case was carried out in three stages:

i) Calculation of the 14th August 2003 scenario earthquake ground motion based on a probabilistic seismic hazard regional map estimated only for rock conditions (site class B, according to 1997 NEHRP site classification system). Ground shaking is amplified by soil amplification factors as proposed by NEHRP 1997 site classification system. NEHRP Provisions originally do not provide soil amplification factors for PGA values. However, HAZUS methodology amplifies rock (i.e. site class B) PGA by the same factor as that specified in Table 1 for short period (0.3sec) spectral acceleration, as expressed in equation (1):

$$PGA_i = PGA * F_{Ai} \quad (1)$$

ii) Evaluation of liquefaction, ground settlement, permanent ground displacement and earthquake induced potential landslides using ground motion maps of the area based on the above probabilistic seismic hazard maps.

iii) Comparison of the previous stage resultant maps to maps depicting actual geotechnical damage.

**Table 1 Soil amplification factors (Hazus 99-SR2 Technical Manual, Chapter 4 – PESH)**

Site Class B Spectral Acceleration	Site Class				
	A	B	C	D	E
Short-Period, $S_{AS}$ (g)	Short-Period Amplification Factor, $F_A$				
$\leq 0.25$	0.8	1.0	1.2	1.6	2.5
0.50	0.8	1.0	1.2	1.4	1.7
0.75	0.8	1.0	1.1	1.2	1.2
1.0	0.8	1.0	1.0	1.1	0.9
$\geq 1.25$	0.8	1.0	1.0	1.0	0.8*

### LOCAL PROBABILISTIC SEISMIC HAZARD ASSESSMENT

Ground motion is calculated based on local seismological parameters and attenuation empirical predictive relationships in terms of different strong motion parameters, such as PGA or PSA, providing thus, user-supplied probabilistic seismic hazard contour maps only for rock site conditions. To account for local site conditions, soil amplification factors proposed for the 1997 *NEHRP Provisions*, as mentioned in above paragraphs, have been used after an appropriate site classification of geologic groups.

Probabilistic seismic hazard assessment (PSHA) is a statistical analysis of the earthquake hazard that addresses the question of “how strong” and “how often” the ground will shake, by considering all possible earthquakes that might affect the examined site. There are various approaches to estimate the ground motions appropriate for HAZUS calculations among them the probabilistic assessment and the numerical modelling technique. In the examined case, there are available strong motion data recorded during the Lefkada 2003 ( $M_w$ 6.2) strong earthquake, and empirical predictive relationships for Hellas, thus a probabilistic assessment of the seismic motion can be applied.

A seismic hazard assessment was performed based on the probabilistic approach proposed by Cornell (1968), for a grid of 144 points covering the entire area of Lefkada island and the adjacent sea area. The computer program used for calculations was FRISK88M, provided by Risk Engineering Inc. (1995). The seismotectonic model used combines both faults and area sources. Seismic hazard calculations have been carried out for the parameter of peak ground acceleration (PGA) and for a variety of return periods, ranging from 10 to 1000 years (figure 2). Based on the above analysis with respect to the recorded peak ground accelerations of the mainshock, 330 and 408cm/sec<sup>2</sup> at the Lefkada station characterized as, soil site conditions (class D according to NEHRP Provisions), it can be concluded that the specific seismic event of 2003/8/14 ( $M_w$ 6.2) corresponds approximately to return periods of 100 and 200 years depending on which seismic component it refers (hereafter, a mean return period of 150 years will be used as representative of the above seismic event).

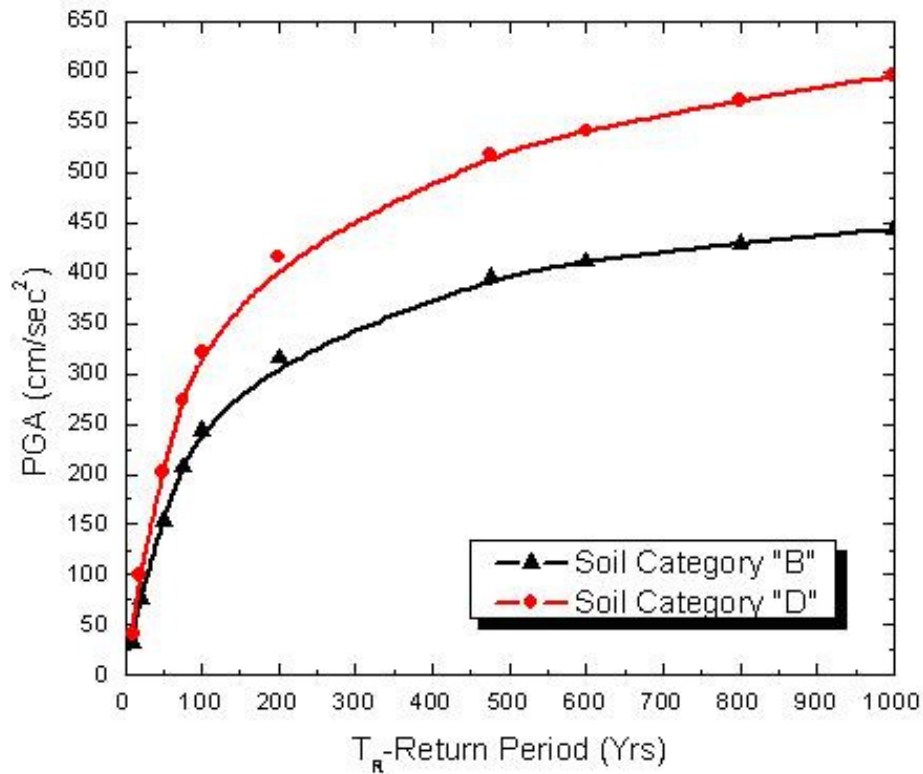
The empirical predictive relationships used, are the one proposed by Skarlatoudis et al. (2003), the most suitable for the Hellenic area, according to the latest instrumental data:

$$\log PGA = 0.86 + 0.45M - 1.27 \ln(R^2 + h^2)^{\frac{1}{2}} + 0.10F + 0.06S \pm 0.286 \quad (2)$$

$$\log PGA = 1.07 + 0.45M - 1.35 \ln(R + 6) + 0.09F + 0.06S \pm 0.286 \quad (3)$$

where,  $PGA$  is a peak ground acceleration (cm/sec<sup>2</sup>),  $M$  is the earthquake magnitude,  $R$  is the distance from seismic source to the examined site,  $h$  is a variable describing the average focal depth (for the area of Hellas it takes a value of 7),  $F$  is a variable that describes the effects of focal mechanisms and  $S$  is a variable describing site conditions. The  $F$  variable equals 0, 1, 2 for normal, thrust and strike slip faults respectively. The  $S$  variable takes values of 0, 1 and 2 for soil categories B, C and D

(according to the classification proposed by *NEHRP 1997*) respectively. In the current study, seismic hazard was estimated for all soil categories, but only site conditions representing class B (rock) have been adopted as a basis on which NEHRP amplification factors were afterwards applied. The difference between equations (2) and (3) is that the first one uses hypocentral distance, whereas the second one, uses epicentral distance. In practice, the two relations are almost identical apart from slight differences in the near field. Results of seismic hazard assessment as a PGA thematic map, are depicted for a mean return period of 150 years, corresponding to the seismic event of 14/08/2003 ( $M_w=6.2$ ) in figure 3.



**Figure 2 Seismic hazard curves showing the relationship between expected peak ground acceleration (cm/sec<sup>2</sup>) in terms of return period (years) for two different site conditions of subsurface geology (B to account for rock and D to account for soil)**

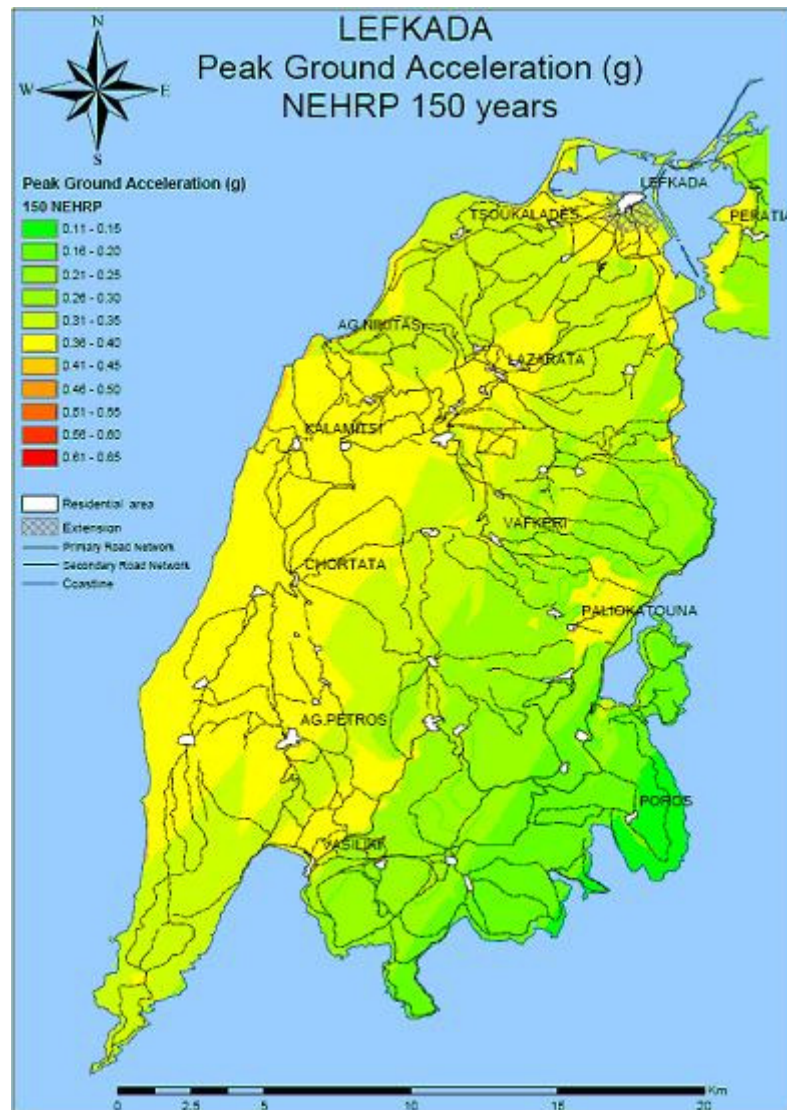
At this point of analysis, a direct comparison between estimated geotechnical damage level and observed post-earthquake geotechnical damage data is undertaken, as a consequence of the 'Lefkada' earthquake, a seismic event corresponding at a mean return period of approximately 150 years. This case study serves as a reliability test for HAZUS methodology focused on estimation of potential geotechnical hazards.

The PESH module estimates ground motion and ground failures (landslides, liquefaction, lateral spreading, dynamic settlements, permanent ground displacements, surface fault ruptures among others). In a previous chapter, regional ground motion is defined for rock outcropping conditions based on a probabilistic seismic hazard assessment in terms of peak ground accelerations (PGA), taking into account the amplifying effect of soil layers. This parameter is by far the simplest to describe the dynamic ground motion, but it is also well known that in a lot of cases it is not sufficient to account for the duration and the complexity of ground shaking. However, in this case only PGA values have been used in order to conform to HAZUS methodology used.

Dynamic ground shaking depends not only on magnitude and distance of the seismic source, but also upon local site conditions, such as subsurface and surface topography and also amplification of seismic motion subjected to the impedance contrast between sediments and underlying bedrock. The fundamental phenomenon responsible for ground motion amplification is trapping of seismic waves



due to impedance contrast between soil layers and the underlying bedrock. This site effect is generally accounted by amplification factors according to NEHRP Provisions (see Table 1) and this is what it has been accepted for our case, whereas subsurface and surface topography effects on seismic motion formation have been ignored according to HAZUS methodology.



**Figure 3 Seismic hazard assessment results for a mean return period of 150 years modified by NEHRP amplification factors according to site categorization**

## **EVALUATION OF GEOTECHNICAL HAZARDS**

### **Liquefaction and side phenomena**

The initial step in liquefaction hazard evaluation is characterization of relative liquefaction susceptibility of a region. Susceptibility is assessed from geologic maps at an appropriate scale (in this case 1:50.000), where information such as: age, depositional environment and material type for every mapped geologic unit, can be found and meet the crude criteria proposed by Youd and Perkins (1978). Liquefaction susceptibility of Lefkada island is stamped on Figure 4. Representation of regions susceptible to liquefaction seems reasonable and expected, even though criteria for liquefaction susceptibility classification are crude, approximate and probably insufficient.

The second step in liquefaction hazard evaluation is the assignment of a credible probability of liquefaction. The conditional liquefaction probability for a given susceptibility category at a specified

level of PGA is represented graphically in HAZUS, based on the state of practice empirical procedures. The conditional liquefaction probability relationships, as presented in PESH module were developed for a  $M=7.5$  earthquake and an assumed groundwater depth of five feet (1.67m). Correction factors to account for different moment magnitudes and groundwater depths have been foreseen since explicitly incorporated in the state-of-practice empirical procedures for evaluation of liquefaction potential. The likelihood of liquefaction is greatly influenced by ground shaking amplitude (PGA), ground shaking duration (indirectly accounted by earthquake magnitude,  $M$ ) and groundwater depth. The probability of occurrence of liquefaction for a given susceptibility category is expressed as:

$$P[\text{Liquefaction}_{SC}] = \{ [P[\text{Liquefaction}_{SC} / \text{PGA}=a]] / [K_M \times K_W] \} \times P_{ml} \quad (4)$$

where,

$P[\text{Liquefaction}_{SC}/\text{PGA}=a]$  conditional liquefaction probability for a given susceptibility category at a specified level of PGA

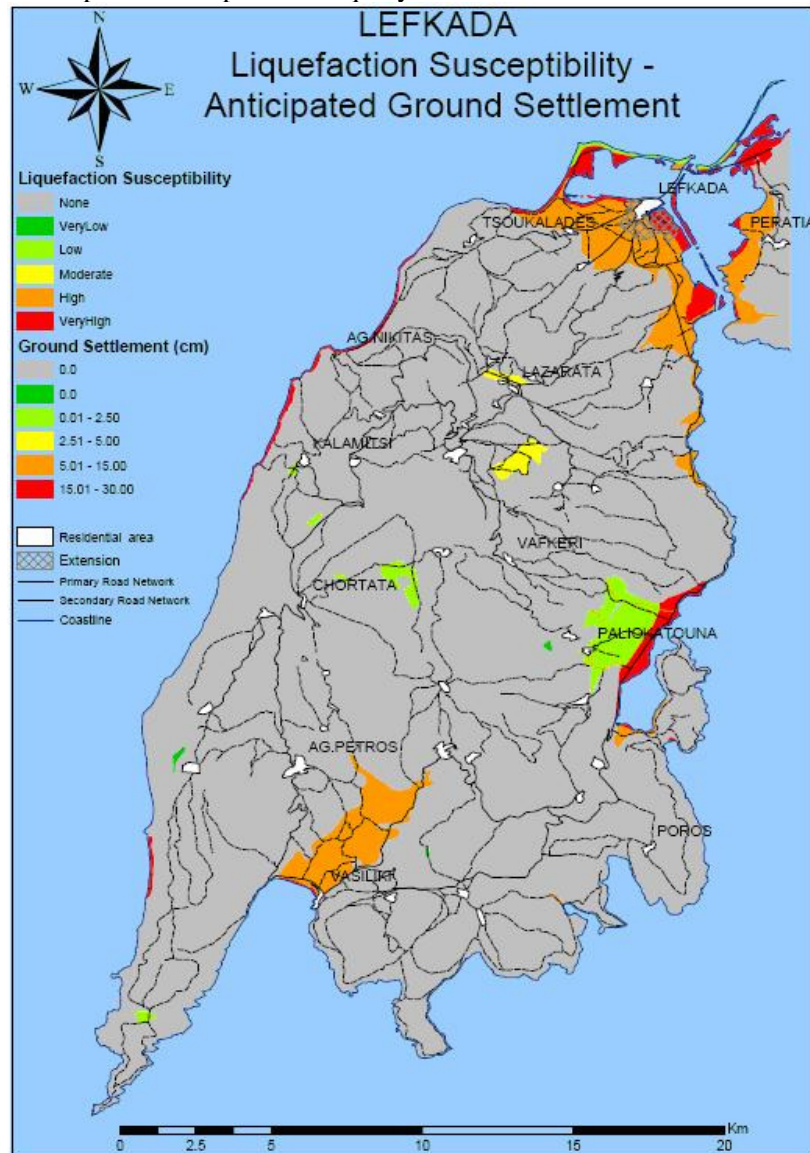
$K_M$  correction factor for moment magnitudes other than  $M=7.5$

$K_W$  correction factor for ground waters depths other than five feet

$M$  magnitude of the seismic event, and

$d_w$  depth down to groundwater table (in feet)

$P_{ml}$  proportion of map unit susceptible to liquefy



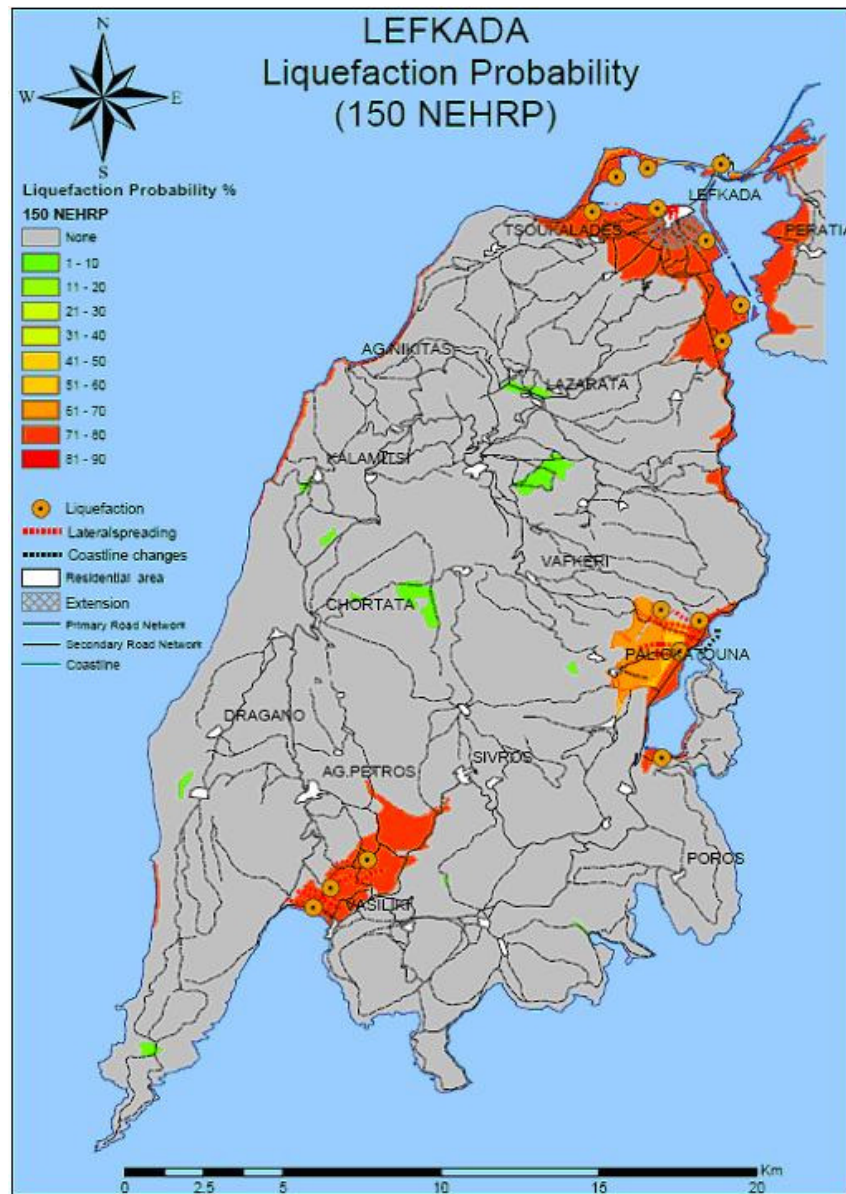
**Figure 5 Liquefaction susceptibility map of Lefkada island together with estimation of the anticipated differential ground settlement**

Modification factors are computed via the following relationships:

$$K_M = 0.0027M^3 - 0.0267M^2 - 0.2055M + 2.9188 \quad (5)$$

$$K_W = 0.022d_w + 0.93 \quad (6)$$

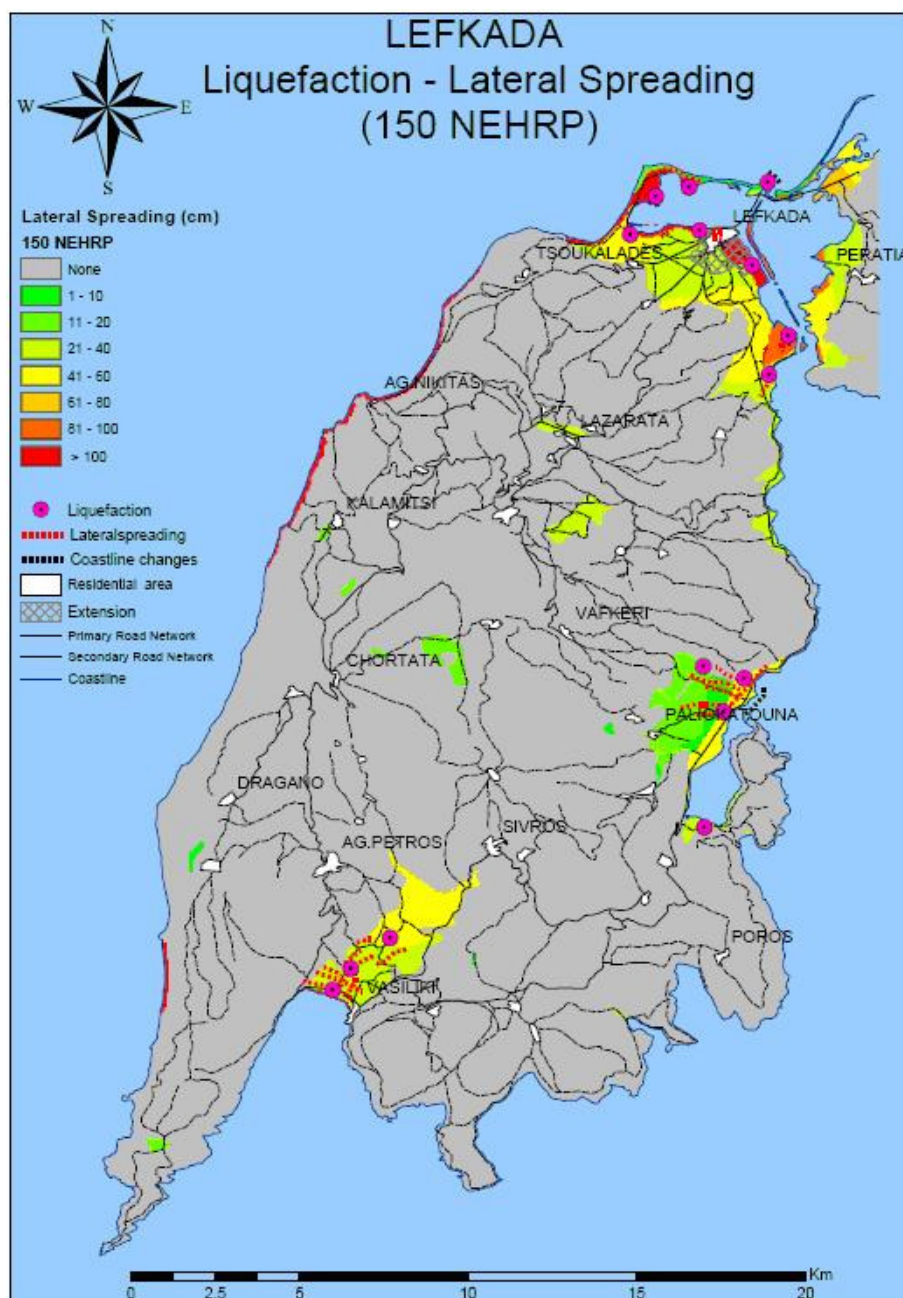
Results of conditional liquefaction probability are derived from the earthquake of 14/08/2003  $M_w=6.2$  corresponding to a mean return period of about 150 years and used herein as ‘validation’ seismic event. The amplification factors used for sites other than rocks (category B) are those of NEHRP Provisions. The distribution of conditional liquefaction probability represents the theoretical approach and is presented on figure 6, whereas on the same thematic map, locations where liquefaction was observed after the ‘Lefkada’ earthquake are also added. It is remarkable that the highest liquefaction probability estimations fit in with the liquefaction post-earthquake observations. It is also interesting to notice that no observation was stated in areas with liquefaction probability less than 60%, whereas the narrow stripe along the mountainous west coastline correspond to the sandy seashore, where indeed sand boils due to liquefaction were observed (Dimitriou et al., 2004; Margaris et al., 2003; Papadopoulos et al., 2003; Papathanassiou et al., 2004)



**Figure 6 Liquefaction probability map of Lefkada island. Location of liquefaction occurrence is also marked on the same thematic map**



Other side effects resulting from liquefaction, such as: lateral spreading and differential ground settlements are also examined. Location and size of theoretical estimation of dynamic ground settlements proved to be rather successful and relatively accurate by comparison to post-earthquake observations. As an example, it is stated that ground settlements of 15 to 50cm have been measured at the coastal part of Lefkada town; the examined methodology used herein, estimated 15 to 30cm for the same locations. On the other hand, lateral spreading has been identified at locations where liquefaction indeed occurred. The range of theoretical estimations varied from 20cm to 1m or even more, in some extreme cases (see figure 7). In situ measurement of lateral spreading is not an easy task, and cannot be done in an accurate and reliable way. However, horizontal movements of 20 to almost 60cm have been detected in liquefying prone zones at an almost flat or very slightly inclined surface ( $<5^\circ$ ).



**Figure 7 Theoretical calculation of lateral spreading. Location of sites where lateral spreading was observed is also marked on the same thematic map**

## Landslides

Another major geotechnical hazard that largely emerged after the examined earthquake is landslides and rockfalls. Landslides might occur both under static and/or seismic conditions. Therefore landslide susceptibility might differ under static and seismic conditions. Conformably to HAZUS methodology the geologic group and the slope angle, characterize landslide susceptibility under static conditions. For every geologic group, a pair of values of effective cohesion ( $c'$ ) and angle of friction ( $\phi'$ ) is assigned for each one of the three categories (A, B and C: see Table 2), whereas the influence of groundwater table is taken into account either as dry conditions (groundwater table below level of sliding), or wet conditions (groundwater level at ground surface). An arbitrary scale from I to X level, with I being the less susceptible class, categorizes landslide susceptibility under static conditions. In case of seismic conditions, critical acceleration ( $a_c$ ), is a crucial parameter that is added to the aforementioned, being a complex function of slope geology, steepness, groundwater table, type of landsliding and history of previous slope performance. The relationship of Wilson and Keefer (1985) is utilized in the methodology adopted herein; being very conservative the above relationship was found to refer only at a part of the susceptible map area.

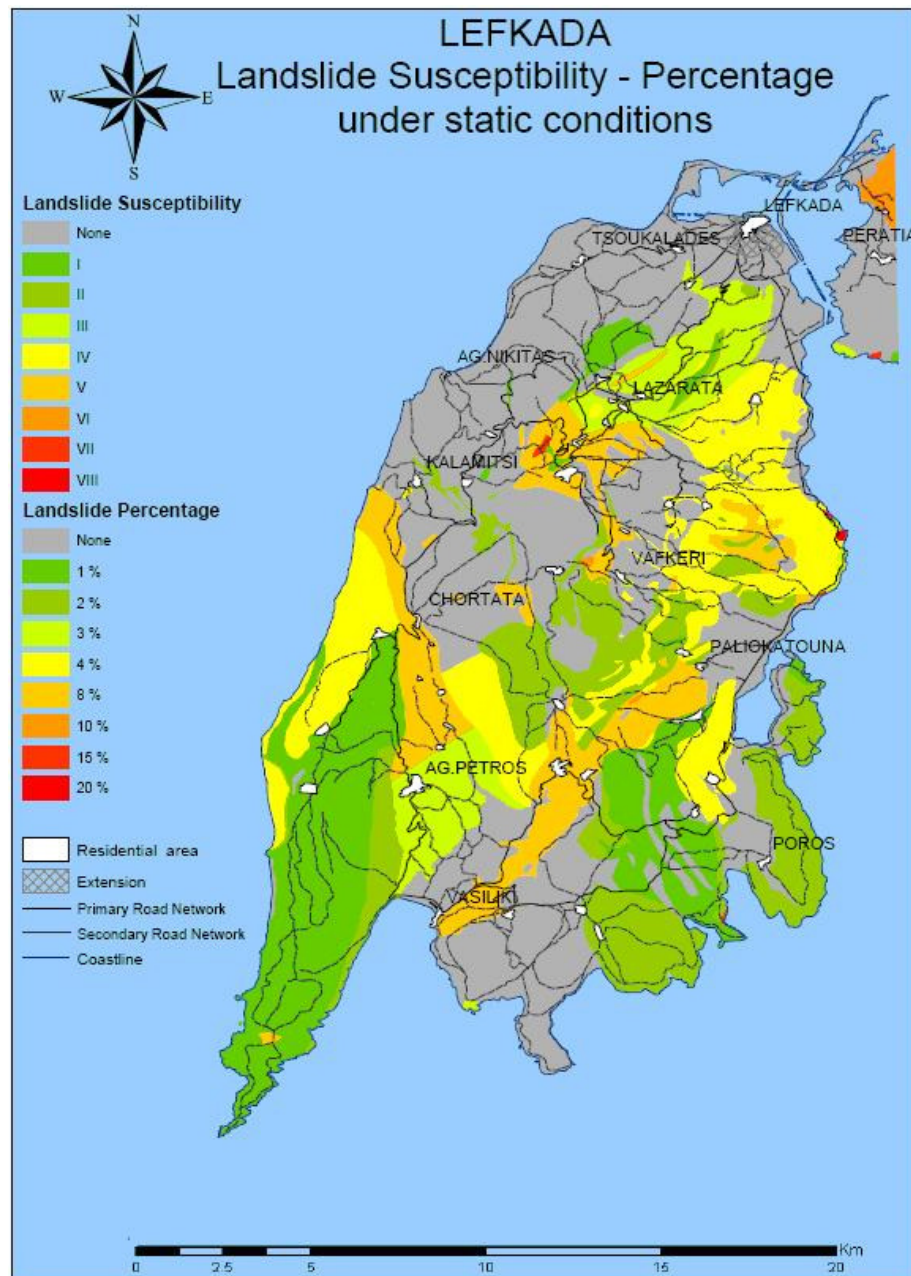
**Table 2 Landslides susceptibility of geologic groups under static conditions (Hazus 99-SR2 Technical Manual, Chapter 4 – PESH)**

Geologic Group		Slope Angle, degrees					
		0-10	10-15	15-20	20-30	30-40	>40
<b>(a) DRY (groundwater below level of sliding)</b>							
<b>A</b>	Strongly Cemented Rocks (crystalline rocks and well-cemented sandstone, $c' = 300$ psf, $\phi' = 35^\circ$ )	None	None	I	II	IV	VI
<b>B</b>	Weakly Cemented Rocks and Soils (sandy soils and poorly cemented sandstone, $c' = 0$ , $\phi' = 35^\circ$ )	None	III	IV	V	VI	VII
<b>C</b>	Argillaceous Rocks (shales, clayey soil, existing landslides, poorly compacted fills, $c' = 0$ , $\phi' = 20^\circ$ )	V	VI	VII	IX	IX	IX
<b>(b) WET (groundwater level at ground surface)</b>							
<b>A</b>	Strongly Cemented Rocks (crystalline rocks and well-cemented sandstone, $c' = 300$ psf, $\phi' = 35^\circ$ )	None	III	VI	VII	VIII	VIII
<b>B</b>	Weakly Cemented Rocks and Soils (sandy soils and poorly cemented sandstone, $c' = 0$ , $\phi' = 35^\circ$ )	V	VIII	IX	IX	IX	X
<b>C</b>	Argillaceous Rocks (shales, clayey soil, existing landslides, poorly compacted fills, $c' = 0$ , $\phi' = 20^\circ$ )	VII	IX	X	X	X	X

In figure 8 the thematic map representing landslide susceptibility and the implicated map area under static conditions, according to HAZUS criteria, resulted in a rather unexpected conclusion. The west part of the island, even though dominated, along the coastline, by mountains with high and rather steep natural slopes, landslide susceptibility is practical null or very low, whereas the flat or smoothed eastern part of the island, dominated by alluvial deposits, presents higher susceptibility. The same observation applies for Vassiliki and the homonymous valley, a village along the southwestern coastal zone at the river mouth of a torrent, built on soft soil deposits. Those theoretical results are obviously contradictory to the vast majority of landslides and rockfalls triggered by the 'Lefkada' earthquake, mainly located at the central, northern and western part of the island. At a first glance, this "paradox" cannot be easily explained, no matter whether static or seismic conditions have triggered the landslide. All observed landslides and rockfalls have been related to the examined seismic event and the seismic ground shaking was the triggering effect.

However, a more thorough examination of the estimated results concerning landslide susceptibility, points out the following:

1. The estimated landslide susceptibility refers exclusively to static conditions
2. Most of the landslides and rockfalls observed were detected on cut slopes, as well as on downstream slopes of road embankments. As survey and geological data used for the relevant thematic maps did not include any information about those cut slopes and downstream road embankment slopes, consequently, no damages could also be estimated for this kind of earthworks. Therefore, the only direct comparison of estimated and observed landslides and rockfalls that can be realistically evaluated is the one on natural slopes

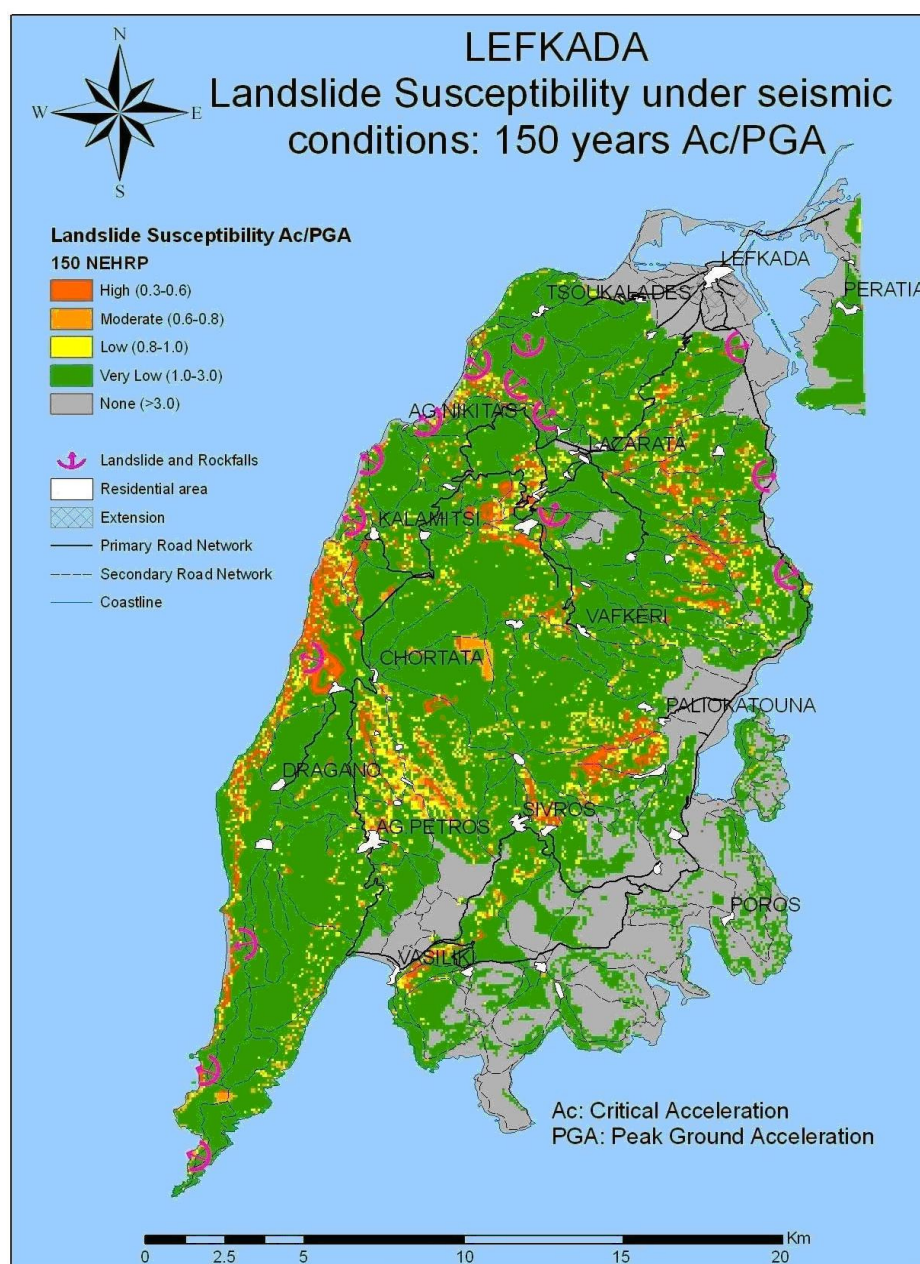


**Figure 8 Landslide susceptibility under static conditions and percentage of the affected map area having a landslide – susceptible deposit**

Once, the parameter of critical acceleration ( $a_c$ ) is taken into account as a function of the geologic group and the slope angle (Wilson and Keefer, 1985) then, ratio  $a_c/PGA$ , is calculated and can be presented as a new thematic map in figure 9. The above ratio can serve as an index relative to the probability of slide occurrence, triggered by a seismic event equivalent to the one of 14 August 2003. Observations of slides triggered by the 'Lefkada' earthquake are sited on the same thematic map of



calculated ratios,  $a_c/PGA$ , graded at an arbitrary scale from a very high ( $>3$ , no triggering effect) to a very low range of values (0.2 to 0.4). By straightforward comparison of estimated and observed slides, it results that the vast majority of post-earthquake slides were mainly observed at the central and the northern part of the island, as well as in the steep western coastal zone along the road axis joining the town of Lefkada, with Tsoukalades, Aghios Nikitas, Kathisma, Kalamitsi, Chortata, Dragano, Komilio (see Fig.10). The slides of the island road network can be categorized as rockfalls, rock sliding (plane and wedge failures), rock toppling and soil type sliding with scree deposits (rock fragments) accumulated as cone deposits at slope toes, with volume ranging from a few (1 to 2)  $m^3$  to some decades (10 to 50)  $m^3$ . The most extended failures were detected in limestones (thick bedded and thin bedded interpolated by thin layers of marly schist) located on steep cut slopes ( $h:v = 2:1$  to  $3:1$ ) and usually less steep natural slopes ( $h:v = 1:1$  to  $2:1$ ) with heights ranging from 20 to 60m and sometimes reaching 100m or even more.



**Figure 9** Landslide susceptibility under seismic conditions for shallow landslides, as those observed after the seismic event of 14 August 2003. Location of earth and rock instabilities observed, are also depicted on the same thematic map



Direct comparison between earth and rock slopes instabilities observed after the examined seismic event and expected by the thematic map highlights the following points:

- ❑ Location of landslides, rockfalls or other type instabilities is only partly redundant with the predicted sites of landslide susceptibility under seismic conditions, equivalent to the registered seismic event of 14 August 2003. There are sites where, even though, the expected possibility of earth or rock instability triggered by the aforementioned seismic event is high, no observation of geotechnical damage is reported. This does not necessarily mean that instabilities did not occur, but also is often due to difficulties in approaching the site for reporting
- ❑ In some other cases, the opposite is noticed; the GIS based tool did not predict geotechnical failures of natural slopes, triggered by the above seismic ground shaking. This also can be attributed either to the accuracy of the data used (survey at a scale 1:50.000), or to the fact that a meaningful part of the emerged landslides or other soil instabilities along some road networks was located at cut slopes or downstream road embankment slopes, which were not included in the survey background (such a detail at the examined scale is not feasible).

A characteristic example of this kind of discrepancy can be observed at the northern part of the western coastal road axis joining Aghios Nikitas to Tsoukalades. The southern part of the above road axis is well predicted by the GIS based tool, as well as geotechnical failures located at the secondary road axis joining Lazarata to the mid way of Aghios Nikitas – Tsoukalades road axis, since natural slopes are more vulnerable to sliding under seismic conditions. On the other hand, the northern part of the road axis Tsoukalades – Aghios Nikitas, even though it suffered from an important number of rockfalls and landslides, the examined tool did not correctly predict them, because the vast majority of them took place on the road cut slopes, which were not stamped at the thematic map (figure 9), and not on the overlying natural slopes less steep than the cut slopes.

### Permanent ground displacements

Permanent ground displacements are determined using the following expression (Hazu 99-SR2):

$$E[PGD] = E[d/A_{is}] * A_{is} * n \quad (9)$$

where,

- $E[d/A_{is}]$  is the expected displacement factor
- $A_{is}$  is the induced acceleration (in decimal fraction of g's)
- $n$  is the number of cycles (see equation 3)

A relationship between number of cycles and earthquake moment magnitude ( $M_w$ ) based on Seed and Idriss (1982) is expressed as follows:

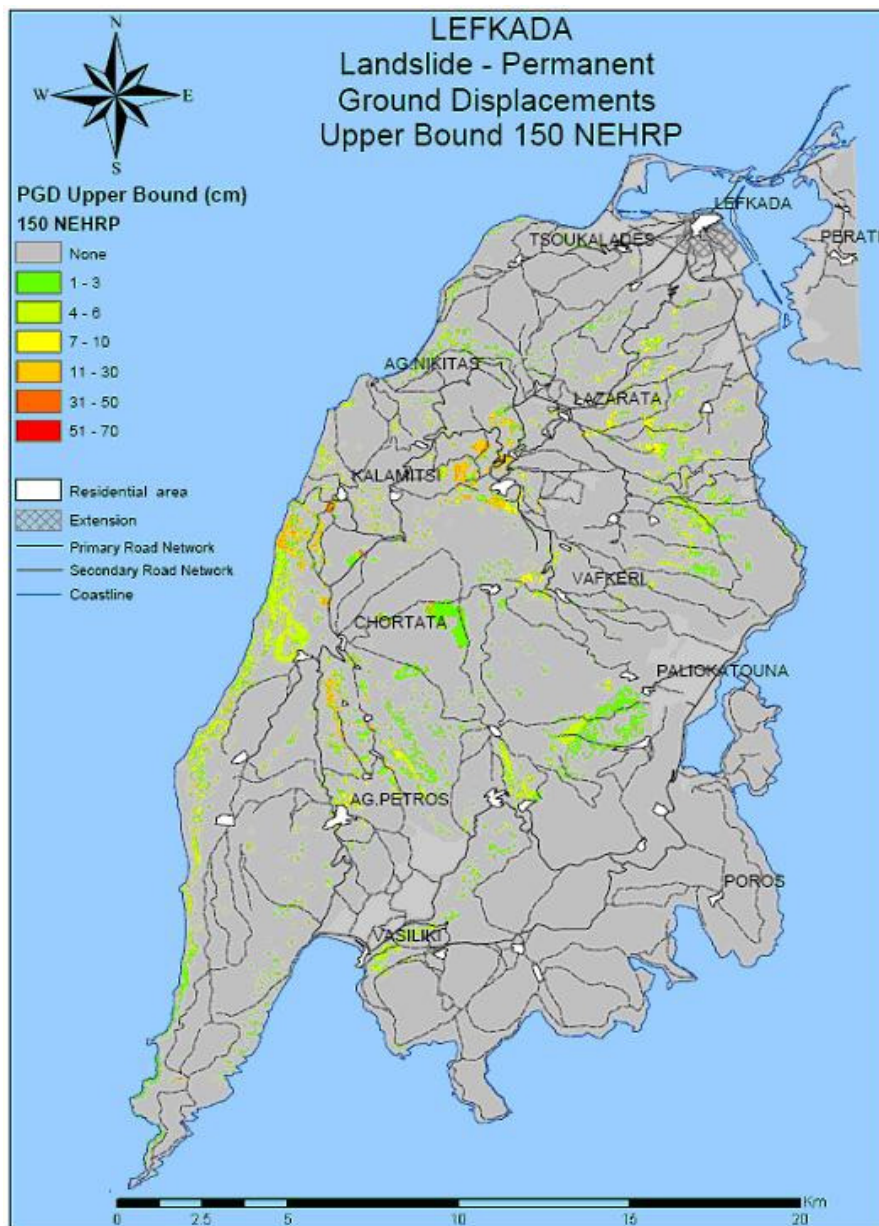
$$n = 0.3419M_w^3 - 5.5214M_w^2 + 33.6154M_w - 70.7692 \quad (10)$$

Therefore, for a known moment magnitude ( $M_w$ ), the number of cycles is determined. In the examined case, the moment of magnitude corresponds to a mean return period of 150 years,  $M_{150}=6.2$ . The induced peak ground acceleration within the slide mass,  $A_{is}$ , represents the average peak acceleration within the entire sliding mass. For relatively “shallow” and laterally small slides,  $A_{is}$ , is not significantly different from the induced peak ground surface acceleration, PGA. Once, the induced peak acceleration and the number of cycles are known, then the expected displacement factor is calculated either as an upper, or a lower bound according to Makdisi and Seed, 1978.

In this work, only the upper bound is calculated, in order to estimate in a conservative way the expected permanent downslope ground displacements triggered by a seismic ground motion, equivalent to the 14<sup>th</sup> August 2003 earthquake.

According to figure 10, the vast majority of the sites suffering from permanent downslope ground displacements, exhibit values less than 5 to 6cm. However, in a few cases substantial permanent

displacements exceeding 10cm are expected, whereas in some rare cases they might reach extreme values of about 30cm or even more. Nevertheless, important landslides where the GIS tool, along the western coastal road axis, joining Tsoukalades – Aghios Nikitas, should predict induced downslope permanent displacements, are missing for the reasons presented previously. Also, the western and southwestern coastal part of the island that suffered an important number of landslides, rockfalls and scree deposits at the toe of the slope, presents a very low number of estimated permanent downslope displacements. This might be explained by the fact that a lot of landslides took place in a very shallow way, throughout a weathered zone of a few meters, where the mechanical properties of the rockmass were seriously degraded compared to the geologic group where they have been originally classified. In that way, the GIS tool prediction corresponded to the expected permanent displacements for a sound rockmass, such as an unweathered thick-bedded limestone, whilst the sliding in reality occurred in the superficial weathered zone of the above rockmass. This kind of details might prove to be crucial for a correct geotechnical failure prediction, and definitely demand a more elaborated approach of the subject, by implementation of an improved methodology.



**Figure 10 Upper bound for expected permanent ground downslope displacements for “shallow” landslides triggered by a seismic event of a mean return period of approximately 150 years, equivalent to the one of 14<sup>th</sup> August 2003**

## CONCLUSIONS

A methodological approach essentially designated by HAZUS, to estimate potential geotechnical earthquake hazards under static and seismic conditions is implemented on a GIS platform, based on a probabilistic seismic hazard scenario simulating the seismic ground motion of the earthquake of 14<sup>th</sup> August 2003 that stroke the island of Lefkada. The reliability of the aforementioned computational tool, is evaluated via direct comparison of expected to observed geotechnical losses, reported after the earthquake that stroke the island of Lefkada at the 14<sup>th</sup> of August 2003.

Liquefaction hazards, as well as side phenomena, such as lateral spreading and dynamic settlements are quite satisfactory estimated by the above tool, based on a probabilistic seismic hazard scenario equivalent to the real seismic event that stroke Lefkada island. The methodological approach implemented, even though relative crude, proved to be suitable and reliable for the construction of relevant thematic maps depicting the above hazards in a both qualitative and quantitative way, for the requirements imposed by a regional scale of 1:50.000.

On the other hand, assessment of susceptibility for “shallow” landslides and permanent ground displacements triggered by the examined earthquake has been only partially successful, since decisive details could not be reported, due to the regional scale used. Landslides on cut slopes and road embankment slopes, even though quite numerous, could not be successfully predicted by the evaluated GIS based computational tool, since neither the former, nor the latter could be reported on the thematic maps produced. Concluding, geotechnical losses can be fairly enough predicted by the above tool at a regional scale, at least for a meaningful number of cases. However, for a more detailed study at a greater scale, a more elaborated tool needs to be designed and implemented for detailed and accurate prediction of expected geotechnical hazards, along road network and lifelines for engineering purposes.

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