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Seismic hazard assessment and its contribution to the ancient monument protection – A case history in Greece

Evaluation du risque de tremblement de terre et sa contribution à la protection des anciens monuments – Un cas en Grèce

K.C.Makropoulos & J.K.Drakopoulos
Department of Geophysics, University of Athens, Greece

G.A.Tselentis
Department of Engineering, Tokyo Metropolitan University, Japan

ABSTRACT: In the present study the estimation of the "design values"for protective works against future seismic load of the ancient monument of Knossos (Crete) is attempted. It is based on the analysis of historical and instrumental seismic data by the method of extreme value statistics and the semi-statistical method proposed by Cornell. The maximum hazard parameters expected to occur at the site within the next 50 and 100 years with probability 90% resulting from these methods are then used as inputs and the response spectrum is constructed for 2% and 5% of critical damping following the technique of Newmark and Hall. Furthermore, the mean spectral acceleration as a function of period for a 5% of critical damping is presented. Taking into account the low periods of oscilation (i.e. 0.1 - 0.2 sec)of such a rigid structures like the Knossos monument,the values of spectral acceleration of 0.21 g and 0.24 g for the next 50 and 100 years and with probability of 90% to be the maximum respectively are the ones found and recommented for possible protective work of this monument.

RESUME:Dans cette etude nous avouns essayé l´estimation de la "valeur d´application,"pour les travaux de protection, contre les séismes, d´ancien monument de Knossos(Crète). Cette etude est basée sur l´analyse historique et instrumentale des donnés sismiques,par la méthode statistique de la valeur extrême et par la méthode semi-statistique, proposée par Cornell.Les paramètres maximaux du risque sont prevus d´arriver àla site historique entre les prochaines 50 à 100 années, avec une probabilité de 90% ,qui resulte par les méthodes ci-dessus mentionées. Les paramètres sont utilisés comme des intrants et le spectre des réponses est construit pour l´effacement critique de 2% á 5%, d´après la technique des Newmark et Hall. Plus avant, l´accélération critique essentielle est présentée, comme une fonction de l´effacement critique de 5%. Avour en vue les périodes basses d´oscillation (ex. 0.1 - 0.2 sec) d´une structure rigide, telle qu´elle soit le monument de Knossos, les valeurs du spectre d´accélération de 0.21 g á 0.24 g, pour les prochaines 50 et 100 années et avec une probabilité de 90%, elles sont celles découvertes et recommendées par les travaux de protectioneventuelles, concernant ce monument.

1 INTRODUCTION

The assessment of the future seismic load due to an earthquake occurrence is an engineering usefull tool not only for an aseismic design of a new structure but also for protective measurements of existing ones.Furthermore,when we deal with ancient monuments such a load could be critical to these rigid strucrures and may trigger geological hazard like rockfalls,land slides subsidense etc.resulting in more extensive damages.

The evaluation of the maximum dynamic load to which a structure will be subject during its life is based on the estimation of the maximum expected earthquake magnitude and the resulting maximum ground motion parameters at the site.That is,on the seismic hazard assessment.

Definition of seismic hazard as "the probability of occurrence of an earthquake in the future" (Lomnitz,1974,Unesco,1979) , implies a degree of future uncertainty. Hence principles of probabilistic forecasting and decision making are essential in any seismic hazard analysis.The choise of the appropriate statistical model is however,based on the degree by which the existing seismic data fulfil the requirements of that specific model.Thus before going into the statistical analysis for the

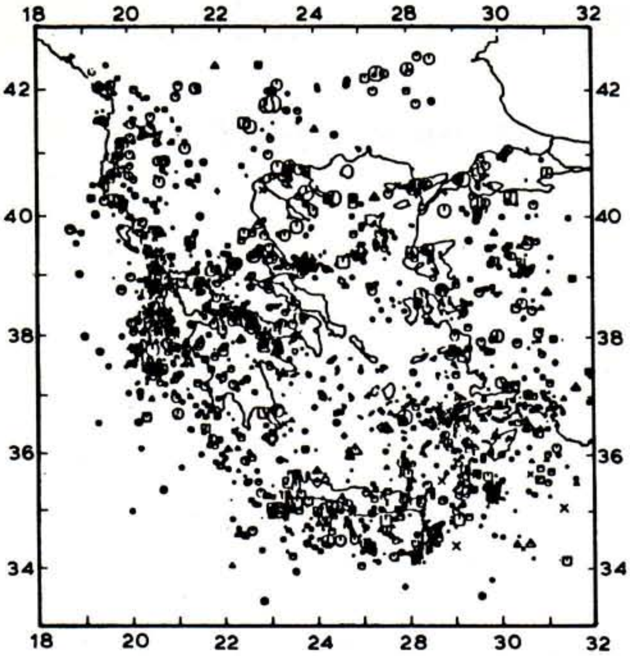

Fig.1 Earthquakes in Greece since 1900 (Makropoulos et al.,1986)

hazard estimation the seismicity and seismic history of the area around the ancient monument will be first examined in the next section.Then,two statistical methods will be employed and the results be further processed leading thus to the response spectra values.In the last part and after taking in to account the monument characterestics , the design values for future protective measurements will be given.

2 SEISMICITY-SEISMIC HISTORY

Figure 1 shows the spatial distribution of earthquakes which occured in the area of Greece (Makropoulos et al.,1986).From this figure it is clear that the island of Crete is characterized by a high seismic ativity especially at its sourhern coast.It belongs to the southern segment of the well defined Hellenic arc which is the front of the collision of the African-Eurasian plates. (Mckenzie,1972, 1978; Mercier et al.,1979; Makropoulos and Burton,1984; Angelier et al.,1982).This also explains the high degree of tectonism of the island (Fitrolakis, 1980),Drakopoulos et al.,1983).

The Knossos site is situated in the Heraclion graben which along with its southern extension, Messara graben,are the areas with the highest concentration of inland foci.Moreover it is situated near to the Heraclio-Tibaki tilting axis of the island with the western part lifting up whereas the eastern part remains stable or submerges with relatively slow rate (Fitrolakis, 1980; Thommeret et al., 1980; Delibasis et al.,1981).

This brief describtion in a certain degree explains the repetition of catastrophs well documented by the long history of the area (Georgiadis,1904; Sieberg,1932; Galanopoulos,1960).A list of the historic earthquakes hitted the Knossos area from 2100 BC to 1900 AD can be found in Makropoulos,1987.The historical data are a vital background factor for the seismic behaviour of the area.However, the main demand of modern seismology for seismic hazard assessment is the existence of an earthquake data set as accurate homogeneous and complete as possible.These requirements restrict thus, usage to mainly instrumentally recorded events (i.e.after 1900).

In the analysis to be followed the earthquakes which occurred after 1900 near the Knossos site are extracted from the catalogue of Makropoulos et al., 1986 and form the data set used.

3 METHODOLOGIES

Two methodologies will be applied here to indicate seismic hazard.First the " part process " asymptotic distribution of extreme values (Gumbel, 1966) will be used to obtain estimates of maximum magnitude recurrence . Secondly,the semi-statistical method proposed by Cornell (1968)will be deployed to estimate the expectations of levels of peak ground acceleration,velocity and dispacement exceedance.

3.1 Magnitude recurrence - Gumbel III method

Seismic hazard and related earthquake engineering purposes usually require estimation of return periods or probabilities of exceedance of specific levels of design load criteria on extremal safety conditions. Thus what is of primary importance in earthquake engineering is compatible with a need to consider extreme value distributions separately from the statistics of the whole process.Extreme value statistical theory seems to satisfy most of the above problems and since Gumbel´s (1935, 1966) developments the theory has been applied to many fields such as hydrological and climatic evaluations (Jenkinson , 1955 ; Gringorten, 1963)as well as to the analysis of earthquake occurrence (Epstein and Lomnitz,1966;Schenkova and Karnik, 1978 ; Makropoulos and Burton,1985 a,b). Furthermore, the extreme value distributions have the advantages that detailed knowledge of the parent distribution is not required and the extreme values themselves are usually better known than the smaller events in a catalogue or times series of data.

The extreme value distribution with an upper bound is used here, called Gumbel III, and is of the form :

$$P(m) = \exp\left[-\left[(w - m)/\ (w - u)\right]^k\right],\ k>0,\ m\leq w \quad (1)$$

with parameters : the upper bound magnitude w, a characteristic extreme magnitude value u, and k (= $1/\lambda$) which relates to curvature of the distribution. P is the probability that a magnitude m is an annual extreme. The principles by which we fit (1) to the observed data are described in detail elsewhere (e.g., Makropoulos 1978; Drakopoulos and Makropoulos, 1983) and we shall not elaborate here. The basic relations used are : (a) the T-year modal maximum:

$$m(T)=w-(w-u)\left[(1-\lambda)/T\right]^{\lambda} \quad (2)$$

and (b) the earthquake magnitude with probability P of being a maximum or not being exceeded in the next T years is :

$$mp(T)=w-(w-u)\left[(-\ln P)/T\right]^{\lambda} \quad (3)$$

with a corresponding average return period T´- years :

$$T' = 1/\ (1 - P^{\frac{1}{T}}) \quad (4)$$

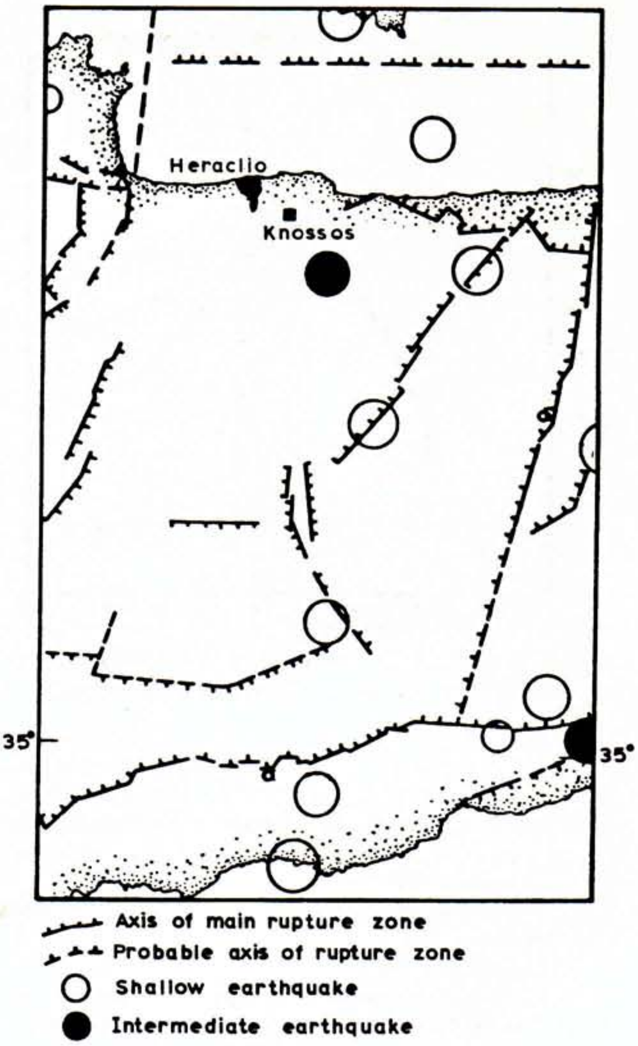

Fig.2 Tectonic futures of the area (Drakopoulos et al., 1983).

3.2 Peak ground motion parameters-Cornell method

For the estimation of the peak ground motion parameters (i.e. acceleration, velocity, displacement) at the site due to an earthquake occurrence, the method proposed by Cornell (1968) is applied here. This method combines the statistical model of Poisson type behaviour distribution with the geological and tectonic pattern of the region under study .

Based on the seismotectonic regime of the area the seismic source geometry is first modeled. Next the contribution of each source to the seismic load at the site is evaluated by estimating the source´s potentiality and transfering that to the site through an attenuation function . The final stage consists of convolving the contribution of all seismic sources giving thus the probabilistic loading at the site. The model accepts three types of sources : point, line and area sources. For more details the reader is refered to Cornell, 1968; Cornell and Merz, 1974 , McGuire , 1977 ; Stavrakakis et al., 1987. In the present study the line source (faults) model is used. It is based on the tectonic features of the area, figure 2, given by Drakopoulos et al., 1983. The attenuation formulae for the peak ground acceleration, velocity and displacement used are :

1. $A = 1264.e^{0.7M}\ (R+20)^{-1.8}$ in cm/sec^2 (5)

2. $V = 0.726.10^{0.52M}\ R^{-1.34}$ in cm/sec (6)

3. $D = 0.0471.10^{0.57M}.R^{-1.18}$ in cm (7)

respectively . Equation (5) is from Makropoulos and Burton, 1985, whereas equations

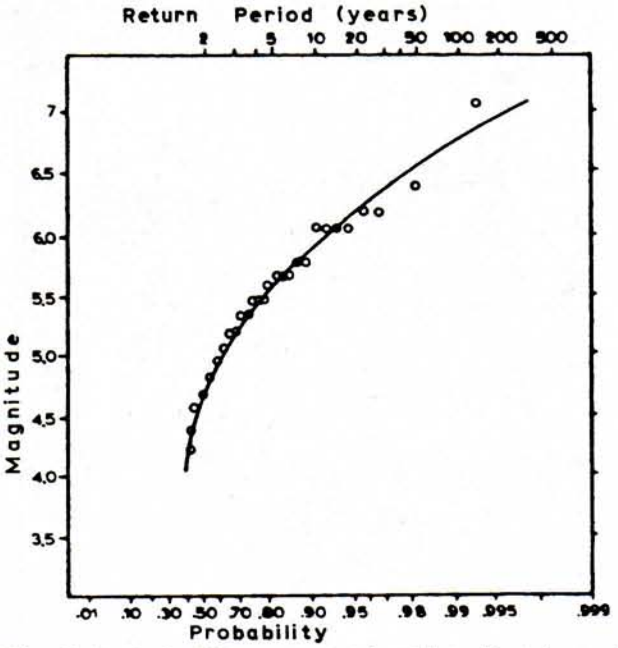

Fig.3 Gumbel III asymptotic distribution of extremes for an area 1° around Knossos monument

Table 1. Earthquake magnitude with probability P to be the maximum in the next T years.

Time (years)	Probability 37%	80%	90%
50	5.6	6.1	6.3
100	5.8	6.3	6.5
150	5.9	6.4	6.7

Table 2. Probability for an earthquake occurrence with magnitude greater than M within the next T years

Magnitude M	Time 50	100	200
5.0	0.99	1	1
5.5	0.69	0.90	0.99
6.0	0.23	0.41	0.66

(6) and (7) are from Orphal and Lahoud, 1974.

3.3. Response spectra -Newmark and Hall method

The peak ground motion parameters with a given probability of ocurrence P within the next T years, resulting from the previous stage, are then used to construct the response spectra. The technique followed is the one proposed by Newmark and Hall, 1969. The peak ground parameters are multiplied by given appropriate factors depending of the parameter (e.g. acceleration) and the percentage of the critical damping selected (e.g. 2% or 5%). All values are then plotted on triple logarithmic paper as a function of the period.

4 RESULTS AND DISCUSSION

Figure 3 shows the Gumbel III asymptotic distribution for the area around Knossos monument. There is a well third-type behaviour of the data. The maximum earthquake magnitudes which with probability 37% (Mode), 80% and 90% are expected to occur within the next 50,100 and 150 years are tabulated in table 1. Table 2 lists the probability of having an earthquake of magnitude greater or equal of m in the next 50,100 and 200 years.

From tables 1 and 2 it can be seen that within the next 50 years there is a 30% probability that the area near of Knossos will experience an earthquake bigger than 5.9 while the probability for an earthquake bigger than 6.3 is only 10%. Furthermore, it is almost certain that during the next 100 years an earthquake of magnitude above 5 will take place whereas with a probability 40% an earthquake with magnitude above 6 is expected to occur within the same time period. Looking back to the seismic history of the area, (Makropoulos 1987) the values of both tables are in good agreement with the already occurrence of such a magnitude earthquakes.

From the above consideration and taking into account that the mean depth of the earthquakes around the Knossos area is about 30-40 km, from the point of maximum expected magnitude the area could be characterized by a moderate seismic hazard.

Table 3 contains the values of expected peak ground acceleration, velocity and dispacement with the probability 90% of being the maximum within the next 50 and 100 years. These are the results after applying the equations (5), (6) and (7) respectively and the above described method.

From table 3 it can be seen that the seismic hazard from the maximum ground amplitude point of view is of low to moderate level. Comparing the results tabulated in tables 1 and 2 with those in table 3 it is clear that the hazard based on expected ground amplitudes is much less than the one based on magnitude distribu -

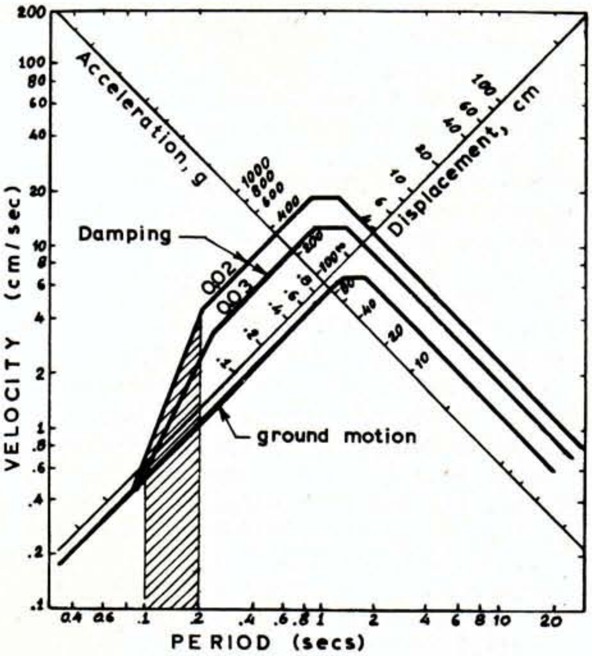

Fig.4. Smoothed response spectra fro Knossos site.

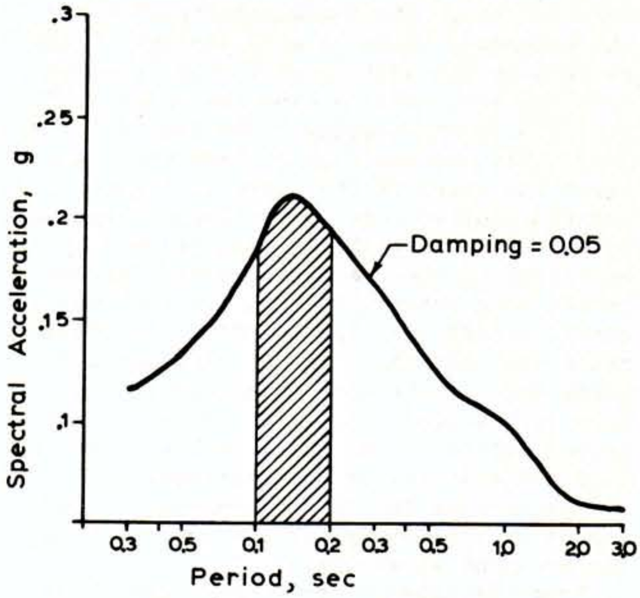

Fig.5. Mean acceleration response spectra for Knossos site.

Table 3. Peak ground motion amplitudes with 90% probability of not being exceeded in T years.

Time (years)	Acceleration cm/sec^2	Velocity cm/sec	Dispacement cm
50	82	6.8	2.3
100	91	7.5	2.2

tion. However, this discrepancy is to be expected because all high magnitude earthquakesare far from the site. But this factor could not be taken into account during the magnitude hazard estimation. This is because for the magnitude, being a measure of the energy released at the focus, there is no tranfering function like those discribing the ground motion propagation (e.g. eq.(5)). Hence the magnitude hazard estimates are equally applicable to the whole area from which the data are taken, which in our case is the area with radius of 1/2 degree around Knossos site. Thus, while the magnitude distribution indicates the potentiality of the whole area around the site to generate large earthquakes,the calculation of seismic hazard based on ground amplitude distribution at the site gives more specific answers for design purposes in cases where the potential earthquake sources are distant ones as in the area under consideration. The formulae used for the peak ground amplitude estimation at the site , eqs(5),(6) and(7) are valid for rock type soil conditions , so the values of table 3.

Although there is a significant diffe - rence in response for different soil conditions for large period of oscillation , let's say above 0.5 sec, for small periods this difference is diminished (Seed et. al. 1974). The Knossos monument consists of rigid columns of low hight and thus periods of the range 0.1 - 0.2 sec dominate the structure. Hence the values of table 3 may serve as ground parameters for the design response spectrum.

Figure 4 shows the smoothed response spectra for the Knossos site. It has been constructed by making use of the peak ground parameters which have a probability 90% of not being exceeded in the next 50 years (i.e. 475 years return period eq.(4)), first row in table 3,and the procedure suggested by Newmark and Hall, 1969, for two damping ratio of 0.02 and 0.05 of critical. In addition, the smothed acceleration response spectra at different periods was drawn. The spectra were normalized to peak acceleration with 90% probabilities of not being exceeded in the 50 years. The mean peak value of peak acceleration was multiplied by the average acceleration amplifications given by Mohraz, 1976, for horizontal components with the largest peak ground acceleration for 0.05 of critical damping. The results are shown in figure 5.

From figures 4 and 5 it can be seen that for the period of 0.1 to 0.2 which is un -

derstood to be the fundamental period of the monument, there is a 10 percent chance that in the next 50 years the spectral accelerations will exceed the value of 0.21 g(0.05 cr. damping). For the next 100 years this becomes 0.24 g. Last but not least the shape of the curve in figure 5 and the similar one for different damping ratios shows that the maximum values of acceleration spectra are observed for the period rang between 0.1 and 0.2 sec which characterized the rigid structures. This means that for this kind of structures to which most of the ancient monuments are part of, the most important factor of the ground motion is the acceleration rather than the velocity or the displacement.

To summarize the hazard analysis performed by this study for the area of Knossos monument shows that:

1. From the expected earthquake magnitude point of seismic hazard, the area can be classified as moderate one. In an area of 0.5 degree radious around the site, the probability that an earthquake with magnitude exceeded 6.5 in the next 50 years will occur is less than 10%.

2. From the point of maximum expected ground motion, the area belongs to the low to moderate seismic hazard category. However, because the monument is a rigid structure with low periods of oscilation where the spectral acceleration takes its maximum, see Figure 15, the hazard for the Knossos monument is relatively high.

3. Within the critical periods of 0.1-0.2 sec and with probability 90% of not being exceeded in the next 50 and 100 years the values of spectral acceleration are found to be 0.21 and 0.24 g respectively. These values can serve as "design value" for future protective measurements concerning the Knossos monument.

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