

# EARTHQUAKE RISK ASSESSMENT CASE STUDY: CYPRUS

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## 1. Introduction

Earthquakes represent a major natural hazard, resulting in loss of life and economic losses due to damage to buildings and businesses. For the people who live in areas affected by major earthquakes, risk management decisions need to be made. Examples of such decisions include the level of the determination of aseismic design whether or not the structural upgrading of buildings is appropriate, and how to cost insurance premiums.

These decisions need to be based on some prediction of future earthquake events. However, existing technology does not enable the direct prediction of future events, and use must be made of historic event time series instead.

The long term aim of the current research is to develop an Earthquake Risk Assessment (ERA) methodology, and to apply that methodology to Cyprus. ERA provides a means of assessing and comparing various risk management strategies for rational decision making. This is achieved by predicting future events and developing strategies which will help manage or mitigate their possible consequences. For the prediction of the possible future event time-series, Monte Carlo simulation techniques, based on historic time series, is implemented. Using this approach the effectiveness and economic viability of various alternative management strategies will be examined. This paper presents some of the initial research findings relating to the spatial and temporal characteristics of Cyprus' historic time series of earthquake events as well as the difficulties associated with the assessment of the island's seismic hazard.

## 2. Seismic Hazard

### 2.1 THE TECTONIC SETTING OF CYPRUS

Cyprus lies within the second largest earthquake-stricken zone of the earth, but in a relatively less active sector. The level of the seismic activity in the Cyprus region is significantly lower than that in Greece and Turkey. This zone stretches from the Atlantic Ocean across the Mediterranean Basin, through Greece, Turkey, Iran, and India as far as the Pacific Ocean. The energy released by the earthquakes in this zone represents 15% of the universal seismic energy.

However, many destructive earthquakes have struck Cyprus over its long history and many of its towns and villages (notably Paphos, Salamina, Kitio, Amathounta, Kourio and Nicosia) have been destroyed by strong earthquakes.

#### 2.1.1 Frequency of Earthquakes in Cyprus

Historically, only the most significant earthquakes have been recorded, whilst for recent years a more complete record is available. Between 1500 AD and the present there were 30 destructive earthquakes of intensity 8 or above on the Mercalli scale. Statistically, this implies that the return period for the  $M_s \geq 8$  event is in the order of 120 years (Solomis, 1995). Alternatively, the German reinsurance company Munich Re., in their universal map of natural disasters, gives a possibility of 20 % in 50 years for an earthquake with intensity 8 or more on the Mercalli scale to occur in Cyprus, meaning that the return period for the  $M_s \geq 8$  event is in the order of 250 years.

Santamas (1988) reports that since 1900, Cyprus has been affected by approximately 800 earthquakes of magnitudes ranging from 4.0 - 7.0 on the Richter scale, 21 of which had magnitude  $\geq 5$ . He concluded that there is a possibility of a potentially damaging earthquake will occur approximately every 12 years and a destructive earthquake every 25 years.

The seismicity of Cyprus during the last century was reappraised by Ambraseys (1992) who derived the following recurrence relationship:

$$\log N = 2.5 - 0.64 M_s \quad (2.1)$$

Where  $N$  = Number of earthquakes per year in an area of six square degrees which will have a magnitude greater or equal to  $M_s$ ;

$M_s$  = surface wave magnitude.

Unfortunately, the assumption of a uniform distribution of events in the area of Cyprus used to derive the formula, which does not correlate with the known seismic hazard (Cyprian Arc) described below, reduces the applicability of this relationship for ERA.

The seismic records for the last 100 years suggest that periods of intense seismic activity have been followed by long periods of seismic tranquillity. For the last three decades relative tranquillity has been observed in the area of Cyprus. During the last five years the island is experiencing a rather intense seismic activity. Since 1995, four very strong but fortunately non-destructive events have occurred with magnitudes ranging from 5.0 to 6.5.

In this paper the historical records will be appraised once more. The record will be examined in terms of seismic energy and the applicability of the exponential recurrence relationship proposed by Ambraseys (1992) will be reviewed. Furthermore the various difficulties encountered as well as the initial findings from the assessment of the islands seismic hazard will be presented.

### 2.1.2 Seismic Zones

The seismic hazard at a place has a direct/immediate connection with the geology in the location. Areas with hard rocks, like the ones of Troodos, have a lower seismic hazard than areas with loose dykes and liquid sediments.

Earthquakes in Cyprus are concentrated on the south coast, in a zone which is referred to as the Cyprian Arc, a tectonic zone which starts at Castelorizo island near Turkey and continues south of Cyprus to end up north at the area of the Turkey-Syria border. In this region the Eurasian and African plates collide. Scientific opinion as to the position of the Cyprian Arc varies considerably, with some scientists positioning it along the southern end of the Troodos Massif (Kenyon and Belderson, 1976; McKenzie, 1976; Ambraseys and Adams, 1992). However, more realistic explanations show the Cyprian Arc curving offshore around the southern coast of the island (Biju-Duval and Montadert, 1976; Robertson and Dixon, 1984).

The structure of the Cyprian Arc is complicated; there is not a clear view on whether it is a plate boundary [(McKenzie, 1972) in Ambraseys and Adams, 1992], or a broad zone of thrusting, [(Rostein and Kafka, 1982) in Ambraseys and Adams, 1992]. There is evidence (earthquakes at subcrustal depths) that subduction is occurring in the Antalya Basin, the north-west part of the arc, and there is an unproven theory that this subduction zone extends towards Cyprus.

The use of simulated time series for earthquake risk assessment is feasible using the whole area recurrence relationship alone. However, it is of considerably greater value if the simulated time series can be associated with appropriate locations, i.e. if the spatial characteristics of the simulated time series can be matched to the observed data. The spatial distribution of historic seismic energy release will be presented in this paper.

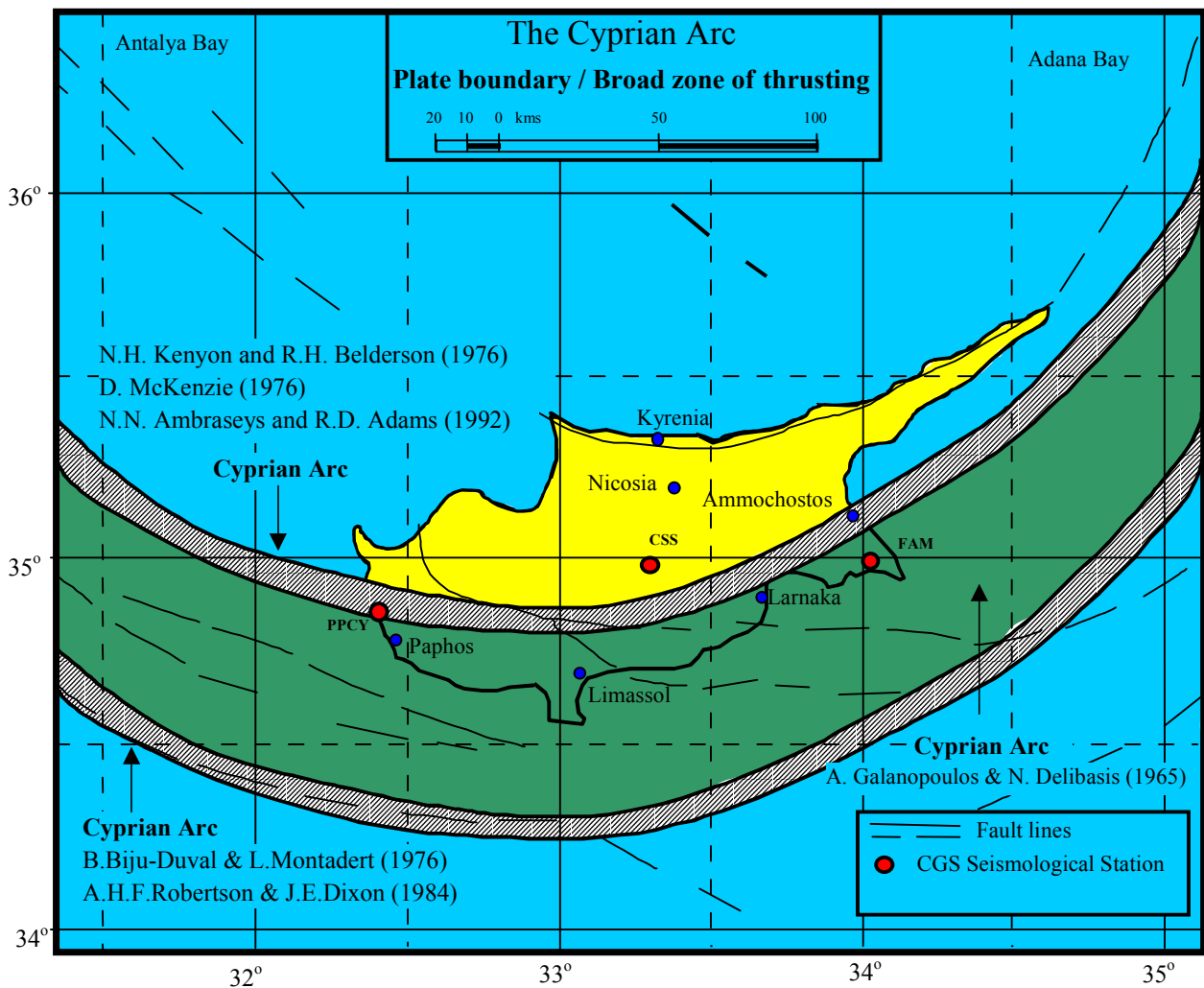


Figure 1 The Cyprian Arc (after Kythreoti *et al.*, 1998)

## 2.2 ANALYSIS OF THE HISTORICAL TIME SERIES FOR CYPRUS

### 2.2.1 Recurrence relationships

The seismic data for the region of Cyprus has been reanalysed. Additional data to that examined by Ambraseys, provided by the Israel Seismological Bulletin (1995), Solomis (1998) and Gajardo *et al.* (1998), has enabled a new more detailed earthquake catalogue to be created.

The four sets of data had differences as far as the record of events is concerned. Since the four catalogues used different expressions ( $M_s$ ,  $M_L$ ,  $m_b$ ) for the representation of the earthquakes magnitudes, a relationship between the various magnitudes was required in order to achieve the creation of a uniform catalogue. It was decided to convert all magnitudes to  $M_s$  since it is the magnitude most widely used.

The new catalogue included all the events with  $M_s > 2.5$  from 1894 - 1998 corresponding to a geographical area of  $33.0^\circ - 37.0^\circ\text{N}$  and  $31.0^\circ - 35.5^\circ\text{E}$ . Two recurrence relationships which related Magnitude to log frequency of both linear and polynomial form were derived:

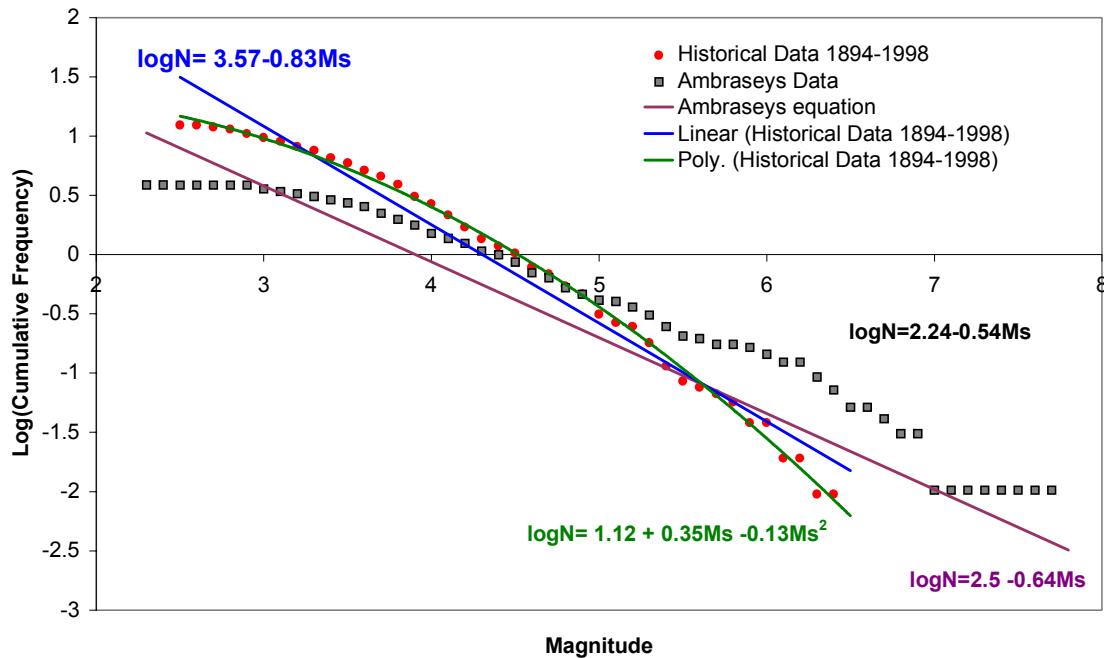
A linear recurrence relationship :

$$\log N = 3.57 - 0.83M_s \quad (2.2)$$

and a polynomial recurrence relationship :

$$\log N = 1.12 + 0.35M_s - 0.13M_s^2 \quad (2.3)$$

In Figure 2 the two relationships are compared to the historical data (1894-1998) and to Ambraseys' (1992) recurrence relationship and data. It can be seen that the newly derived linear fit overestimates the frequency of occurrence for the large magnitude events and underestimates the smallest events, whereas Ambraseys' equation overestimates the frequency of occurrence for both the large and small magnitude events. The polynomial curve fits the historical data rather better.



**Figure 2 Earthquake Recurrence Relationships for Cyprus**

### 2.2.2 Seismic Energy Release

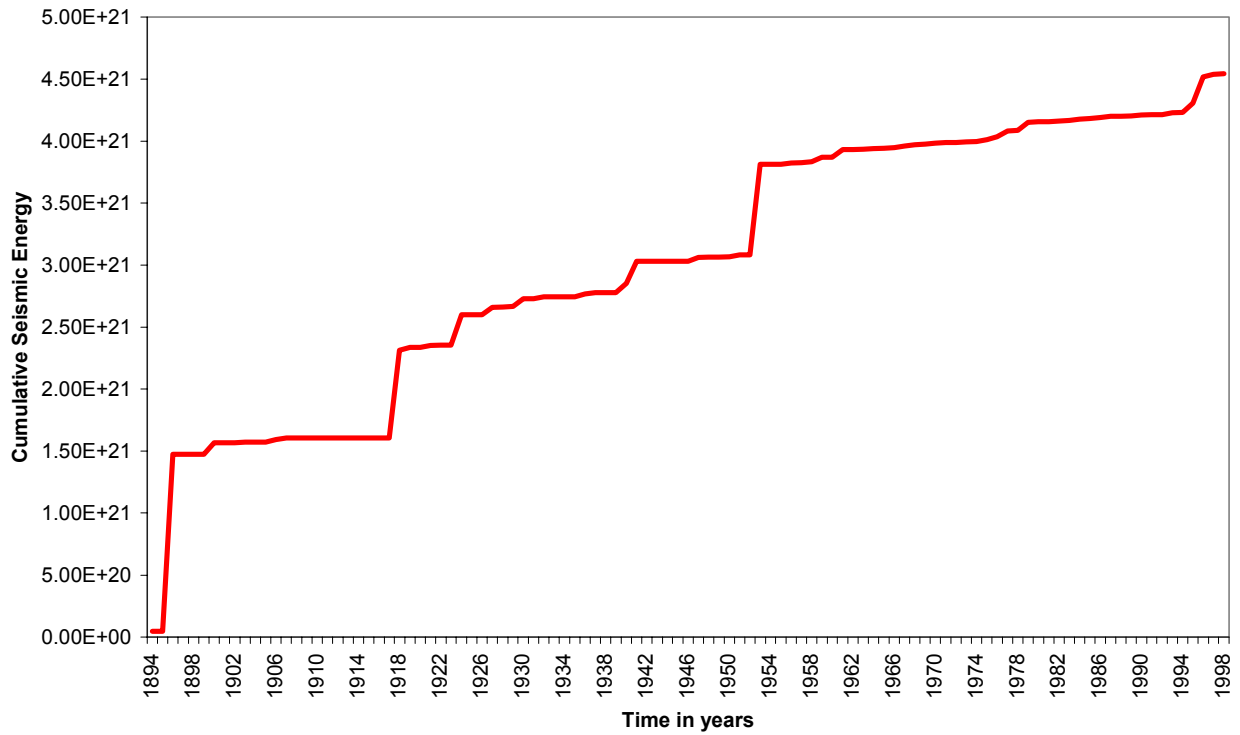
The approximate seismic energy release (E) of the historical events was estimated from:

$$\log E = 11.4 + 1.5M_s \quad (\text{Richter, 1958}) \quad (2.4)$$

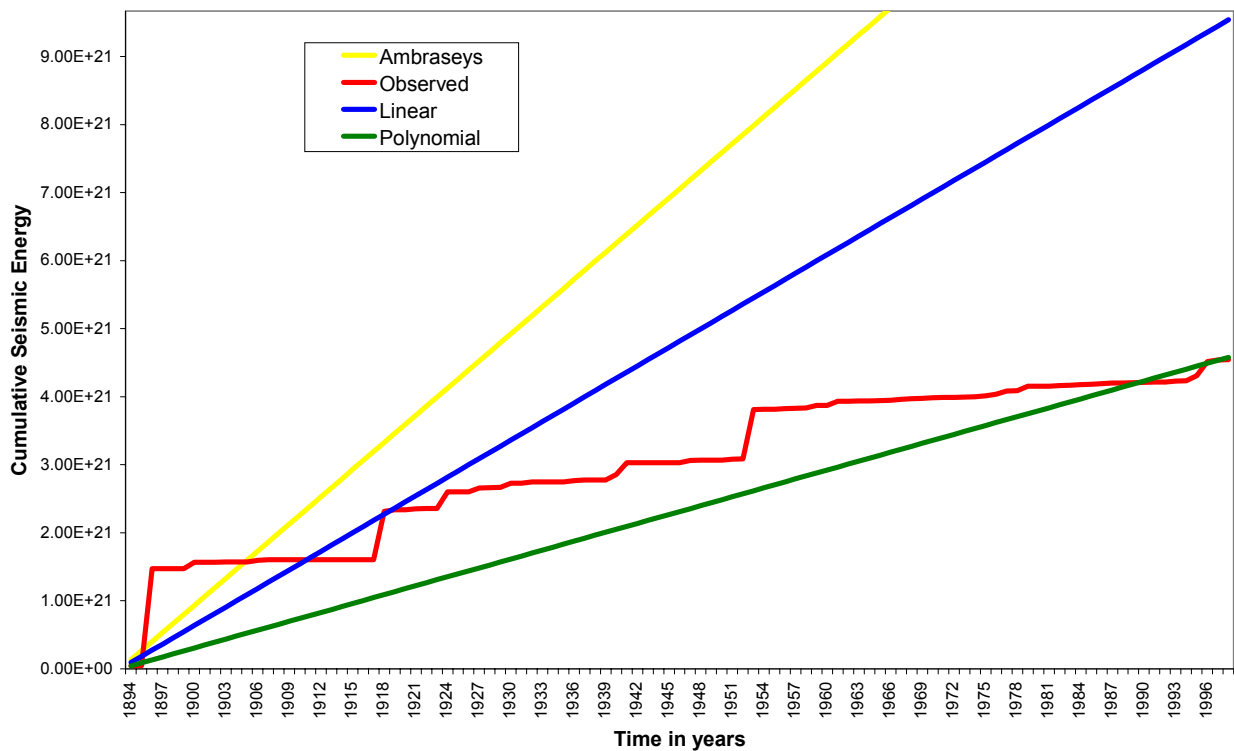
The cumulative energy from all recorded events is shown in Figure 3. The figure clearly shows that, several periods of intense seismic activity may be identified. Between these periods the increase in energy release is minimal, although it does appear to be the case that the largest energy releases are preceded by small releases. The time interval between consecutive periods of intense seismic energy release averages 12 years, although it may be seen that a 20-year tranquil period preceded the current phase of intense seismic activity.

The observed energy release data was compared to the energy release which would be predicted using each of the three recurrence relationships presented in the previous section. In each case it was assumed that no events with  $M_s > 6.5$  would occur. This assumption was based on the fact that no earthquakes of a higher magnitude have been recorded in this region to date. Figure 4 suggests that Ambraseys' recurrence relationship overestimates the energy released. This is clearly a result of the fact that this relationship over-predicted the frequency of occurrence of large events. The current level of energy released falls exactly on the value predicted by the polynomial recurrence relationship. It can be seen however, that should further large events occur in the current high intensity phase, then it could well be the case that the new linear relationship might offer a closest correlation.

On average, the seismic energy release for the above defined area of Cyprus is  $4.32 \times 10^{19}$  ergs per year.



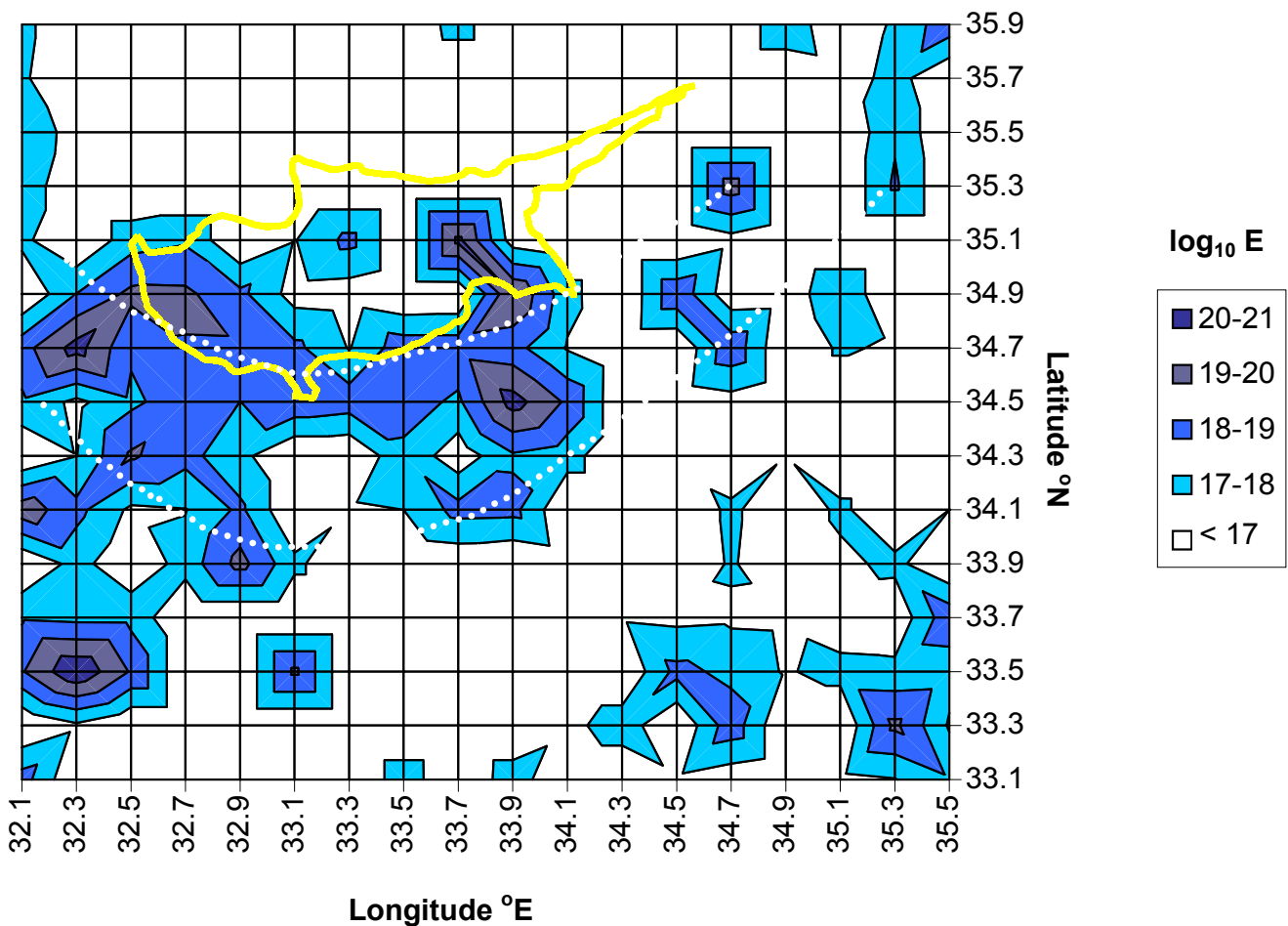
**Figure 3 Cumulative seismic energy release (1894-1998)**



**Figure 4 A comparison of the observed energy release and the energy release predicted by recurrence relationships**

### 2.2.3 Spatial aspects of the historical record

In addition to the identification of periods in time which have been subject to intense seismic energy release, the spatial distribution of energy release was considered.



**Figure 5 Spatial distribution of energy released in the area of Cyprus from 1919 until 1995 (Kythreoti et al., 1997)**

Figure 5 shows that the distribution of energy in space is not uniform; in the immediate vicinity of Cyprus the energy appears to be concentrated around two arcs, one following the line of the south coast, and the other parallel to it but nearly  $1^\circ$  of latitude further south. This data may be compared with the existing theories relating to the structure of the Cyprian Arc. If the Cyprian Arc is a plate boundary, then either a single arc, or possibly two parallel arcs, would be expected. If there is only a single arc, then the low energy release noted at  $33.2^\circ\text{E}$ ,  $34.2^\circ\text{N}$  could represent a seismic gap. There would be an enhanced probability associated with future large events occurring in this area. On the other hand, if the arc is actually composed of two parallel fault lines, then the gap would represent a genuine zone of low seismic activity. Equally the theory that the Cyprian Arc corresponds to a broad zone of thrusting is not contradicted by this evidence.

From this initial analysis, the complexity of the seismicity of the island became apparent. Therefore the use of the single recurrence relationship would not be accurate enough for ERA. A different way of addressing the problem of the non-uniform seismicity involves the application of attenuation equations with aim the calculation of the seismicity of each administrative area separately.

## 2.3 ATTENUATION EQUATIONS

Strong-motion attenuation equations (i.e. Peak Ground Acceleration equations) are considered a very important parameter for any earthquake hazard analysis and are very significant on the resulting earthquake design loads (Ambraseys and Bommer, 1995). Despite the fact that the number of strong-motion accelerographs has been increasing, for some hazard and risk assessment purposes the intensity scales remain an important measure of strength of ground shaking in earthquakes (Dowrick, 1992).

There is a large number of attenuation relationships available for both PGA and intensity, which allows the selection of the most appropriate or the most convenient equation for each particular situation. One of the main criteria for the selection and application of an attenuation law is that the seismological and strong-motion input data have been completely reconsidered and published and that they are typical of the seismotectonic environment of the area under consideration (Ambraseys and Bommer, 1995).

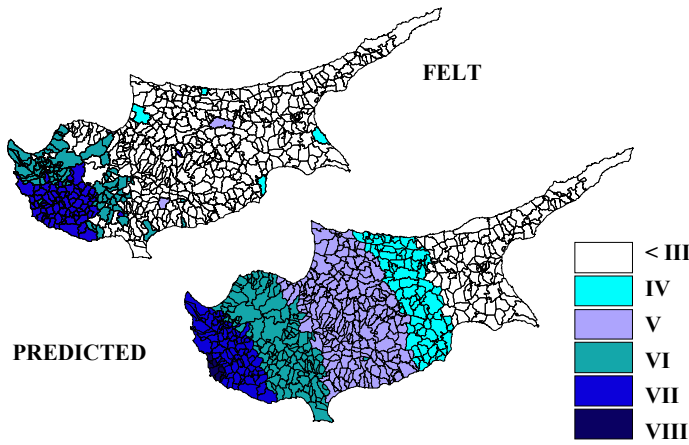
As far as this research is concerned it has been decided that both the Peak Ground Acceleration (PGA) and Intensity ( $I_{MM}$ ) will be examined.

### 2.3.1 Attenuation Laws for PGA

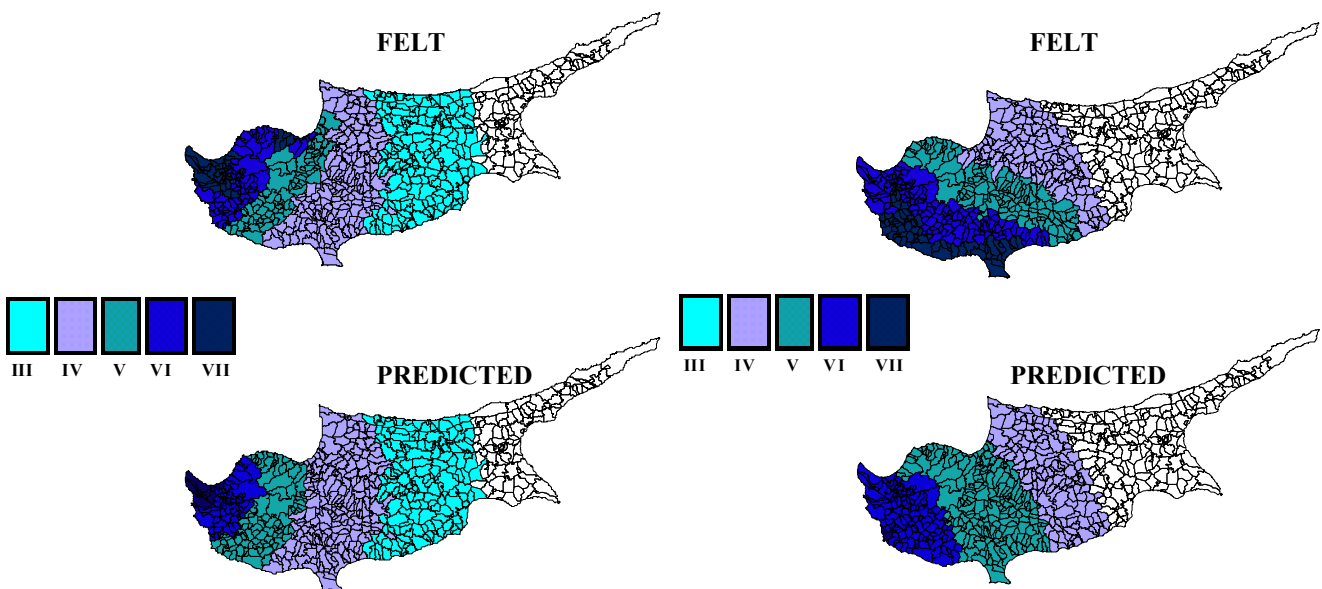
Concerning the attenuation relations for Cyprus the best solution would be relations based on strong motion data (Theodulides, 1999). Until today there is not such a data bank for the island. In such cases, usually attenuation relations based on data from comparable seismotectonic environments are adopted. A suitable relation for an environment is (eq. 3a and 3b) proposed for the area of Greece by Theodulidis and Papazachos (1992). Other equations eq. 2a and 2b (Ambraseys and Bommer, 1991) or eq. 5a (Ambraseys, Simpson and Bommer, 1996) were derived based on data obtained from earthquakes in Greece as well as areas of similar seismotectonic environments have been obtained and are listed in Appendix I with their individual limitations.

The obtained equations have been analysed and compared and their limitations were taken into consideration. All, had their advantages and disadvantages and it is difficult to identify the most suitable. Despite the difficulties, it was decided that Theodulidis and Papazachos (1992) relations provide the most consistent set of equations best suited for the case of Cyprus. The decision was mainly based on the limitations of the equations, which could basically care for all the data of the earthquake catalogue of the island. Furthermore the fact that this equation set included an equation to deal with the transformation of the accelerations to intensities made the selection of this set easier.

Another factor, which helped in the selection, was the results obtained during the verification process. The obtained isoseismal / damage data of three earthquakes (1953, 1995, 1996) were plotted and compared to the predicted intensities estimated using the equation derived by Theodulidis and Papazachos (1992). The results were better than expected with the real and predicted intensities being very similar (Figure 6, Figure 7, Figure 8).



**Figure 6** Felt and predicted Intensities in various areas of the island as a result of the 10th of September 1953 double earthquake ( $M_S=6.1$   $M_S=6.0$ )



**Figure 7** Felt and predicted Intensities in various areas of the island as a result of the 23<sup>rd</sup> of February 1995 earthquake ( $M_S=5.7$ )

**Figure 8** Felt and predicted Intensities in various areas of the island as a result of the 9<sup>th</sup> of October 1996 earthquake ( $M_S=6.5$ )

### 2.3.2 Attenuation Laws for IMM

The only available data for Cyprus regarding Earthquake Response and damage are a function of  $I_{MM}$ . It is therefore essential to have models that predict Intensity values. The availability of Intensity ( $I_{MM}$ ) attenuation equations is rather limited compared to the ones for acceleration. Only one equation (2.5) was found for a similar region and was derived based on earthquakes in Greece (Theodulides and Papazachos, 1992).

$$\ln(a) = 0.28 + 0.67I_{MM} + 0.42S \quad (2.5)$$

Other equations for the calculation of the Intensity were also obtained, but the source of the earthquake data used for their derivation was either the USA or New Zealand.

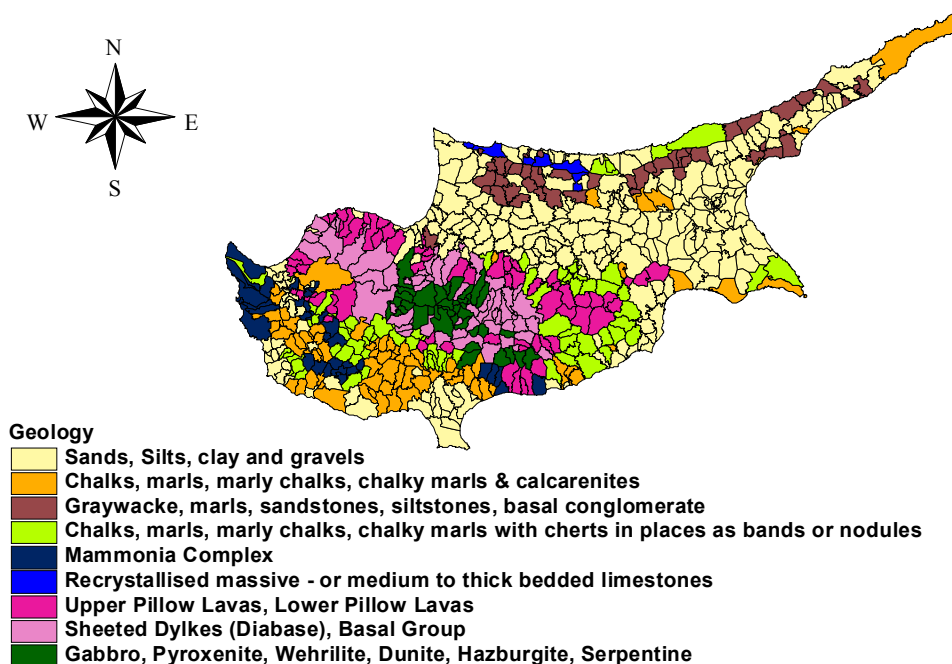
### 3. Geological Influence on PGA and $I_{MM}$

One factor, which affects the attenuation of the seismic waves, is the geology. The effect of the geology can either be taken into consideration whilst the PGA or  $I_{MM}$  are calculated (Equations 3a, 3b, 4c, 5a – Appendix I) or once they have been estimated for rock they can be adjusted appropriately. This section deals with the classification and the analysis of the geology.

According to Ambraseys and Bommer (1995) there is no common definition of site classification and contradictory models exist. A model has predicted a soil site of having higher accelerations (Sabetta and Pugliese, 1987) whereas another one predicts higher accelerations on rock (Theodulidis and Papazachos, 1992). It can be therefore concluded that this type of soil classification (S=0 for soil and S=1 for rock) is not objective and site effect results, must be used with discretion.

A different way to improve the classification of the local geology is by using the shear-wave velocity to model the site effects (Ambraseys and Bommer 1995). Unfortunately, in the case of Cyprus information on the shear-wave velocity are not available and therefore the only solution would be to either use the S-values or once the Intensity is calculated to use a value that modifies the  $I_{MM}$ .

Based on the Geological Map of Cyprus the nine main formations were identified and numbered from 1-9. The appropriate formation number was then assigned to each village or town (Figure 9). Theodulidis (1999) suggested as a preliminary approach, to group the 9 formations according to their geological age and assign to them one of the three values (0, 0.5, 1). For instance, recent alluvial and pleistocene deposits could be assigned to S=0. Troodos ophiolites, triassic, cretaceous, permo-carboniferous formations could be assigned to S=1. Solomis (1999), assessed the hardness of the 9 geological formations and characterised each of them with one of the three values. These are the values adopted.



**Figure 9 Spatial Distribution of the Main geological formations of Cyprus**

## 4. Vulnerability

One of the main input parameters for the estimation of the earthquake risk is the vulnerability of the building stock of the area under consideration. For the vulnerability to be involved in the calculation of the risk it is necessary to develop a correlation between the earthquake intensity and the extent of loss for the buildings in Cyprus. The development of such relationships is a major task and for the island of Cyprus such studies (Schnabel, 1987) produced a set of loss degree curves based on careful comparison of all the data and information available and taking into consideration the contrasting building standards in various countries.

Schnabel (1987) separated the building stock of Cyprus into three main groups, buildings with less than four storeys, buildings with more than 4 storeys, and industrial halls (Table 1). A further classification was made based on the quality of the construction and the building stock was divided into Superior Construction and Standard/Substandard construction (Table 1).

**Table 1 Mean Damage Ratios (MDR) selected for Cyprus (Schnabel, 1987)**

Type of Construction	SUPERIOR CONSTRUCTION					STANDARD / SUBSTANDARD CONSTRUCTION				
	INTENSITY									
	VI	VII	VIII	IX	X	VI	VII	VIII	IX	X
<b>Buildings</b>										
< 4 storeys	0%	5%	11%	25%	40%					
> 4 storeys						8%	17%	36%	75%	100%
<b>Industrial Halls</b>										
	1%	4%	12%	30%	60%					
Factors to be applied on MDR building / hall	0.2	0.25	0.33	0.50	0.67					

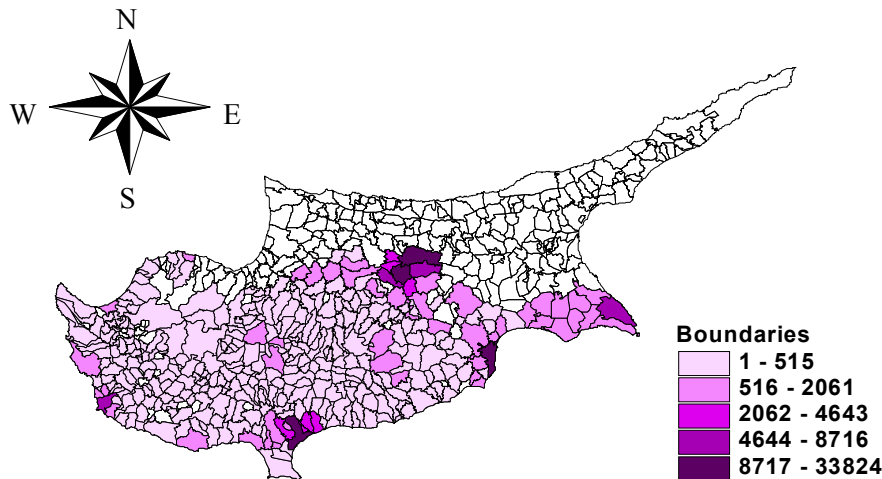
Despite the fact that the curves are a subjective interpretation of just a few data and according to Schnabel (1987) they should not be regarded as conservative curves particularly for higher intensities, they still represent the best possible approximation of the actual conditions. Whilst it is appreciated that theoretical loss forecasts are highly unreliable, it was decided to use these curves due to the unavailability of other data which would enable the estimation of the vulnerability of buildings. Some adjustment to the values will be necessary to accommodate for the different types of construction.

## 5. Statistical Data

The building stock data, used for the analysis of the vulnerability were obtained from the Census of Population (1992) published by the Department of Statistics and Research of the Ministry of Finance.

For each village and town area the number of houses (Figure 10), based on the year of construction but not the type of construction is known. The year of construction and the type of construction combined are only given in a more general form based on rural and urban residence.

According to the Department of Statistics and Research of the Ministry of Finance (1994) the tendency of the Cypriot population to leave their villages and move to the cities has been a major problem for the island, which created large scarcely populated areas and smaller very densely populated areas.



**Figure 10 Spatial Distribution of the building stock – conventional dwellings of Cyprus.**

In order to be able to use the Mean Damage Ratios (Schnabel, 1987) it was necessary to assign the various types of conventional dwellings to one of the three categories selected by Schnabel (1987). This allocation was not based on actual data rather than from experience with the general building stock of the island (Table 2).

**Table 2 Types of Conventional Dwellings**

Buildings with < 4 storeys which will be called low rise buildings	Single Houses
	Semidetached or duplex
	Row Houses
	Backyard Houses
	Not stated
Buildings with > 4 storeys which will be called high rise buildings	Apartment blocks
	In partly residential building
	Other

The year of construction of a particular structure played an important role in its classification as being a superior or standard/substandard construction. Table 3 presents the percentages assigned for each quality. These percentages were selected from experience, based on the known construction practice in the island. For instance reinforced concrete structures, which could be classified as superior construction, were first introduced in the 1960s and the aseismic code was introduced in the mid 1980s. For simplicity purposes the buildings with unknown year of construction (Not stated) were equally divided and added to the other periods (decades) of construction. It must be stressed that these values were not obtained from any calculations or analysis rather than simply selected in a way that would characteristically represent the quality of the building stock of the island.

**Table 3 Assigned percentages of the superior and standard/substandard construction for each time period**

Year of construction	Superior construction	Standard/Substandard construction
Before 1950	20%	80%
1950-1959	30%	70%
1960-1969	50%	50%
1970-1979	60%	40%
1980-1979	75%	25%
1990-1992	90%	10%

The information on the dwellings whatever their type (houses, apartments etc.) is very detailed whereas there are no information on the industrial halls, dams, roads, hospitals etc. in the Construction and Housing statistics (1994). The number of some establishments in each village and town are known. These are separated based on the branch of economic activity they belong. The various branches are given below:

*Mining & Quarrying*

*Manufacturing*

*Electricity/Gas/Water*

*Construction*

*Trade*

*Restaurants*

*Transport/Communication*

*Financing/Insurance*

*Services (such as: Medical, Education, Public Administration, Hairdressers, Beauticians, Photographers etc.)*

In order for the model to be more representative of the building stock of Cyprus, other Ministries have been contacted and information regarding the water dams, hospitals and airports have been obtained. These structures will be considered of superior construction.

These data and assumptions were used in conjunction with the data obtained for the values of the buildings to predict the possible damage costs due to earthquakes of specified magnitude.

## 6. Value of elements at risk

The study performed by KORONIDA (Hadjiloizi, 1998) as far as the value of elements at risk is concerned came to two main conclusions. The 1974 Turkish invasion and occupation of the 38% of the North part of the island created a high demand of cheap housing for the refugees. For the period 1974 – 1982 most of the residential units constructed had a relative low cost of construction (£5000 to £10000 CY, constant 1982 prices). The average cost of RC, adobe and stone buildings will be calculated in 2000 prices and will be used for the buildings constructed during that period.

The second conclusion concerns the RC houses and apartments. Table 4 presents the prices from 1990-1996 for the houses and apartments for each town. It is apparent that both the houses and apartments are more expensive in Nicosia and least expensive in Famagusta.

The prices given by KORONIDA were adopted but some assumptions were necessary due to the lack of complete data. The values given by KORONIDA had to be adjusted with the appropriate inflation rates to represent current prices.

**Table 4 Cost per house and apartment for each town from 1990-1996 (Hadjiloizi, 1998)**

YEAR	NICOSIA		FAMAGUSTA		LARNACA		LIMASSOL		PAPHOS	
	Houses	Apartments	Houses	Apartments	Houses	Apartments	Houses	Apartments	Houses	Apartments
1990	41110	19973	30127	12349	36869	13940	36813	17118	41382	12711
1991	46494	24882	33626	13884	37435	15541	39893	18126	37875	16596
1992	51780	26605	40817	14356	36542	16128	41427	20120	40936	17115
1993	50659	35064	31745	16592	52617	19056	51192	23272	50020	19966
1994	62500	35197	63952	19577	56050	25506	54210	28528	53501	20984
1995	67028	38134	66011	23328	61861	27932	64586	34751	56521	25268
1996	71980	38787	58860	23458	62364	31694	64960	33970	64300	34320

## 7. Verification of the results

The damage costs incurred, due to the earthquakes of 1995 and 1996 were obtained from the Rehabilitation and Reconstruction Services, Town Planning Department of the Ministry of Interior (Kyriakides, 2000). The magnitude of the events, the number of fatalities and injuries as well as the number of compensation applications and the total costs of the restorations have been gathered and presented in Table 5.

These data were used in an attempt to check whether the predicted damage costs are near to the true ones. Various factors may affect the comparison of the two values (i.e. the real earthquake cost to the predicted one). The total restoration costs are the money paid by the government for compensation. It does not necessarily mean that this is the actual total damage cost of the earthquake since many people might have not made a claim for their damaged property, or they might have had private insurance which paid for the damage or even the buildings if unoccupied have not been repaired.

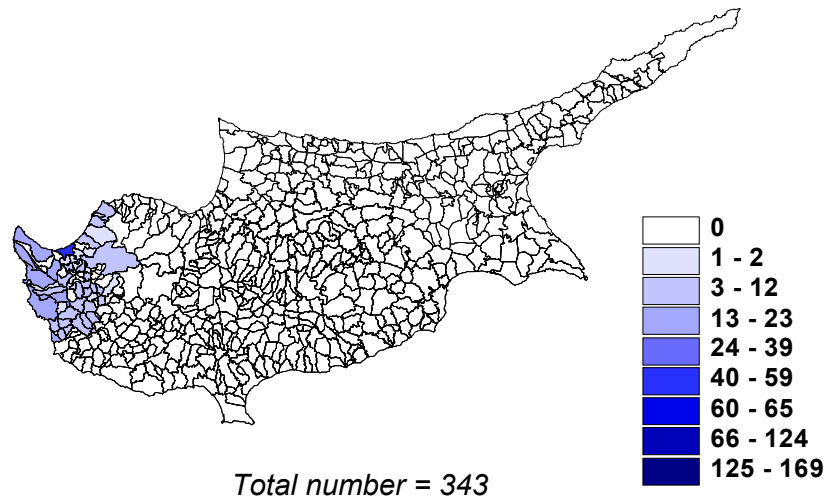
**Table 5 Fatalities, Injuries, Damage Applications and Costs of restoration caused by the earthquakes of 1995 and 1996 in Cyprus (Kyriakides, 2000)**

EARTHQUAKE EFFECT		23 February 1995	9 October 1996
<b>Magnitude</b>		$M_s = 5.7$	$M_s = 6.5$
<b>Fatalities</b>		2	1
<b>Injuries</b>		21	13
<b>Damage Applications</b>	Nicosia	400	500*
	Limassol	-	8000
	Paphos	3500	3000
	Larnaca	-	500*
<b>Total</b>		3900	12000
<b>Cost of Restoration</b>		£3,800,000 CY	£3,600,000 CY

\*The number of damage applications given for the Nicosia and Larnaca for the 1996 event were selected discretely since for these towns the data obtained gave a single number of 1000 for both.

Part of the process of verifying the predicted damage results involved their comparison with the real cost of damage experienced. The 1995 earthquake was chosen since it is believed that the data concerning that event are more complete whereas the 1996 data appear less reliable or incomplete.

The whole process involved initially three cases with a first prediction of 1377 to a final prediction of 50 totally damaged buildings. Due to the fact that the last case reduced the number of the predicted damaged building at a much lower value than the real value a fourth case which involved the adjustment of the mean damage ratios was examined (Figure 11).



**Figure 11 Predicted damaged buildings with 100% damage**

In addition to the number of damaged buildings and in an attempt to be more accurate the total cost of the damage was also examined. As far as the Reinforced Concrete buildings either houses or apartments are concerned, their values were taken from Table 4. For each district the appropriate price was used. Since the price given for RC Houses includes the price of the land a final adjustment involved the subtraction of £20000 CY pounds from the total amount. The final costs used for this study are given in Table 6 and are given in 1996 prices.

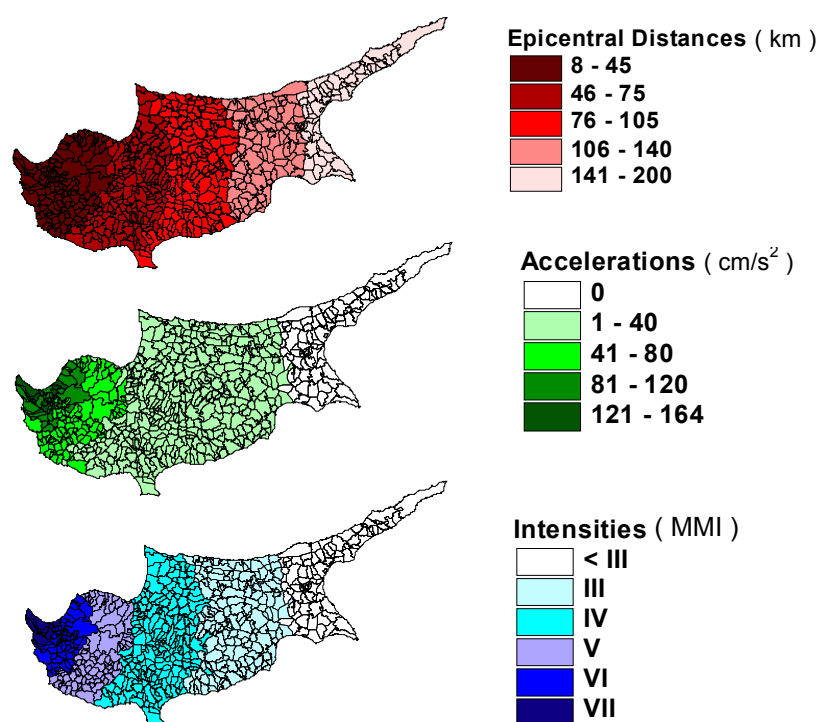
**Table 6 Costs for the three types of construction in 1996 prices**

			PRICE
Reinforced Concrete	NICOSIA	Houses	£51980
		Apartments	£38787
	FAMAGUSTA	Houses	£38860
		Apartments	£23458
	LARNACA	Houses	£42364
		Apartments	£31694
	LIMASSOL	Houses	£44960
		Apartments	£33970
	PAPHOS	Houses	£44300
		Apartments	£34320
	Adobe / Stone	All Districts	£6185

The predicted total damage cost was found to be equal to £5,930,404 CY with a relative difference to the actual costs of restoration £4,015,764 CY (1996 prices). As it was mentioned before the restoration costs given by the Rehabilitation and Reconstruction Services does not necessarily represent the actual total damage cost of the earthquake. Therefore the results obtained will be considered satisfactory.

## 8. ERA Model

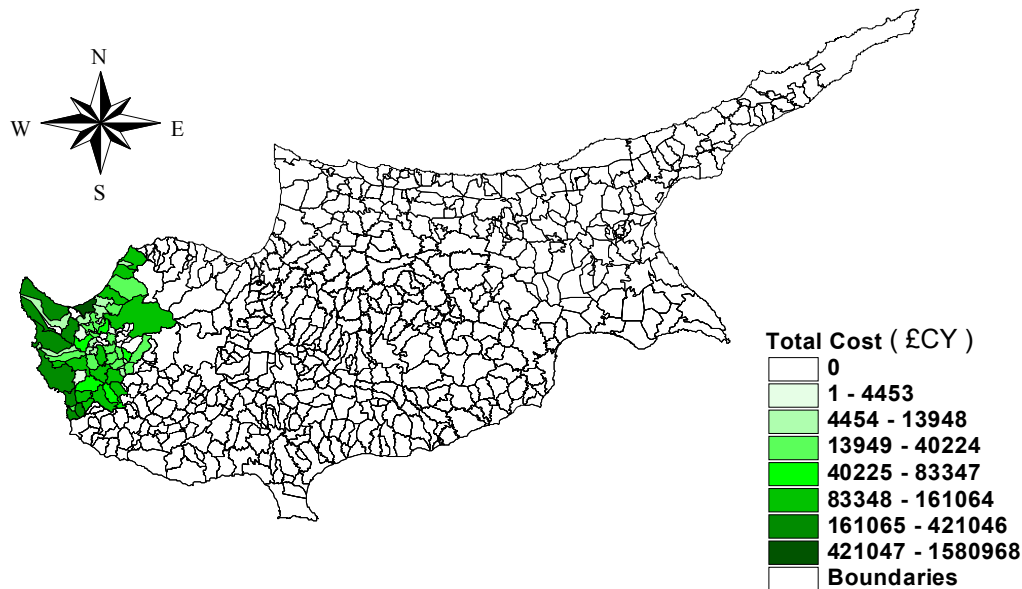
By using basic geometry, the epicentral distances from all the villages and towns were calculated. Then with magnitude and geology (i.e. the soil classification value S-value) known the Theodoulides and Papazachos (1992) relationships were applied to find the accelerations and therefore the intensities each event caused to each village or town. As an example the 1995 earthquake was selected and the resulting maps are presented in Figure 12.



**Figure 12** Calculation of the epicentral distances, accelerations and intensities caused by the earthquake which occur on the 23<sup>rd</sup> of February 1995 with Ms=5.7 using Theodoulides and Papazachos (1992) equations

Based on the intensity of each village and town the appropriate damage ratio is selected for each different type of building and the total number of damaged buildings for each type is calculated. Once the number of the total damaged buildings (Figure 11) is found the total damage cost is estimated Figure 13.

This procedure can be repeated for all the earthquakes of the catalogue and a set of accelerations or intensities will be created for each of the villages and towns of the island. The frequency of occurrence of either accelerations or intensities can be easily calculated and therefore each area will have its own characteristic recurrence relationship.



**Figure 13** Estimation of damage cost based on the total dwelling stock, the predicted intensities and the mean damage ratios; caused by the earthquake which occur on the 23<sup>rd</sup> of February 1995 with Ms=5.7

## 9. Conclusions

This paper has presented a reanalysis of the historic seismic data for the area of Cyprus. Two new recurrence relationships have been derived, and it was found that a polynomial form of the relationship fitted the observed data best.

The energy release associated with each of the events in the historic data series has been calculated, and a plot of cumulative energy release over time was presented. It was observed that periods of intense seismic activity have been separated by tranquil periods, typically twelve years in duration. The plot of cumulative seismic energy release produced using the polynomial regression relationship fitted the observed data very well. On average, the seismic energy release for the area of Cyprus is  $4.32 \times 10^{19}$  ergs per year.

The spatial distribution of released energy has been analysed. The distribution could indicate a seismic gap centred on the point 33.2°E, 34.2°N. On the other hand, if the structure of the Cyprian Arc is a double fault or a broad zone of thrusting then the lack of seismic activity in this zone is less significant.

Further work into the analysis of the seismic hazard, involved the identification of suitable attenuation equations for use in Cyprus. These were applied in order to calculate the accelerations and intensities caused by the individual events of the earthquake catalogue to the various towns and villages of the island. Once the accelerations and intensities caused by each earthquake to each area were calculated it was possible to estimate their frequency of occurrence and therefore the individual seismic hazard of each town and village. It is appreciated that the proximity of the island of Cyprus to other complex tectonic zones as well as the "non-linearity" of the historical seismicity and the fact that the recorded/available data occur during a relatively quiescent century, impose a limitation in the hazard analysis.

The vulnerability of the building stock of Cyprus was addressed and whilst it is appreciated that the path followed (i.e. the use of the mean damage ratios) is a crude way of approaching this aspect, it was necessitated due to the lack of adequate data. For the vulnerability of the buildings to be realistic, a vast range of building parameters are required. The most commonly used parameters are Age, building height, insured value, regularity and symmetry, building use, building quality (base shear), subsoil, and type of construction material (Cochrane and Schaad, 1992). These are applied to describe differences in the vulnerability of building groups.

Unfortunately, for the case of Cyprus such data are unavailable and therefore the use of Schnabel's loss degree curves was unavoidable. It is accepted that this way in which the vulnerability has been approached has its limitations. Nevertheless it will not be considered as a major problem towards the development of the model since the aim is not to develop a detailed model but a model capable of dealing, predicting and suggesting solutions and management strategies.

Verification studies showed that despite the use of such crude mean damage ratios, relatively accurate damages were predicted. Once the appropriate information become available they can be included in the model and better predictions should be expected.

The value of the elements at risk is another parameter involved in the calculation of the earthquake risk. Various assumptions were involved in dealing with the cost, which unquestionably might reduce the correctness of the results of the model. Despite the fact that the limitations of these assumptions are appreciated they were necessary due to the small number of available information. If and when a better database is available it can be employed for a more realistic result. Nevertheless the verification of the results proved very promising with a small difference in the actual damage costs and the predicted ones.

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**Ambraseys, 1975**

$$1 \quad \log(a) = 0.46 + 0.64M - 1.10\log(R)$$

(Based on data generated by earthquakes in Greece, Iran, Italy and former Yugoslavia)

Where:  $a$  is the peak horizontal ground acceleration  
 $M$  is the earthquake magnitude  
 $R$  is the source-site distance

**Ambraseys and Bommer, 1991**

$$2a \quad \log(a) = -1.09 + 0.238M - \log\sqrt{(R^2 + 6.0^2)} - 0.00050\sqrt{(R^2 + 6.0^2)}$$

$$2b \quad \log(a) = -0.87 + 0.217M - \log\sqrt{(R^2 + h^2)} - 0.00117\sqrt{(R^2 + h^2)}$$

(Based on data generated by earthquakes in Europe, North Africa and the Middle East)

Where:  $a$  is the peak horizontal ground acceleration  
 $M$  is the earthquake magnitude  
 $R$  is the source-site distance  
 $h$  is the focal depth

**Theodulides and Papazachos, 1992**

$$3a \quad \ln(a) = 3.88 + 1.12M - 1.65 \ln(R + 15) + 0.41S$$

(FOR SHALLOW EARTHQUAKES)

$$3b \quad \ln(a) = 3.47 + 0.75M_w - 0.85 \ln R_{CER} + 0.27S$$

(FOR INTERMEDIATE EARTHQUAKES)

If  $6.0 \leq M_s \leq 8.0$  then  $M_w = M_s$

If  $4.2 \leq M_s \leq 6.0$  then  $M_w = 0.56M_s + 2.66$

Usually if  $M_s > 5.5$  then  $M_w = M_s$

$$R_{CER} = \sqrt{(R^2 + h^2)}$$

(Based on data generated by earthquakes in Greece but also included 16 records from Japan and Alaska)

Where:  $a$  is the peak horizontal ground acceleration  
 $M$  is the earthquake magnitude  
 $R$  is the source-site distance  
 $h$  is the focal depth

$S$  is a soil term taking a value of 0 at alluvial sites, 0.5 at intermediate hardness sites and 1 at rock sites.

**Ambraseys, 1995**

$$4a \quad \log(a) = -1.43 + 0.245M - 0.786\log\sqrt{(R^2 + 2.7^2)} - 0.0010\sqrt{(R^2 + 2.7^2)}$$

$$4b \quad \log(a) = -1.06 + 0.245M - 1.016\log\sqrt{(R^2 + h^2)} - 0.00045\sqrt{(R^2 + h^2)}$$

$$4c \quad \log(a) = -1.05 + 0.245M - 0.786\log\sqrt{(R^2 + 2.7^2)} - 0.0010\sqrt{(R^2 + 2.7^2)} - 0.15\log(V_s)$$

(Based on data generated by earthquakes in Albania, Algeria, Bulgaria, Greece Iceland, Iran, Israel, Italy, Pakistan, Portugal, Romania, Spain, Turkey, the former USSR and former Yugoslavia)

Where:  $a$  is the peak horizontal ground acceleration

$M$  is the earthquake magnitude

$R$  is the source-site distance

$h$  is the focal depth

$V_S$  is a term for the site geology represented by the average shear-wave velocity (m/s)

### Ambraseys, Simpson, Bommer 1996

$$5a \quad \log(a) = -1.48 + 0.266M_S - 0.922\log(r) + 0.117S_A + 0.124S_S$$

$$r = \sqrt{(d^2 + 3.5^2)}$$

(Based on data generated by earthquakes in Europe and adjacent regions)

Where:  $a$  is the peak horizontal ground acceleration

$M_S$  is the surface magnitude

$r$  is the source-site distance

$d$  is the shortest distance from the station to the surface projection of the fault rupture in km

$S_A$  takes a value of 1 for stiff soil sites otherwise 0

$S_S$  takes a value of 1 for soft soil sites otherwise 0

$S_A$  and  $S_S$  takes a value of 0 for rock sites

Table 1. Characteristics of the attenuation equations

No	Units	No events	h max	M	Mmin	Mmax	R	Rmin	Rmax
1	cm.s <sup>-2</sup>	58	15	M <sub>L</sub>	3.5	5.0	r <sub>e</sub>	5	30
2a	g	529	25	M <sub>S</sub>	4.0	7.3	d <sub>f</sub>	1	313
2b	g	529	25	M <sub>S</sub>	4.0	7.3	r <sub>f</sub>	1	313
3a	cm.s <sup>-2</sup>	40	18	M <sub>S</sub>	4.5	7.5	d <sub>e</sub>	1	130
3b	cm.s <sup>-2</sup>	28	159	M <sub>W</sub> , M <sub>JMA</sub>	5.2	8.0	r <sub>e</sub>	40	230
4a	g	1260	25	M <sub>S</sub>	2.0	7.3	d <sub>f</sub>	1	313
4b	g	828	25	M <sub>S</sub>	4.0	7.3	r <sub>f</sub>	1	313
4c	g	145	25	M <sub>S</sub>	4.0	7.3	d <sub>f</sub>	1	45
5	g	157	30	M <sub>S</sub>	5.0	7.5	d <sub>f</sub>	1	200

Source Distances can be epicentral (d<sub>e</sub>), hypocentral (r<sub>e</sub>), closest horizontal distance to the projection of the fault rupture at the surface (d<sub>f</sub>) or to a horizontal plane at the focal depth (r<sub>f</sub>).

Magnitudes can be surface wave magnitude (M<sub>S</sub>), local magnitude (M<sub>L</sub>), Japan meteorological agency magnitude (M<sub>JMA</sub>).