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Earthquake loss estimation and benefit-cost analysis of mitigation measures for buildings in Greece: case study of Pylos town

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ABSTRACT Using observed-damage based vulnerability functions derived in an accompanying paper, we conduct loss estimation scenarios for the town of Pylos in south-western Peloponnese (Greece). Benefit-cost analysis for three different seismic retrofit programmes is then carried-out. These concern the strengthening of pre-1985 reinforced concrete (RC) buildings to the level of seismic performance of modern buildings, and two different retrofit programmes for the old unreinforced load-bearing stone masonry buildings (strengthening with steel tie-rods or a more extensive retrofit where wooden floors are replaced by RC flooring, introduction of RC ring beams and external and internal jacketing with shotcrete of the load-bearing stone walls). We conducted sensitivity analysis for parameters such as the cost of retrofit and the statistical value of human life and concluded that for the stone masonry buildings strengthening with steel tie-rods is cost effective with a time horizon of 10 to 19 years.

Key words: seismic risk, benefit-cost analysis, earthquake risk mitigation, loss estimation, building strengthening, Greece, SEAHELLARC.

1. Introduction

Earthquake loss estimation is used extensively for the development of risk assessment, preparedness and protection programs around the world. Loss estimation can be made for one single element at risk (e.g., a critical facility such as a hospital) or for a whole group of elements at risk in a town, city, region or country. In the present study we undertook to make a detailed assessment of the loss potential from various earthquake scenarios for the town of Pylos (Greece) before and after the implementation of specific strengthening measures.

Pylos town is a provincial town with a mix of buildings typical for a town of its size in the region of Peloponnese. The changing profile of the buildings in Pylos municipal department based on the Hellenic Statistical Authority (EL.STAT., 1970, 1990, 2000) Building Census data (December 1970, 1990 and 2000) over the last 30-year period was firstly checked. In addition, a building by building survey of the Pylos building stock was carried out in order to obtain further information for every single building. Furthermore, the assessment of the vulnerability of the buildings was necessary for loss estimation scenarios to be developed and then for the efficiency of mitigation options to be examined. This is presented in an accompanying paper (Pomonis *et al.*, 2014).

Four distinct earthquake intensity scenarios have been developed (VI to IX in EMS-98). The potential direct losses to buildings can be significantly reduced when well-planned mitigation measures are put in action. In this article we will explore the potential economic benefits to Pylos town from the implementation of various mitigation measures directed towards the reduction of the vulnerability of the existing building stock, in particular the most vulnerable buildings [i.e., the old unreinforced stone masonry and the pre-1985 reinforced concrete (RC) buildings].

We estimate the vulnerability of the post-retrofit buildings in order to assess the potential reduction in economic losses. We also employ human casualty modelling by estimating the pre- and post-retrofit collapse probabilities of the targeted buildings and assign probabilities of loss of life during a night-time earthquake and the non-holiday period in the case of building collapse. Finally, we use standard cost-benefit analysis methodology to assess the benefit brought about by each mitigation option.

2. The Pylos town building stock

For the development of building-related earthquake loss estimation and mitigation studies, it is most important that a detailed understanding of the characteristics of the study zone is at first obtained. In Greece detailed building stock data are provided for any settlement in the country by the Hellenic Statistical Authority (EL.STAT.) on the basis of the Buildings Census (conducted in December 1970, 1990 and 2000: EL.STAT., 1970, 1990, 2000) and the Population and Dwellings Census (the last conducted in March 2001: EL.STAT., 1971, 1981, 1991, 2001).

The town of Pylos is situated in south-western Peloponnese (36.92°N-21.70°E) at the south-eastern part of Pylos Bay (also historically known as the Navarino Bay) which is enclosed by Sphacteria Island, providing excellent natural protection and used since the antiquity as a natural port. The town is characterized by its amphitheatric pattern of development and is currently expanding towards the higher grounds to the east of the town centre. Pylos town has characteristics of a traditional-historic provincial town, with a strong commercial centre servicing the population of the town and surrounding area (Fig. 1).

Pylos municipality includes the town of Pylos with 2,111 inhabitants and 19 neighbouring villages with 3,291 inhabitants (March 2001 Population and Dwellings Census). The 2001 census registered 1,299 regular dwellings in Pylos town (1.63 people per regular dwelling). In the Pylos Municipal Department (the subdivision that contains Pylos town and 4 nearby villages), the 2001 census recorded 899 households with 2,449 members (2.72 people per household) who lived in 893 permanently occupied dwellings, whereas 635 dwellings are listed as “vacant” (41.4% vacancy rate). The vacant dwellings include: homes on the market for letting or purchase, secondary-holiday homes and dwellings that have been vacated due to rapid urbanisation and are occupied by their owners for few days in the year, while homes for letting to tourists are registered separately in the category of hotels.

In terms of buildings, the census of December 2000 recorded 896 buildings (610 residential, 147 residential mixed with other occupancies and 139 non-residential) in the town of Pylos. The non-residential buildings consisted of: 71 office and/or retail buildings, 10 hotels, 3 educational, 2 worship, 2 industrial, 2 health sector buildings and 49 of other use/occupancy (primarily

Fig. 1 - Partial view of Pylos town (view from the main harbour pier towards the NE).

agricultural warehouses). In terms of number of floors, 33% (297) of the town's buildings were single-storeyed, 52% (467) were two-storeyed, 14% (127) were three-storeyed and only 5 buildings had four storeys.

In terms of age (period of construction) 38% (336) were built prior to 1945, 16% (145) were built in the 1945-1960 period (i.e., to the introduction of the first Greek earthquake code in 1959), 31% (277) were built in the 1961-1985 period (i.e., prior to the introduction of the 1984 Greek earthquake code upgrade), 10% (92) were built in the 1986-1995 period (i.e., prior to the introduction of the modern earthquake code of Greece in 1995) and just 5% (46) were built or were under construction in the 1996-2000 period based on modern earthquake engineering design principles. In terms of load-bearing structure, 48% (427) of the buildings were recorded as RC structures, 51% (459) as stone masonry structures and 1% (10) as other structural types (timber frame, brick masonry, metal frame). In terms of roof cover type, 74% (660) had pitched roofs with clay tiles and 25% (225) had flat RC slabs.

Analysis of the successive EL.STAT. Building Census data (December 1970, 1990 and 2000, respectively) proved quite valuable as it provided a first insight into the composition of the Pylos building stock over the period 1970 to 2000. In addition, the digital GIS files of Pylos developed by EL.STAT. using aerial photography of 1997 were a valuable tool that we used in the construction of thematic maps, as well as in the derivation of built-up floor area based on the outline footprints of the existing buildings and the number of floors. Following the analysis of the existing statistical data, a street level building by building survey was also carried-out by the authors.

2.1. Building by building street level survey of Pylos town

A building by building street level survey was carried-out in October 2008 in order to gain first-hand experience on the typologies and condition of the buildings in Pylos, so that first-level seismic vulnerability classification could be made at the individual building level (as the EL.STAT. data were available only at sector level). The street level survey was also necessary in order to bring the information up-to-date, so that changes in the period 2001-2008 could be detected (demolished buildings, ruined buildings, buildings recently constructed, renovated buildings and buildings under construction). Finally, we also wanted to capture the numerous buildings of mixed structure (masonry and reinforced concrete) which are not shown in the December 2000 buildings census and which, from previous experience we expect would have different earthquake vulnerability than the masonry or RC buildings (Pomonis *et al.*, 2014).

With this work we were able to further improve the accuracy of the database in each of the town's blocks and add further qualitative elements such as:

- construction type of each building (based on the material used for the load-bearing structure);
- condition (state of repair) of masonry buildings;
- period of construction of RC buildings using 4 age bands according to the earthquake code developments in Greece (based on empirical assessment);
- location of ruined, abandoned buildings;
- location of new building activity;
- photographs of each building for posterior use.

All the surveyed buildings were photographed and the photos were subsequently used in refining the information that was summarily collected in the field. The collected data refers to 838 buildings situated in 85 town blocks. From these buildings, 18 were in a state of ruin or clearly abandoned and were not used in the analysis. Our street level survey conducted in October 2008 covered over 90% of the Pylos town building stock. Only some areas in the outskirts of the town were not surveyed. Detailed analysis of the findings of the street level survey can be found in Pomonis and Gaspari (2009).

In terms of structural type, masonry buildings (44% of the surveyed buildings and 32% of the built floor area) are built using local stone material some being older than 250 years. The roofs are tiled in the traditional style found in Greece (semi-crescent clay tiles). A number of listed for preservation buildings exist (primarily around the Three Admirals Square) having remarkable architectural value (arches, frames around the openings, etc.). Newer buildings (since circa 1960) are made from RC frames with horizontally perforated clay brick infill walls (48% of the surveyed buildings and 63% of the built floor area). These can be found mostly in the peripheries of the historic town centre which is situated near the port. A further 7% of the existing buildings have mixed structural type (unreinforced load-bearing masonry and RC frames) and are scattered around the town. Fig. 2 shows maps of Pylos town where the spatial distribution of the building stock in terms of structural type (left), and level of earthquake code for the RC buildings (right) can be seen.

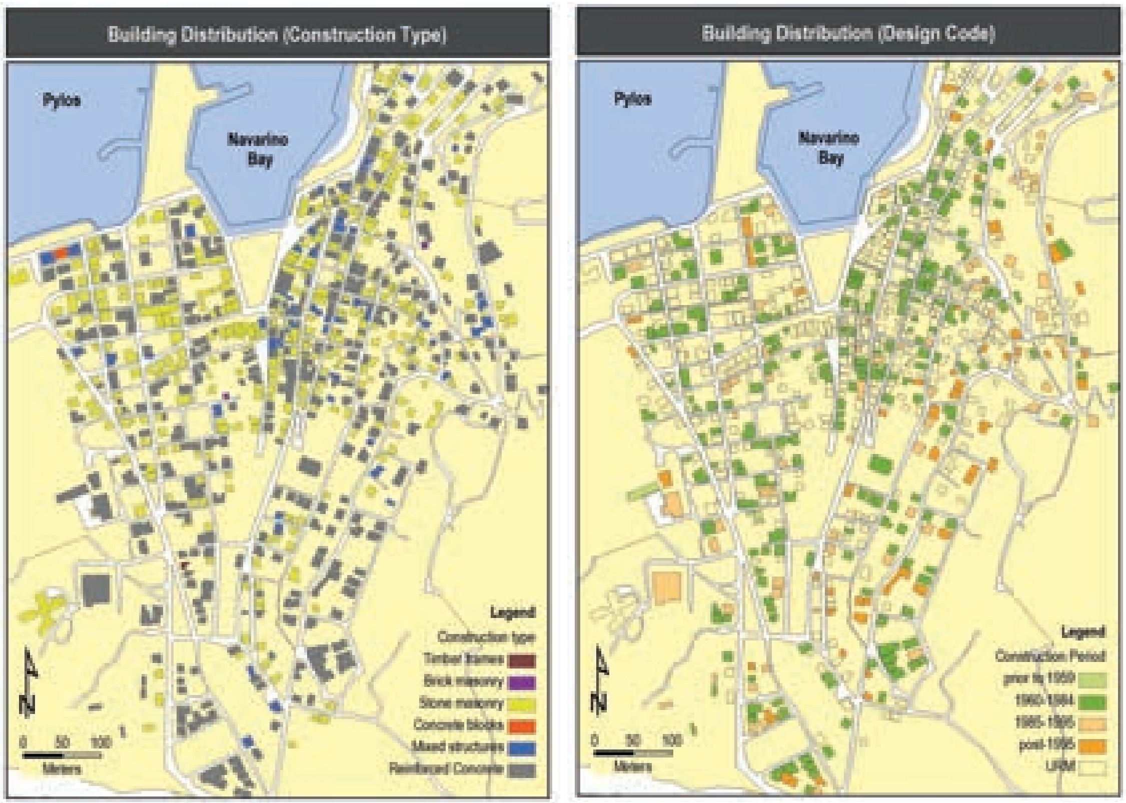

Fig. 2 - Pylos town building stock by structural type (left) and RC buildings by earthquake code level (right) as of October 2008.

For the development of earthquake loss estimation scenarios, it is necessary for the buildings to be grouped in categories for which derivation of empirical (observed damage based) vulnerability functions have been produced (Pomonis *et al*., 2014). These categories are summarized in Table 1. It resulted that 55 of the 820 surveyed buildings would not be included in the loss estimation analysis (7% of the total) either because they were public buildings of higher importance (thus designed and built based on higher standards, e.g., the 5 school buildings, the health centre, etc.), or 4-storeyed RC buildings (9), or 3-storeyed masonry buildings, or buildings on pilotis, or the few wooden and brick masonry buildings for which there was not sufficiently detailed damage information to derive reliable empirical vulnerability functions. Two typical examples of buildings in Pylos are shown in Fig. 3.

3. Earthquake loss scenarios for Pylos town

Earthquake scenarios refer to the various types of damage or levels of loss that can happen as a result of the occurrence of an earthquake, such as damage to the infrastructures (e.g., buildings, bridges, roads, lifelines, etc.), effects on humans (e.g., number and types of injuries, fatalities), financial losses resulting from the interruption of the normal day-to-day economic activities,

Fig. 3 - A typical two-storey residential unreinforced load-bearing stone masonry building (left), a typical 3-storey RC frame with infill masonry walls apartment building of the period 1985-1994 (right).

social losses (e.g., number of people made homeless for short or long periods of time, number of people becoming unemployed, etc.). Usually the first step for any earthquake scenario is the evaluation of the damage to constructions, particularly to buildings. The preparation of a damage scenario of buildings, as described by Dolce *et al*. (2006) and Gaspari (2009), requires pieces of information regarding:

- the inventory of the buildings of interest in the study zone;
- knowledge about the vulnerability of the buildings of interest to the expected ground motion;
- knowledge of the characteristics of the expected ground motion including possible site effects.

The present study combines the vulnerability curves developed for Greek buildings (Pomonis

Table 1 - Structural type categories and distribution found in Pylos town that have been used in the development of the earthquake loss estimation scenarios.

Structural Code	Load-bearing structure	Period of construction	Number of floors	Number of buildings	Floor area (m²)
RC1-L	Reinforced Concrete Frame (without soft-storey)	Pre-1959	1 to 3	5	755
RC2-L		1959-1984	1 to 3	243	70,906
RC3-L		1985-1994	1 to 3	67	18,848
RC4-L		Post-1994	1 to 3	56	16,529
LBSM-L	Load Bearing Stone Masonry	pre-1970	1 to 2	340	55,716
MIXS-L	Mixed (stone masonry & RC frame)	-	1 to 2	54	9,307
			Total	765	172,061

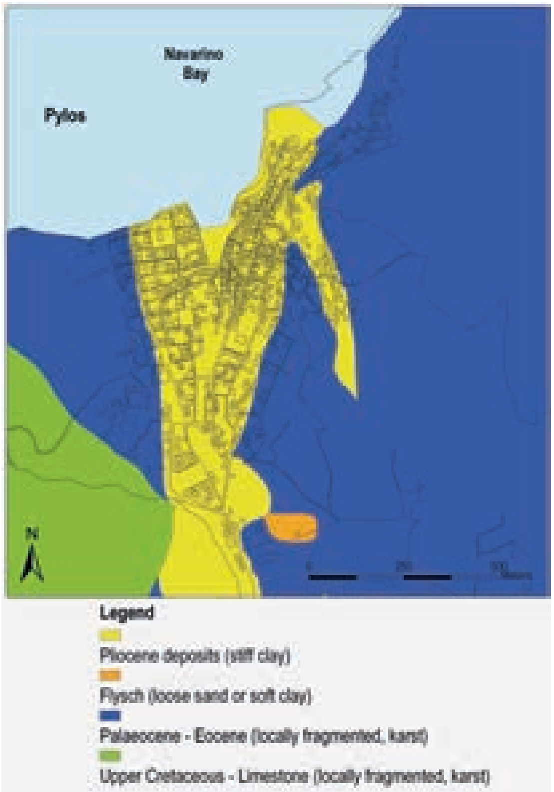

Fig. 4 - Geotechnical map of Pylos town overlaid on the town plan (source: EPPO, 1987).

et al., 2014) of RC, unreinforced stone masonry and mixed structures (with stone masonry and RC elements), with the results of our building by building surveys in Pylos town (described above) to develop four distinct earthquake scenarios for the town of Pylos, estimating the potential losses to the town's building stock if it is subjected to ground motion of EMS-98 intensity VI to IX.

3.1, Soil conditions in Pylos town

To investigate the potential for local site effects in Pylos town we collected information at first from the relevant 1:50,000 map sheet of the Institute of Geology and Mineral Exploration (IGME) – the Koroni-Pylos-Skhiza map sheet (IGME, 1970). A more detailed study (scale 1:5,000) on the soil conditions in the town of Pylos was carried-out in 1987 for the Earthquake Planning and Protection Organization (EPPO, 1987). There is general agreement between these two studies.

The proposed geotechnical map is shown in Fig. 4 and has been derived from the aforementioned studies. According to this map, most of Pylos town is founded on post-Alpine Upper Pliocene to Lower Pleistocene formations composed of marls, sandstones and some marly limestones (shown in yellow in Fig. 4). The Pliocene formations are surrounded by Palaeocene-Eocene limestone hills to the east and west (shown in blue in Fig. 4). These limestone formations have a total thickness of about 150 m. The northern entrance to the town lies on these hills as do the eastern and western extremities of the built-up areas of Pylos town. These two formations are of marine origin being surrounded by neritic carbonate sediments that belong to the autochthonous Gavrovo-Pylos Unit (shown in green in Fig. 4).

The EPPO (1987) report gives reference of the mechanical properties of marly limestone and limestone samples from Pylos based on data from three adjacent boreholes. According to this study, the compressive and tensile strengths of the samples showed great scatter due to the differences in the degree of weathering, karsting and fragmentation. The marly limestones were classified as "soft rock or stiff clay" and the limestone as "strongly weathered rock of average strength". Other geotechnical, strong motion or microtremor studies and recordings are not available for Pylos town. Therefore we cannot be certain about the mechanical properties or representative shear wave velocities in these two formations.

Based on the above, the engineering characterization of the two formations found in Pylos town has been made according to the soil classes in the Eurocode 8 (Eurocode-8, 1998) which categorizes soil conditions in 5 classes (A to E). We propose that all of Pylos town is founded on class B subsoil which is defined as follows: "Deposits of very dense sand, gravel, or very stiff clay, at least several tens of metres in thickness, characterised by a gradual increase of mechanical properties with depth". Besides, an analysis of the distribution of the surveyed Pylos building stock by geologic formation showed that 78% of the buildings and 73% of the total built area are sited on the Pliocene deposits and the remaining on the Palaeocene-Eocene deposits.

The present loss estimation and benefit-cost analysis of mitigation measures for Pylos town is using the European Macroseismic Intensity scale (Grünthal, 1998) as descriptor of the ground motion severity. Although it is possible that within the boundaries of Pylos town there will be zones that may experience stronger shaking at certain frequency range due to local soil or topographic conditions, such as near the Pylos stream (situated near the town centre) which forms a steep and strongly eroded 100 m wide and 15 m deep valley of approximately 500 m length (EPPO, 1987), we believe that at present there is no sufficient evidence for us to differentiate shaking intensity within this small town.

3.2. Historic evidence of seismic intensities in Pylos town

There is historic evidence that seismic intensities in Pylos town are lower than in neighbouring Yalova village founded on alluvium. Yalova is an area of expanding tourist developments 5 km north of Pylos town (Fig. 5). A summary of the intensities reported in Pylos and surrounding villages from the three strongest earthquakes that have affected the region in the last 124 years (the August 27, 1886; the January 22, 1899 and the October 6, 1947 earthquakes) is shown in Table 2 [based on the isoseismal maps and descriptions in Galanopoulos (1941a, 1941b, 1949, 1953)].

Since 1947 there has not been a damaging earthquake in the Pylos area. On February 18, 2008 a magnitude 6.7 earthquake occurred south of Koroni and Methoni in the region around Pylos. The epicentre was approximately 115 km south of Pylos. There was slight to moderate damage in the town of Koroni but in Pylos, except for the fall of some objects and books from shelves (suggestive of EMS-98 intensity V to VI), other effects were not observed (ITSAK, 2008).

Table 2 - Seismic intensities reported in Pylos town and its neighbouring villages during the 1886, 1899 and 1947 earthquakes.

	Seismic event		
Location	**27.8.1886 (M7.3, crustal)**	**22.1.1899 (M6.5, crustal)**	**6.10.1947 (M6.7, crustal)**
Pylos	VII-VIII	VI-VII	VII
Yalova	X-XI	VII	IX
Elaiophyton	X	VII	IX
Palaioneron	VII	VI	VII
Schinolakka	VI-VII	VII	VII

Fig. 5 - Pylos municipality boundaries with location of Pylos town, nearby villages and neighbouring municipalities (Koroni and Methoni).

3.3. Macroseismic intensity-based scenarios

We have developed four distinct earthquake loss scenarios for EMS-98 intensities VI to IX respectively. Here we will present loss statistics for the scenarios of intensity VIII and IX. The most important parameter to be established is the financial loss that will result from these scenarios (i.e., the cost incurred in order to repair and reconstruct the buildings so that life is brought back to the pre-earthquake standards). This parameter is the basic guide for decision-making regarding the pre-earthquake preparedness in a study zone (Kappos *et al*., 2002).

It must be noted that the estimates of loss that follow, refer only to the direct cost to repair and reconstruct the affected buildings. The actual costs of an earthquake include other sources of loss related to damage in other infrastructures, the cost of disruption of the normal economic activity, the cost of the injuries and fatalities, the cost of content losses, etc..

The unit of analysis is the individual town blocks (*b*) of Pylos town (85 blocks) but the results are also summed for the whole town. In order to derive the financial loss for each block, we first need to derive the block's mean damage factor (MDF_b) which is obtained through Eq. (1), where MDF_i is the mean damage factor for each structural class i [as were proposed in the EMS-98 based vulnerability functions proposed in Pomonis *et al*. (2014)], A_i is the built floor area for each building class in a town block, and A_b is the total built floor area of each town block:

$$MDF_b = \frac{\sum A_i MDF_i}{A_b} \quad . \tag{1}$$

Town blocks that contain buildings of higher vulnerability will, as a result experience, higher mean damage factors. Therefore, MDF_b indicates the most vulnerable blocks in a town and becomes a useful tool for the preparation and prioritization of pre-earthquake preparedness and damage mitigation measures (e.g., detection and strengthening of vulnerable buildings, upgrading buildings of higher importance, preparation of emergency plans, designation of open areas for setting-up temporary housing facilities, etc.).

Furthermore, the loss ratio (*V*) for the whole town, expressed as a loss ratio relative to the replacement value of the whole town's analyzed building stock, is derived by summing the products between the mean damage factor (MDF_b) and the built area of each town block (b) divided by the total existing floor area in the town (A = 172,061 m^2) as shown by Eq. (2):

$$V = \sum \frac{MDF_b \times A_b}{A} \quad . \tag{2}$$

The actual direct financial losses (*L*) [Eq. (3)] are derived by the product of the total loss ratio (*V*) with the total replacement value of the town's buildings C = 172.1 million € assuming a unit cost of replacement equal to 1,000 € per square-metre (the average cost of new RC construction in Greece in 2010, based on construction industry data, for ready to occupy housing):

$$L = V \times C \quad . \tag{3}$$

Assuming uniform seismic intensity VIII or IX across Pylos town, the estimated damage distribution for the unreinforced stone masonry (LBSM) and the mixed structures (masonry and RC) based on the 5 damage grades of EMS-98, and the RC buildings based on EPPO+ damage scale (4 damage grades) as described in Pomonis *et al*. (2014), are shown in Tables 3 and 4 respectively. The results show that under intensity VIII we estimate that 60.5% of the total built floor area of LBSM and mixed structure buildings, and 30.6% of the total built floor area of RC buildings respectively will be damaged. Fig. 6 shows the mean damage factor of each town block (MDF_b) under intensity VIII and IX (left and right). It is seen that the losses at the individual block level do not exceed 20% for intensity VIII whereas they reach up to 36% under intensity IX.

Table 5 shows the summary results for all four intensity level scenarios (VI to IX) by building vulnerability class. The total loss ratio (*V*) ranges from 1.2% for intensity VI to 15.5% for intensity IX, while the direct financial losses (*L*) reach € 2.0 and 26.7 million respectively. At intensity VIII the total loss ratio (*V*) is 7.5% with the greatest contribution (70.1%) to this loss ratio coming from the LBSM buildings, while the direct financial losses reach 13.0 million €. These results will be used in the assessment of the cost efficiency of potential mitigation policies which follow.

4. Benefit-cost analysis of mitigation measures

For the benefits of the mitigation options to be comparable, it is necessary to initially calculate the various types of losses that can result if no mitigation measures are employed. The direct financial losses resulting from physical damage to the existing residential buildings of Pylos town under increasing seismic intensities were described in section 3 of this paper. The other categories of losses considered in this study and how these are calculated are summarized in Table 6. In addition to the direct losses (damage to the buildings and their installations), we have to take into

Fig. 6 - Distribution of mean damage factor (*MDF*) in each block of Pylos town for I_{EMS} = VIII (a); for I_{EMS} = IX (b).

account the potential losses to the contents of the buildings (house ware, furnishings, valuable properties, etc.) as well as other indirect losses (e.g., loss of income, need for additional living expenses, need for alternative housing or workplace during the repair or reconstruction works, etc.). We also have to take into account the losses resulting from potential fatalities that have considerable psychological and financial impact. In the present study we do not assess the costs resulting from the occurrence of physical injuries, which are also significant and can become extremely costly in the case of injuries that cause temporary or permanent disabilities.

The content losses have been assumed to amount to a constant 30% of the direct losses (Kappos and Dimitrakopoulos, 2008). As far as indirect losses are concerned, based on data presented in Pomonis (2002), we derived that the amount paid by the Greek government following the 1999 Athens earthquake reached approximately 20% of the cost for repair and reconstruction of the affected residential properties (the direct financial loss).

The statistical value of human life (*SVHL*) deserves special attention due to its high importance and uncertainty. Estimating the *SVHL* can be based on various methods and is rather controversial as it has economic, social, political, legal, ethical and moral dimensions. Razani and Nielsen (1984) propose a method by taking into account the increase in life expectancy and average age of the population over time and the increase in per capita expenditure for survival needs over the same period. Based on the “deferred future earnings” method, the *SVHL* for an individual depends on the

Table 3 - Expected damage distribution for LBSM-L and mixed structure buildings (MIXS-L) under macroseismic intensity I_{EMS} = VIII and IX.

Damage Grade	Cost of Repair (% of Replacement Value)	Damaged built floor area of LBSM-L and MIXS-L buildings (m², %)			
		EMS- VIII		EMS-IX	
Slight damage	3.5	7,479	11.5%	5,255	8.1%
Moderate damage	14.5	18,922	29.1%	19,129	29.4%
Heavy damage	30.5	7,822	12.0%	13,397	20.6%
Very heavy damage	80	4,075	6.3%	11,163	17.2%
Collapse	95	1,011	1.6%	5,467	8.4%
SUM		39,308	**60.5%**	54,412	**83.7%**

age, the life expectancy, the future earnings potential brought to present through the use of discounting methods and rates, while some analysts subtract the expected future consumption from the expected future gross earnings (Razani and Nielsen, 1984). FEMA (1992) describes the “courts award” approach, based on the indemnities paid in cases of death from the state or insurance companies. In this study we used this latter approach and assign a value for the *SVHL* from 50,000 to € 500,000. Kappos and Dimitrakopoulos (2008) used the same method and value range whilst they also provide a brief history of recent Greek court decisions. In addition more recently a Greek court awarded compensation of almost € 500,000 per victim to family relatives of 39 workers that lost their lives in the collapse of an industrial building during the September 7, 1999 Mount Parnitha earthquake near Athens (Anonymous, 2010).

Regarding the human casualties caused by building collapse during earthquakes, the method proposed by Coburn *et al*. (1992) has been used, enabling a straight correlation of casualties with the vulnerability and the function of the buildings. A requirement in this method is the assessment of the probability of collapse of the various building classes. It is also necessary to know the level of occupancy of the buildings in question (i.e., the number of people per dwelling and per building)

Table 4 - Expected damage distribution for RC buildings under macroseismic intensity I_{EMS} = VIII and IX.

Damage Grade	Cost of Repair (% of Replacement Value)	Damaged built floor area of RC buildings (m², %)			
		EMS- VIII		EMS-IX	
Slight damage	5	20,369	19.0%	26,940	25.2%
Moderate-serious damage	15	12,162	11.4%	22,236	20.8%
Heavy – very heavy damage	80	182	0.2%	654	0.6%
Collapse	100	0	0.0%	0	0.0%
SUM		32,713	**30.6%**	49,830	**46.6%**

Table 5 - Loss ratio (% of total replacement value of all examined buildings in Pylos town) by vulnerability class and direct financial loss (€) for scenarios VI – IX (EMS-98).

	Loss Ratio (%)			
Structural Class	**EMS-VI**	**EMS-VII**	**EMS-VIII**	**EMS-IX**
LBSM-L	0.43	1.81	5.34	11.78
MIXS-L	0.03	0.10	0.25	0.52
RC1-L (pre-1959)	0.01	0.01	0.02	0.04
RC2-L (1959-1984)	0.50	0.87	1.53	2.55
RC3-L (1985-1994)	0.11	0.17	0.26	0.38
RC4-L (post-1994)	0.08	0.10	0.15	0.21
Sum of all classes	**1.15**	**3.06**	**7.54**	**15.49**
Direct Loss (€)	2.0 millions	5.3 millions	13.0 millions	26.7 millions

which depends on the use of the building, the season and time of occurrence of the earthquake. Residential building occupancies are highest during the night and non-residential building occupancies are higher during the work time of normal (non-holiday) week days. The assessment of the potential fatalities that follows is made assuming that the earthquake takes place in the early morning hours (1 to 6 am) during the non-holiday season when the overwhelming majority of the population is expected to be inside their houses and asleep.

The probable number of fatalities in collapsed buildings for EMS-98 intensity scenarios VI to IX is derived using Eq. (4):

$$No.\,of\,deaths = \sum_{i=1}^{6} P_i \times N_i \times D_i \times R_i \qquad (4)$$

where:

P_i: is the probability of collapse of buildings of structural type i under EMS-98 intensity VI to IX;

Table 6 - Economic parameters used in the benefit-cost analysis.

Category of Loss	**Value of Loss**
Direct Loss (physical damage to buildings)	Loss Ratio (%) × Built Area (m^2) × Unit Replacement Cost (€/m^2)
Household Contents Loss	30% × Direct Loss
Indirect Loss (income support, rental subsidies, tax waivers, etc.)	20% × Direct Loss
Human Loss	Statistical value of human life × No. of deaths
Direct Retrofit Cost	Retrofit Cost × Built Area
Indirect Retrofit Cost	20% × Direct Retrofit Cost

Table 7 - Probabilities of collapse for pre and post-retrofit LBSM-L buildings.

	Macroseismic Intensity (EMS-98)			
Building Class	VI	VII	VIII	IX
LBSM (pre-retrofit)	0.01%	0.19%	1.80%	9.75%
LBSM1 (post-retrofit)	0.00%	0.01%	0.06%	0.38%
LBSM2 (post-retrofit)	0.00%	0.05%	0.84%	5.53%

N_i: is the number of examined buildings of structural type i;

D_i: is the average number of people living in buildings of structural type i;

R_i: is the occupant probability of death upon collapse in structural type i under EMS-98 intensity VI to IX;

i: 6 structural types are examined (see Table 1).

The probabilities of collapse (P_i) are summarized in Table 7. The probability of collapse for the examined structural typologies (i) has been derived from the vulnerability curves proposed by Pomonis *et al*. (2014). In addition, probabilities of collapse are proposed for the retrofitted LBSM buildings (LBSM1 for mitigation Option 2 and LBSM2 for mitigation Option 3) which are described in paragraphs 4.2.2 and 4.2.3 respectively.

We note that the probability of collapse for low-rise (1 to 3 storeys) RC buildings with regular ground floor (without soft-storey) was considered to be zero regardless of the period of construction under EMS-98 intensity VI to IX for buildings in zones II and III of the current Greek earthquake code (Pylos is situated in zone II). This is because Pomonis *et al*. (2014) report that there has not been a single such building to have collapsed among 10,320 buildings in the four examined earthquakes. During the M_w6 earthquake of September 7, 1999 near Athens, 54 low-rise (1 to 3 storeyed) RC buildings partially or totally collapsed (Karabinis *et al*., 2003), 18 of which caused loss of life. The overwhelming majority of these cases though were buildings with soft-storey at ground floor level. All were built prior to 1985 and many were constructions that had no official building permit (Pomonis, 2002). Those built to code were designed with seismic coefficients lower than those used in Pylos as the affected areas were sited in zone I of the 1959 code.

For the human loss estimation, the building occupancy per structural type in Pylos town was estimated based on the EL.STAT. 2000 Buildings and 2001 Population and Dwellings Census and refers only to the residential buildings and the buildings of mixed-occupancy with residential being the primary use, as the scenario we are considering here is for an earthquake in the night time. The data are shown in Table 8 where the number of residential buildings by structural type (N_i) is also shown. The number of residential building occupants by structural class (D_i) was estimated equal to 3.2 people per RC building and 2.2 people per LBSM and mixed structure building (as many LBSM buildings are vacant, while the RC buildings often contain more than one dwelling). We thus note that the analysis on human losses concerns 703 exclusively or predominantly residential buildings with an estimated 1,890 residents, while the other losses (direct, contents and indirect losses) are calculated for the 765 buildings used in the loss estimation analysis presented in section 3 of this paper.

Table 8 - Number of buildings and estimated occupant distributions of the residential buildings in Pylos town.

Structural Type	Number of residential buildings, N_i	% of buildings	% of occupants
LBSM-L	311	44.2%	36.2%
MIXS-L	49	7.0%	5.7%
RC1-L	4	0.6%	0.7%
RC2-L	225	32.0%	38.1%
RC3-L	62	8.8%	10.5%
RC4-L	52	7.4%	8.8%
Total	**703**	**100.0%**	**1.890**

The probability of death given collapse (R_i), which is the product of the entrapment rate under the rubble of the collapsed buildings and the lethality rate of the trapped people, is summarized in Table 9. The LBSM probabilities are those proposed by Coburn *et al*. (1992) while those for retrofitted LBSM buildings are based on the hypothesis that the volume loss will be reduced by one third for mitigation Option 2 (LBSM 1) and by a sixth for mitigation Option 3 (LBSM 2). The probability of death is increasing as the scenario intensity increases, because the number of collapsed buildings and the extent of volume loss of the indoor space in the collapsed buildings increases with ground motion severity. Conversely, the ability to extricate the trapped people alive from the rubble decreases when search and rescue operations need to take place in many sites over a short period of time (the probability of live extrication from the rubble of collapsed buildings rapidly reduces after the first 24 hours).

The estimated losses by seismic intensity before the introduction of building strengthening (mitigation) measures are shown in Table 10. We see that at intensity IX the total loss is approximately seven times greater than at intensity VII and that the contribution of human losses to the total loss reaches 23%.

4.1. Description of the mitigation options

We examine the expected benefits due to loss reduction from the application of targeted building

Table 9 - Proposed probability of death among occupants of collapsed LBSM buildings (*Ri*), by structural class and EMS-98 macroseismic intensity.

	Fatality Rates (R_i)		
	Macroseismic Intensity (EMS-98)		
Building Class	VII	VIII	IX
LBSM-L (pre-retrofit)	3.0%	18.0%	36.0%
LBSM1-L (post-retrofit)	2.0%	12.0%	24.0%
LBSM2-L (post-retrofit)	2.5%	15.0%	30.0%

Table 10 - Pre-retrofit losses by EMS-98 intensity and their distribution by category of loss.

Category of Loss	**Macroseismic Intensity (EMS-98)**			
	VI	VII	VIII	IX
Direct Loss (%)	66.7%	66.5%	63.0%	51.2%
Human Loss (%)	0.0%	0.3%	5.4%	23.2%
Content Loss (%)	20.0%	19.9%	18.9%	15.4%
Indirect Loss (%)	13.3%	13.3%	12.6%	10.2%
Total (pre-retrofit) Loss (€)	*2,972,977*	*7,905,553*	*20,577,724*	*52,085,457*

strengthening programmes. In terms of the pre-earthquake strengthening of existing buildings, there is a variety of technologies and methods that can be employed, but the optimal solution depends on the relationship that exists between the cost of the employed method and its effectiveness in reducing the damage. The purpose of this section is not to examine distinctively the cost and potential increase in earthquake resistance of retrofit methods proposed for the various structural typologies, but to investigate the benefit-cost potential from the investment in the application of certain commonly employed retrofit methods. We will examine three alternative mitigation options as follows:

- mitigation Option 1: strengthening the pre-1985 RC buildings to the level of seismic performance of modern buildings designed based on the 1995 Greek earthquake code;
- mitigation Option 2: strengthening the LBSM buildings with the introduction of RC flooring, RC ring beams and the external and internal jacketing with shotcrete of the load-bearing stone walls;
- mitigation Option 3: strengthening the LBSM buildings with steel tie rods on all sides and floors.

We evaluate each mitigation option through benefit-cost analysis, a procedure that helps in the selection of the optimal earthquake protection policies, having as criterion the maximization of the benefits in relation to the cost of an investment (Coburn and Spence, 2002).

The direct retrofit cost depends on the structural type. The direct cost covers all expenses for materials and the retrofit work, and obviously depends on the type of the strengthening method [some methods are less labour intensive than others, but may involve more expensive materials (Penelis and Kappos, 1997)]. In assessing the total retrofit cost, the indirect retrofit costs were also taken into account, which cover the expenses regarding the engineer's fees and the cost of issuing a permit for construction works, taken to be equal to 20% of the direct cost (FEMA, 1992).

4.2. Evaluation of the mitigation options

The most widely used method for choosing between alternative investments designed to achieve some socially desirable outcome is Benefit-Cost Analysis (BCA). The evaluation of the mitigation alternatives usually comprises two different tasks. The first is expressing all consequences (benefits, costs) in terms of the same units (typically monetary), and the second is converting all monetary values to present time, so the various consequences can then be summarised.

The available methods can be classified either on the basis of whether they assume that the

Table 11 - Annual occurrence exceedance probabilities of EMS-98 macroseismic intensity in Pylos.

	Macroseismic Intensity (EMS-98)			
	VI	VII	VIII	IX
Annual Occurrence Exceedance Probability	19.75%	6.00%	1.60%	0.39%

annual probabilities of future earthquakes are constant or not, or on the basis of whether the efficiency of the retrofit is time-independent or not. If these probabilities are constant per year (time-invariant), future benefits are also constant per year. This is the assumption of the BCA analysis according to FEMA (1992) adopted in this study. In Table 11, we see the annual occurrence exceedance probability of EMS-98 intensity VI to IX on stiff soil conditions (Slejko *et al*., 2010, 2014) derived for the town of Pylos in the framework of SEAHELLARC project (Papoulia *et al*., 2014).

The expected annual benefits (B_o), which are constant per year, are calculated using Eq. (5), while the benefits over the planning horizon (B_t), in present monetary value, are estimated according to Eq. (6) (FEMA, 1992):

$$B_o = \sum_{j=VI}^{IX} N_j R_j C_j \qquad (5)$$

$$B_t = B_0 \frac{1 - (1+\lambda)^{-t}}{\lambda} \qquad (6)$$

where:

N_j is the expected number of earthquakes annually (shown in Table 11);

R_j is the efficiency of the examined retrofit option (equivalent to the difference in vulnerability before and after strengthening);

C_j is the total loss (included direct, content, indirect losses and losses resulting from fatalities);

λ is the discount rate used to convert losses from future earthquakes into present (monetary) value; and

t is the time (planning) horizon of the investment, i.e., the assumed lifetime of the project or the time duration for which the monetary benefits of the mitigation option are considered.

The benefit-cost ratio (B/C) is obtained by dividing the expected future benefits (in today's values) with the cost of the retrofit programme reduced by 10% (FEMA, 1992; Kappos and Dimitrakopoulos, 2008) due to the increase in the market price of the retrofitted buildings. If the expected benefits exceed the total cost, the net present value of the programme is positive (i.e., the benefit-cost ratio is greater than one) and the retrofit investment is considered economically justified. The benefit-cost ratios are calculated with

$$B/C = \frac{B_t}{R_C - V_S} \qquad (7)$$

where: $R_C – V_S$ is the reduced cost of the retrofit programme, expressed as the total cost of the mitigation programme (R_C) minus the (present) salvaged value of the building (V_S), i.e., the cost of the mitigation programme reduced by 10% (after allowing for the increase in the value of the strengthened buildings).

4.2.1. Mitigation Option 1

Under mitigation Option 1, we examine the benefit-cost ratio potential of strengthening the 248 pre-1985 low-rise RC buildings (without soft storey) in Pylos town to the level of seismic performance of modern RC buildings designed based on the 2004 Greek earthquake code. By implementing this mitigation option, there will be a reduction in the town's overall loss ratio under the examined EMS-98 intensity scenarios. A substantial number of seismic rehabilitation techniques are currently available for RC buildings (Penelis and Kappos, 1997). For a retrofit scheme, that upgrades an old RC building to the level of seismic performance of modern RC buildings, Kappos and Dimitrakopoulos (2008) propose that the direct cost of the retrofit is 12% of the building's replacement value. In this study we assume that the direct retrofitting cost would be 15% of the replacement value for the pre-1959 RC buildings, and 12% of the replacement value for the buildings constructed during the period 1959-1984, i.e., 150 €/m^2 and 120 €/m^2 respectively.

Table 12 summarises the distribution and value of the modeled losses for each EMS-98 intensity scenario after the programme has been completed (the total loss amount concerns the entire examined building stock of 765 buildings). The total cost of the investment is € 10.35 millions. It can be seen that the expected annual benefits from the application of this mitigation programme are € 212,146. In Fig. 7 we present the benefit-cost ratio for three different discount rates (3, 4 and 5% respectively). The benefit-cost ratio approaches 0.58 when the planning horizon is 50 years (λ = 3%). This is quite low, partly because the human benefits (from the value of avoided deaths) are zero, since in our model (Pomonis *et al*., 2014) it is considered that, for intensity VI to IX, the collapse probability of pre-1985 low-rise RC buildings (without soft storey) is zero (pre- and post-retrofit). The human losses appearing in Table 12 are related to the collapse of masonry (LBSM-L) and mixed structure (MIXS-L) buildings. It is therefore concluded that this investment is economically not beneficial. In addition, relocation costs of the occupants whilst strengthening works are taking place would make the cost of this programme even higher.

4.2.2. Mitigation Option 2

Under mitigation Option 2, we examine the benefit-cost potential of strengthening the 340 LBSM buildings of Pylos town with the introduction of RC flooring (to replace the flexible wooden floors), RC ring (collar) beams above the window level (in the full perimeter of the building, to brace the load-bearing walls together) and the external and internal jacketing with shotcrete of the load-bearing stone walls (to further improve the lateral load resistance of the walls). This combination of strengthening techniques is the most efficient (Karantoni and Fardis, 1992). Due to lack of empirical observed damage data or analytical studies for this mitigation option it is assumed that after this intervention, the LBSM buildings will perform similarly to the mixed structure (LBSM and RC) buildings.

The direct retrofit cost of LBSM buildings in reasonably good condition (i.e., not damaged by earthquakes) for mitigation Option 2 is considered to be on average equivalent to 30% of the

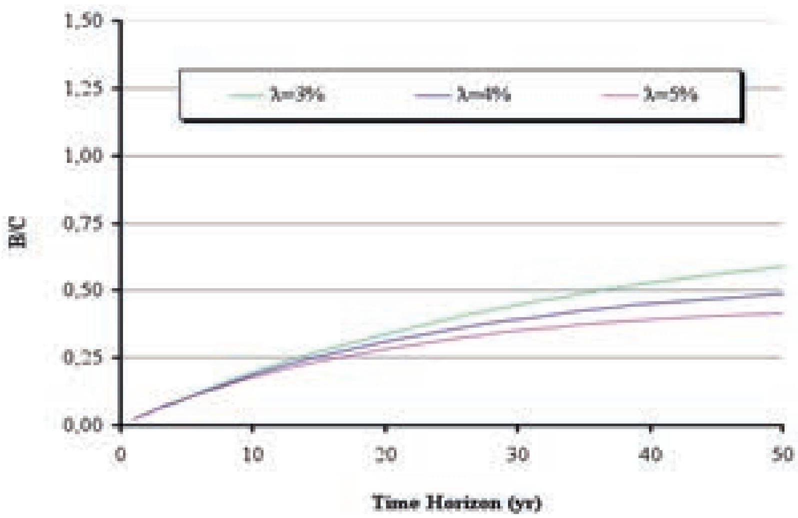

Fig. 7 - Benefit-cost ratios in relation to time (planning) horizon and discount rate for mitigation Option 1.

replacement value of these buildings, based on detailed analysis of costs for 3 typical two-storeyed LBSM buildings in Peloponnese retrofitted with this particular method (Karantoni, 2004). Table 13 summarises the distribution and value of the modeled losses for each EMS-98 intensity scenario, after this mitigation option has been completed. The total cost of the investment is € 16.71 millions. In comparison to mitigation Option 1, the expected annual benefits are almost triple, as they reach € 628,104.

In Fig. 8 we present the benefit-cost ratio for three different discount rates (3, 4 and 5% respectively) for mitigation Option 2 whilst assuming the upper bound value (€ 500,000) for the statistical value of human life. We see that, for discount rates 3 and 4% the benefit-cost ratio exceeds unity when the planning horizon is 43 and 81 years respectively, whilst noting that there is

Table 12 - Modeled losses by EMS-98 intensity, their distribution by category of loss, total retrofit cost and expected annual benefits for mitigation Option 1.

Category of Loss	**Intensity (EMS-98)**			
	VI	VII	VIII	IX
Direct Loss (%)	66.7%	66.5%	62.6%	49.8%
Human Loss (%)	0.0%	0.3%	6.2%	25.3%
Content Loss (%)	20.0%	19.9%	18.8%	14.9%
Indirect Loss (%)	13.3%	13.3%	12.5%	10.0%
Total Loss (€)	2,518,260	6,777,321	18,216,815	47,759,646
Direct Retrofit Cost (€)	8,621,926			
Indirect Retrofit Cost (€)	1,724,385			
Total Retrofit Cost (€)	*10,346,311*			
Expected Annual Benefits (€)	*212,146*			

Table 13 - Modeled losses by EMS-98 intensity, their distribution by category of loss, total retrofit cost and expected annual benefits for mitigation Option 2.

	Intensity (EMS-98)			
	VI	VII	VIII	IX
Human Loss (%)	0.0%	0.0%	0.4%	2.2%
Content Loss (%)	20.0%	20.0%	19.9%	19.6%
Indirect Loss (%)	13.3%	13.3%	13.3%	13.0%
Total Loss (€)	2,330,046	4,719,548	9,513,273	17,999,963
Total Retrofit Cost (€)	*16,714,908*			
Expected Annual Benefits (€)	*628,104*			

significant sensitivity for the assumed discount rate and that for discount rate 5% the benefit-cost ratio becomes asymptotic. If a 15% salvaged value of the building is assumed, then the time horizon reduces to 60 years (discount rate 4%). Considering that these time horizons are obtained when using the upper bound value for the statistical value of human life it is concluded that this investment is not economically beneficial, as the planning horizon is quite long when we consider that it concerns buildings that are already more than 50 years old. In addition, there are significant indirect costs associated with this retrofit method, in particular the need for relocating the occupants for a significant period of time.

In Figs. 9a and 9b we present the expected annual losses and benefits respectively by type of loss and type of benefit for each intensity scenario for a 81-year time horizon and discount rate λ = 4%. It is observed that the greatest annual losses and benefits are expected under intensity scenarios VI and VII, as the annual occurrence probability of these is significantly greater. We

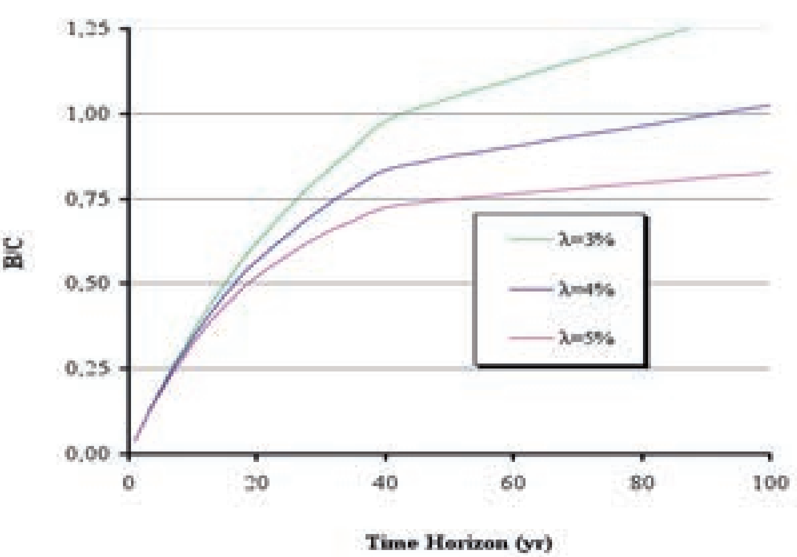

Fig. 8 - Benefit-cost ratios in relation to time horizon and discount rate for mitigation Option 2.

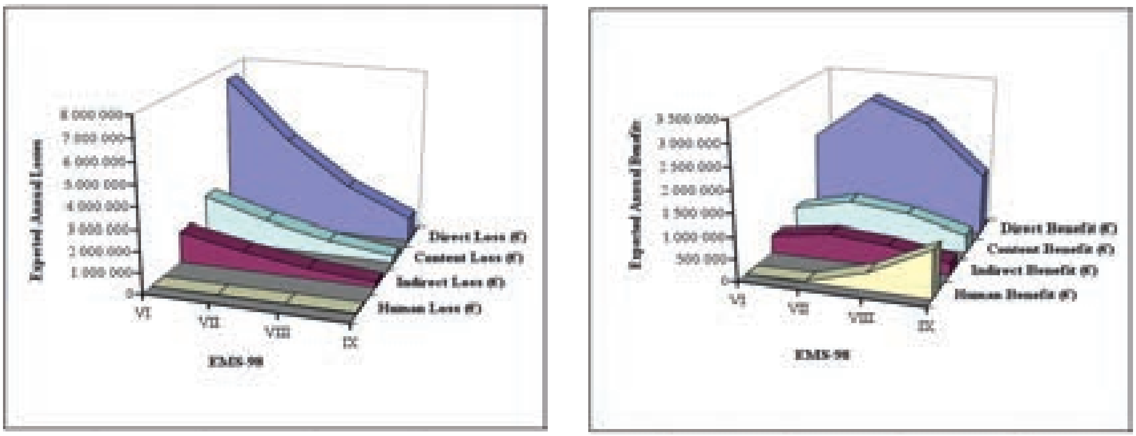

Fig. 9 - Distribution of expected annual losses (a) and annual benefits (b) in relation to seismic intensity and category of loss for a 81-year time horizon and discount rate 4% for mitigation Option 2.

also note that there are significant benefits in terms of the value of avoided deaths especially in the case of intensity IX.

4.2.3. Mitigation Option 3

Under mitigation Option 3, we examine the benefit-cost potential of strengthening the 340 LBSM buildings of Pylos town with steel tie rods on all sides and floors of the building (circumferential) including connections between the masonry walls and the wooden floors. D'Ayala *et al*. (1997), Spence *et al*. (2000) as well as Rota *et al*. (2008), assess the comparative performance of masonry buildings with and without steel tie rods. Examining these studies, we find that the mean damage factors of buildings with steel tie rods are reduced compared to the buildings without tie rods, with the effect of retrofitting progressively reducing as intensity increases from VI to IX. Based on the above, we proposed a new set of EMS-98 intensity-based vulnerability curves for LBSM buildings retrofitted with steel tie rods as shown in Fig. 10. These are improved compared to the equivalent vulnerability curves of un-retrofitted LBSM buildings presented in Pomonis *et al*. (2014). In addition we used the curve for damage grade D5 to derive the collapse probability of the retrofitted with steel tie rods LBSM buildings (shown in Table 7).

The direct retrofit cost of LBSM buildings in reasonably good condition (i.e., not damaged by earthquakes) for mitigation Option 3 is considered to be on average equivalent to 7% of the replacement value of these buildings including the indirect costs (for the works permit and engineer's fees). D'Ayala *et al*. (1997) proposed a 5% direct cost for the same method of retrofit for masonry buildings in Lisbon. Additional costs for temporary relocation of the occupants of a building while the strengthening work is going will also be incurred, but in comparison to the previously examined mitigation options are much lower as the duration of the works is shorter.

Table 14 summarises the distribution and value of the modeled losses after completion of this mitigation option for each EMS-98 intensity scenario. We see that the total cost of the investment (€ 5.57 millions) is much lower than the previous two examined mitigation options. We also see that, in comparison to mitigation Option 2, the expected annual benefits (€ 433,860) are 30%

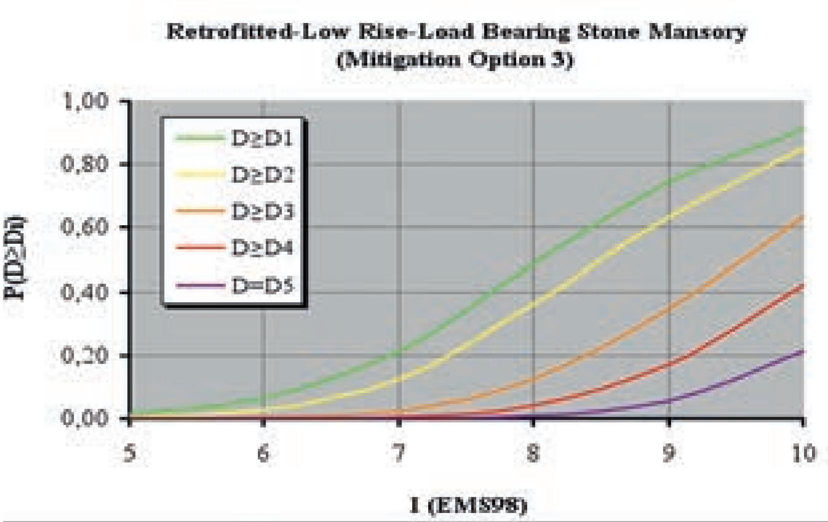

Fig. 10 - Proposed vulnerability curves for LBSM buildings retrofitted with steel tie rods on all sides.

lower and the cost of the investment is also 56.5% lower.

In Fig. 11 we present the benefit-cost ratio for three different discount rates (3, 4 and 5% respectively) for mitigation Option 3 whilst assuming the upper bound value (€ 500,000) for the statistical value of human life. We see that, regardless of discount rate, the benefit-cost ratio exceeds unity when the planning horizon is greater than approximately 10 years, whilst noting that there is limited sensitivity for the assumed discount rate. It is therefore concluded that this investment is definitely economically beneficial. The LBSM buildings are very important to the history and traditional character of Pylos town, and although quite old they still provide good quality housing and services. It is therefore desirable that these buildings are preserved. Mitigation Option 3 provides a protection strategy that is more in line with these buildings' character, being less intrusive, cost-efficient and causing limited disruption to the daily lives of

Table 14 - Modeled losses by EMS-98 intensity, their distribution by category of loss, total retrofit cost and expected annual benefits for mitigation Option 3.

	Intensity (EMS-98)			
	VI	VII	VIII	IX
Direct Loss (€)	66.7%	66.6%	64.6%	56.5%
Human Loss (€)	0.0%	0.1%	3.1%	15.3%
Content Loss (€)	20.0%	20.0%	19.4%	16.9%
Indirect Loss (€)	13.3%	13.3%	12.9%	11.3%
Total Loss (€)	2,342,905	5,483,504	14,412,329	35,303,013
Total Retrofit Cost (€)	*3,900,145*			
Expected Annual Benefits (€)	*433,860*			

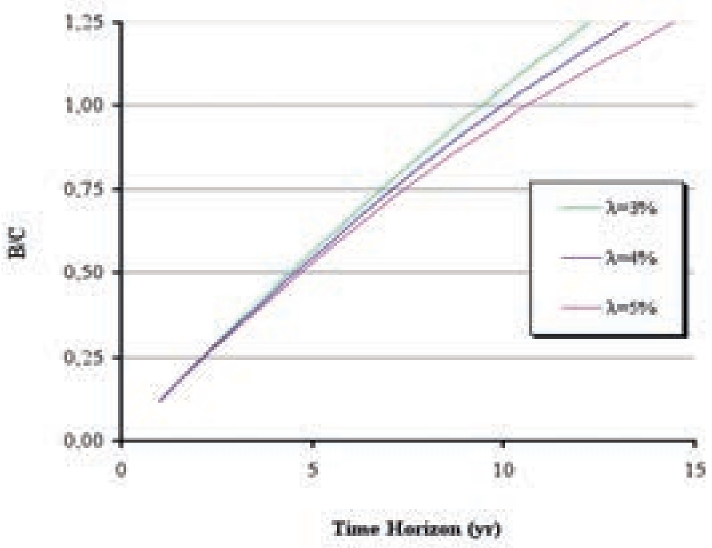

Fig. 11 - Benefit-cost ratios in relation to time horizon and discount rate for mitigation Option 3.

the occupants during the retrofit works.

In Figs. 12a and 12b we present the expected annual losses and benefits respectively by type of loss and type of benefit for each intensity scenario. It is observed that again the greatest annual losses and benefits are expected under intensity scenarios VI and VII, as the annual occurrence probability of these is significantly greater. We also note that there are significant benefits in terms of the value of avoided deaths especially in the case of intensity IX.

4.2.4. Uncertainties and sensitivity analysis

The benefit-cost analysis discussed in this paper is of course subject to significant uncertainties associated with the estimation of the many parameters needed for this analysis to be completed. Uncertainties exist in the estimation of the seismic hazard as well as in the estimation of the vulnerability of the examined structural classes (pre-and post-retrofit), in the estimation of the collapse probability and the lethality of collapse, in the estimation of the statistical value of human life, in the estimation of the retrofit costs and the repair costs by damage grade, in the estimation of indirect losses and indirect retrofit costs, as well as due to the fact that injuries resulting from building collapse have not been taken into account.

The benefits of the mitigation programmes include reduction in post-earthquake rebuilding costs and other associated losses, the saving of human lives (for the LBSM class), but also the preservation of the architectural heritage of Pylos town that is one of its advantages as a tourist destination. Due to the above uncertainties none of these benefits can be calculated with precision, while some have not even been addressed here (e.g., the value of the risk reduction to the town's architectural heritage).

To examine the sensitivity of the *B/C* for the most economically beneficial mitigation Option 3 we consider incrementally the effect of changes in the following parameters: cost of retrofit, statistical value of human life and salvaged value of the building. We find that if the statistical

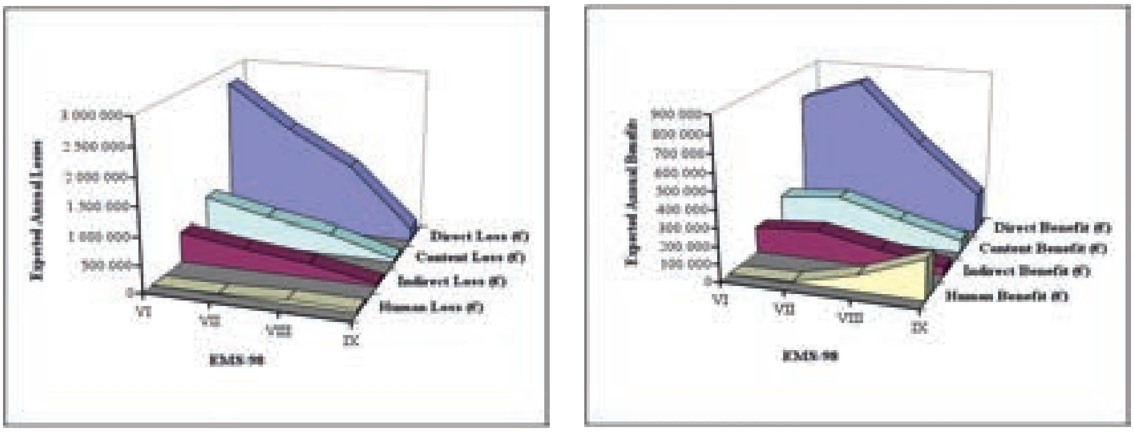

Fig. 12 - Distribution of expected annual losses (a) and annual benefits (b) in relation to seismic intensity and category of loss for a 10-year time horizon and discount rate 4% for mitigation Option 3.

value of human life is 50,000 € (instead of 500,000 €) the time horizon increases from 10 to 11 years, whilst if the cost of retrofit is also increased to 10% (to take into account additional indirect costs such as temporarily relocating the occupants) the time horizon further increases to approximately 18 years (in both cases we assumed discount rate of 4%). If the salvaged value of the building is halved to 5%, the time horizon further increases to approximately 19 years. It is thus concluded that mitigation Option 3 continues to be economically beneficial under these less advantageous assumptions and that for this mitigation option the benefit-cost ratio is more sensitive to the assumed cost of the retrofit.

5. Conclusions

We examined the evolution of the Pylos town building stock over the period 1970 to 2008 by analyzing the building census data of 1970, 1990 and 2000, in conjunction with our building-by-building survey in 2008. In Greece, there is a strong trend for replacing old LBSM buildings with newly built RC buildings and this trend is also taking place in Pylos town. The gradual demolition of LBSM buildings changes the traditional character of Pylos town, a fact that cannot be assessed in economic terms. Pylos is a traditional-historic town and the preservation of its old and architecturally valuable masonry buildings is of significant importance.

At first we assess the level of loss that can take place in the town without any targeted mitigation program. Then, we present benefit-cost analysis for three different mitigation options related to building strengthening programs (one for the pre-1985 RC buildings and two for the LBSM buildings). We find that the mitigation program for strengthening the LBSM buildings in Pylos (mitigation Option 3) is economically beneficial, while the strengthening methods 1 and 2 are not economically justified [a conclusion also drawn by Kappos and Dimitrakopoulos (2008) for the pre-1985 RC buildings].

For mitigation Option 2 (strengthening the stone masonry buildings with the introduction of RC flooring, RC ring beams and the external and internal jacketing of the load-bearing walls) the time horizon needed for the mitigation program to become beneficial is 43 to 81 years (depending on the discount rate chosen). Mitigation Option 3 (strengthening the stone masonry buildings with steel tie rods on all sides) becomes economically beneficial in a much shorter time horizon, 10 to 19 years (depending on the discount rate, statistical value of human life, cost of retrofit and salvaged value of the building). This is because mitigation Option 3 is a much cheaper solution, but achieves significant reductions in vulnerability and therefore loss. We consider therefore that mitigation Option 3 is the most beneficial mitigation option as it is also less intrusive and less disruptive and can thus become easily accepted by building owners and preservation specialists. Similar conclusions are drawn by D'Ayala *et al*. (1997) and Spence *et al*. (2000) for other towns of historic importance elsewhere in Europe.

The results of the benefit-cost analysis heavily depend on the assumed post-retrofit performance of the LBSM buildings, an area where more research is needed. It must also be pointed out that the time horizons needed for each mitigation program to be beneficial heavily depend on the assumed costs of each mitigation program and, to lesser extent, on the assumed statistical value of human life.

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REFERENCES

Anonymous; 2010: *Rizospastis Newspaper*. Athens, June 20, 2010.

Coburn A.W. and Spence R.J.S.; 2002: *Earthquake protection*. John Wiley & Sons Ltd, West Sussex, UK, 420 pp.

Coburn A.W., Spence R.J.S. and Pomonis A.; 1992: *Factors determining human casualty levels in earthquakes: mortality prediction in building collapse.* In: Proc. 10th World Conf. Earthquake Eng., Madrid, Spain, pp. 5989-5994.

D'Ayala D., Spence R.J.S., Oliveira C. and Pomonis A.; 1997: *Earthquake loss estimation for Europe's town centres.* Earthquake Spectra, **13**, 773-793.

Dolce M., Kappos A., Masia A., Penelis G. and Vona M.; 2006: *Vulnerability assessment and earthquake damage scenarios of the building stock of Potenza (Southern Italy) using Italian and Greek methodologies.* Eng. Struct., **28**, 357-371.

EL.STAT.; 1970, 1990, 2000: *Buildings Census, December 1970, December 1990, December 2000.* Hellenic Statistical Authority.

EL.STAT.; 1971, 1981, 1991, 2001: *Population and Dwellings Census of Greece, March 1971, March 1981, March 1991, March 2001.* Hellenic Statistical Authority.

EPPO; 1987: *Geomorphology, geology, tectonics, hydrogeology, seismological data and technical geology for Pylos.* Department of Geology (University of Athens) for the Earthquake Planning and Protection Organization, 100 pp. (in Greek).

Eurocode-8; 1998: *Design of structures for earthquake resistance. Part 1: general rules, seismic actions and rules for buildings.* EN 1998-1, 229 pp.

FEMA; 1992: *A benefit/cost model for the seismic rehabilitation of buildings (FEMA 227/228)*. Vol. 1 and 2, VSP Associates, Sacramento, CA, USA, 130+125 pp.

Galanopoulos A.G.; 1941a: *Das riesenbeben der Messenischen küste vom 27 August 1886.* Prakt. Athens Acad., **16**, 120-126.

Galanopoulos A.G.; 1941b: *Das erdbeben von Messenien vom 22 Januar 1899.* Prakt. Athens Acad., **16**, 127-134.

Galanopoulos A.G.; 1949: *The Koroni (Messinia) earthquake of October 6, 1947.* Bull. Seism. Soc. Amer., **39**, 33-39.

Galanopoulos A.G.; 1953: *Katalog der erdbeben in Griechenland fur die zeit von 1879 bis 1892*. Ann. Geol. Pays Hellen., **5**, 140-229.

Gaspari M.; 2009: *Assessment of the earthquake vulnerability of low-rise buildings in Greece with application in Pylos town (Messinia prefecture).* Master of Science Thesis, Department of Geology and Geoenvironment, National Kapodistrian University of Athens, Cross-Institutional Post-Graduate Programme on the Prevention and Management of Natural Catastrophes, 144 pp.

Grünthal G.; 1998: *European Macroseismic Scale 1998.* Cahiers du Centre Europeen de Geodynamique et de Seismologie, vol. 15, Centre Europeen de Geodynamique et de Seismologie, Luxembourg, 99 pp.

IGME; 1970: *Geologic map of Greece, Koroni-Pylos-Skhiza sheet. 1:50,000 scale.* Institute of Geology and Mineral Exploration (bi-lingual).

ITSAK; 2008: *The Koroni earthquake (S. Messinia) of February 14, 2008 (M6.7).* A brief reconnaissance report by the Institute of Engineering Seismology and Earthquake Resistant Structures (ITSAK), 24 pp.

Kappos A. and Dimitrakopoulos E.; 2008: *Feasibility of pre-earthquake strengthening of buildings based on cost-benefit and life-cycle cost analysis, with the aid of fragility curves.* Nat. Hazards, **45**, 33-54.

Kappos A.J., Pitilakis K.D., Morfidis K. and Hatzinikolaou N.; 2002: *Vulnerability and risk study of Volos (Greece) metropolitan area.* In: Proc. 12th Eur. Conf. Earthquake Eng., London, UK, Paper 74.

Karabinis A., Plesias A., Fotopoulou M. and Avramopoulos I.; 2003: *Conclusions on the seismic vulnerability of buildings from the Athens earthquake of 7 September 1999.* In: Proc. 14th Conf. Reinf. Concr., Kos, Greece (in Greek).

Karantoni F.; 2004: *Load-bearing masonry construction: design and repairs.* Papasotiriou Publishing, Athens, Greece, 531 pp. (in Greek).

Karantoni F. and Fardis M.N.; 1992: *Effectiveness of seismic strengthening techniques for masonry buildings.* J. Struct. Eng., **118**, 1884-1902.

Penelis G.G. and Kappos A.J.; 1997: *Earthquake-resistant concrete structures*. E & FN Spon (Chapman & Hall), London, UK, 572 pp.

Papoulia J., Makris J., Mascle J., Slejko D. and Yalçiner A.; 2014: *The EU SEAHELLARC project: aims and main results.* Boll. Geof. Teor. Appl., **55**, 241-248, doi: 10.4430/bgta0100.

Pomonis A.; 2002: *The Mount Parnitha (Athens) earthquake of September 7, 1999: a disaster management perspective.* Nat. Hazards, **27**, 171-199.

Pomonis A. and Gaspari G.; 2009: *Risk assessment and mitigation.* Seismic and Tsunami Risk Assessment and Mitigation Scenarios in the Western Hellenic Arc (Seahellarc), Work Package 7 Report, 98 pp.

Pomonis A., Gaspari G. and Karababa F.S.; 2014: *Seismic vulnerability assessment for buildings in Greece based on observed damage data sets.* Boll. Geof. Teor. Appl., **55,** 501-534 doi: 10.4430/bgta0069.

Razani R. and Nielsen N.N.; 2008: *Valuation of human life in seismic risk analysis.* In: Proc. 8th World Conf. Earthquake Eng., vol. 7, pp. 947-954.

Rota M., Penna A. and Strobbia C.; 2008: *Processing Italian damage data to derive typological fragility curves.* Soil Dyn. Earthquake Eng., **28**, 933-947.

Slejko D., Santulin M. and Garcia J.; 2010: *Seismic hazard estimates for the area of Pylos and surrounding region (SW Peloponnese) for seismic and tsunami risk assessment.* Seismic and Tsunami Risk Assessment and Mitigation Scenarios in the Western Hellenic Arc (Seahellarc), Work Package 5 Report, 33 pp.

Slejko D., Santulin M. and Garcia J.; 2014: *Seismic hazard estimates for the area of Pylos and surrounding region (SW Peloponnese) for seismic and tsunami risk assessment.*. Boll. Geof. Teor. Appl., **55,** 433-468, doi: 10.4430/bgta0090.

Spence R.J.S., Oliveira C.S., D'Ayala D.F., Papa F. and Zuccaro G.; 2000: *The performance of strengthened masonry buildings in recent European earthquakes.* In: Proc. 12th World Conf. Earthquake Eng., Auckland, New Zealand, Paper 1366.

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