SEISMIC HAZARD ANALYSIS FOR ZONES OF INTERMEDIATE SEISMICITY

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SUMMARY

Portugal is located to the north of the Azores-Gibraltar fracture zone between this interplate boundary and the european intraplate region, in a so-called intermediate tectonic environment. The seismicity of this country is influenced by strong distant earthquakes occurred at the boundary and by moderate nearby earthquakes related to the faults in the continent.

Hazard analysis for intermediate tectonic environment take into account, by means of parameter modelling, the large uncertainties of this seismic process: (i) on the location of active faults in the continent; (ii) on near-field ground motion assessment and (iii) due to the low rate of earthquake occurrences (moderate to strong). Existance of 10 centuries of historical data reduces uncertainties on final estimates.

INTRODUCTION

Seismic hazard analysis gives the primary input for quantification of seismic loads to consider in the design of structures. Models for computing hazard curves and quality of data needed for their calibration will depend on the required risk level (probability of failure) which, of course, is set according to the type of structure under study. Fig 1 presents a sketch in form of a pair of matrices indicating the different possible cases.

Many hazard analysis have been done in different areas of the world, specially in zones of either high or very low seismicity (inter or intraplate tectonic environment). In the present case we will be dealing with an intermediate tectonic environment with a long historical information. In fact, Portugal is located a couple hundred kilometers (100-300) to the north of the Azores-Gibraltar interplate plate boundary, Fig 2 a), where a relative 1 to 1.5 cm/year movement of collision between the Euro-Asiatic and African plates is taking place (Ref.1 and 2). This movement is the result of the evolution of the openning of Atlantic Ocean in the last 150 million years (M.Y.). The old continental crust shows fault alignements along NE-SW and NW-SE directions, Fig 2 b); some of them exibit signs indicating that the mean principal deformation in the region have changed, in the geological times, from a right lateral strike-slip to a left-lateral and back to a reverse situation. The general compression derived from the present state of collision (no subduction) is transmitted to the intraplate region of the stable Iberian Meseta and Central Europe by the small plates in which the continent is subdivided. Based on recent studies on seismology and geotectonics of the region, (Ref.3) a preliminary selection of the most important faults was made, Fig 2 b). Until recently, no evidence has been found at the continent for historical movements, surface rupture or creep in the last 10 000 years, indicating that deformation is taking place at a very slow rate. However, large vertical movements gave rise to the formation of grabens and horsts, in the last 5 M.Y emphasizing the influence of gravity forces in this compression state of stress.

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The tectonic environment described above, which we will name intermediate, is responsible for large earthquakes produced in the collision zone causing in the far-away continent (100 km or more) long duration and low frequency ground motions, and for small to moderate earthquakes occurred inland causing short but intense high frequency ground motions in the nearby sites.

ANALYSIS OF EXISTING DATA

Existing data on seismic activity in Portugal come from three sources of information (Ref.1 and 2): 1 - historical catalogue of earthquakes since the 10th century, Fig 3; 2 - a catalogue of instrumental recording since 1902 obtained from the Instituto Nacional de Meteorologia e Geofísica, Lisboa with a typical plot in Fig 4 a) representing the seismic activity during two most active decades of this century; and 3) isosseismal maps of the larger earthquakes since 1902. Epicentral locations, spread throught the continent, exibite errors, in some historical events, of more than 50 km; up to 1930, 15-20 km and recently 5 to 10 km. With this data it is not possible to set correlations between seismic events and specific active faults but define zones of difuse seismicity. Focal depths are generally less precise. But as, according to seismological experiments, continental earth crust in this region is about 30 km thick, we took an average focal depth equal to 15 km for all earthquakes. Uncertainties in the assessment of magnitude values are of great importance specially for earthquakes of vital influence on the characterization of inland seismicity. Based on data analysis, the following should be emphasized. Mean average of strong historical occurrences since the 11th century is low, approximatly 0.005/year. The 1755 Lisbon earthquake, (M_L=8.75 to 9.) which destroyed great part of the city was the last event. These events, naturally connected to the plate boundary, alternate with the occurrence of local earthquakes (inland) which show high intensities only over a restricted area of influence. ($\lambda_1 \simeq 0.1$/year $4 \leqslant M_L \leqslant 6$). The catalogue of earthquakes in this century with more than 700 ($M_L \geqslant 3$) recorded within a circle of 500 km centered at Lisbon, is dominated by the inland 1909 Benavente earthquake, (M_L=5.6 to 6.), which destroyed completely the village with the same name and by the North Atlantic earthquake of February 28, 1969, (M_L=7.6), with epicenter some 280 km SW Lisbon and felt all over the country. Generation in time is not regular and has occurred alternatively in different regions of the country. Besides the influence of Benavente earthquake which was followed by a large number of aftershocks, the earthquakes post-1920 show approximatly constant rate of dissipation of energy, whereas earthquakes occurred in the sea dissipate, in a descontinuous fashion, much more energy, Fig 4 b).

The statistical treatment of instrumental data (1902-1975), as far as time and magnitude are concerned, lead to the results: 1) Poisson model of generation can be accepted for $M_L \geqslant 4.5$ with a significance level of 28% with an average $\alpha_{m=4} = 1.09$ /year/10^5 km^2. 2) Magnitude distribution was analysed separatly for inland and far-away earthquakes using the entire family or the yearly maximum events. Inland results are shown in Fig 5. For the entire sample the best fitting was obtained with the parabolic law $\ln N_m = \alpha + \beta_1 \cdot (m - m_0) + \beta_2 (m^2 - m_1{}^2)$ for $m_0 \leqslant m \leqslant m$, where Nm is the number of earthquakes with magnitude equal or greater than m, and m_0 and m_1 are respectively lower magnitude threshold and upper truncation value. Estimates of $\hat{m}_0$ and $\hat{m}_1$ were judged from geotectonic and seismological data and $\hat{\alpha}$, $\hat{\beta}_1$ and $\hat{\beta}_2$ using mean square techniques. A type III extremal distribution, $G_M(m)$, $G_M(m) = \exp \left\{ - \left[(m_1 - m)/(m_1 - m_0)\right]^k \right\}$ with $k > 0$, $m \leqslant m_1$, $m_0 < m_1$ was used to adjust the yearly maximum magnitude events, m, and estimation of $\hat{m}_0$, $\hat{m}_1$ and $\hat{k}$ was made with the help of largest magnitude, (Ref.4). For inland earthquakes $m_l = 6.25$ to 7.15 which is in quite good agreement with geotectonic information and historical data. No upper truncation on magnitudes was observed for the earthquakes occurred in the sea.

There are some similarities between the 1755 and the 1969 earthquakes even though the second one is not the repetition of the first one, (Ref.2): occurred in the most active zone of the boundary (Goringe Bank) and show similar attenuation patterns, (R^{-1} where R is the focal distance). Intensities felt in the continent differ from 3 Mercalli units. To explain the strong effect and the long duration of vibrations of the 1755 in far-away zones, it is suggested a mechanism of a propagating rupture along two predominant directions, Fig 7 d). The mechanism of generation for Benavente earthquake is not yet well understood but is seems connected to the presence of a normal fault Fig 2 b). Historical earthquakes in 1531 and 1858 might be related to the same geologic structure.

From isosseismal maps of 24 earthquakes, using Gutenberg and Richter's empirical law $\log(a_{max}) = I/3 - 0.5$ ($a_{max} \equiv$ peak acceleration; $I \equiv$ MMI) and from the strong motion accelerogram of the 1969 earthquake (the only one record existing in Portugal), two types of formulae were derived: $a_{max} = 14 \exp(0.8\,m)\,(R^2 + 20^2)^{-0.5}$ for earthquakes occurring in the sea and $a_{max} = 1230 \exp(0.8\,m)\,(R + 15)^{-2}$ for inland earthquakes. Dispersion of data leads to $\sigma_{ln}(a_{max}) = 0.4$, Fig 6. It should be referred that development of response spectrum for near-field ground motions is of great importance in this type of environment; influence of stress-drop may be critical in a normal or reverse faulting generation. Due to these uncertainties, other formulae taken from literature were used (Ref.1). Local geology and topographic features have not been considered.

HAZARD MODELLING AND MAIN RESULTS

Earthquake generation was represented by three separate space-time-magnitude stochastic-point processes. To account the spacial generation of earthquakes, four different alternative models of area-sources were analysed in this work, Fig 7. The 1st case with two source-areas is the simplest model. The 2rd case is a refinement of the 1st one taking into consideration the non-homogeneity of recorded inland seismicity. Zones were defined according to the main tectonic fault lines referred in Fig 2 b). It was not reasonable to squeeze the zones into fault-sources because of uncertainty in the overall model generation. Cases 3rd and 4th were used to test the influence of two different mechanisms of generation: the Benavente fault and the 1755 propagating mechanism of rupture. The seismic characteristics of each zone are presented in Fig 7 e).

The techniques of analysis used inhere have already been explained in (Ref.5) and are summarized as follows. (i) the experimental method which uses directly the family of occurred earthquake and studies directly the extreme value distribution of yearly maximum values at the site under study; (ii) the analytical method follows closely Cornell's point-source (Ref.6) with some adaptation to take into account the 1755 mechanism of generation. Differences between those two methods are also referred in (Ref.5).

The exit of adjustments of distribution to the empirical method depend essencially on the presence of nearby earthquakes which creates a long type II tail. When there are no earthquakes near the site, the empirical distribution shows a curvature to the side of low risk. Several different techniques were used for extrapolation to the 1000 years mean return period for the 39°N-9° W site, Fig 8 a): type II with a 5 and 95% confidence interval; parabolic in a type II plot; historical earthquakes were also plotted type I from the 95% fractile onwards and type III distribution. One can see that type II distribution is no good and should not be used; parabolic adjustment gives higher estimates than the extreme type III. Historical determination are very good indicators for 1000 years mean return periods extrapolations. Instrumental data alone may induce tremendous errors.

The study of sensitivity done with the analytical method is resumed in Fig 8 b) for the same site. Results differ quite a bit from alternative to alternative not only in the zone of small risks ($\leq 10^{-3}$) but also at moderate risks (10^{-1} to 10^{-2}). The smaller the risk the more dependent on m_1 value the distribution becomes. The inclusion of the 1755 earthquake zone in the 2 - zone case increases the estimates more on the small risk levels, specially to the north of the country. For 10^{-2} risks variations are of 20% in the north and 5% in the south, while for 10^{-3} these values change to 50% and 20%. The concentration of seismicity in faults change quite substancially the overall regional hazard values. For instance, the consideration of a narrow fault in Benavente decreases to 50% the 10^{-3} hazard estimates measured in Lisbon. The influence of parameter uncertainties is also very important. For risks $< 10^{-3}$ changes in α , β's and m_1 lead to variations up to 30%. Greater is the influence of attenuation parameters specially for the small epicentral distances. The consideration of dispersion on the attenuation law increases 100% the 10^{-3} estimates.

To account for the uncertainties in parameter estimates, on source areas, and on model of analysis, which are obvious at intermediate tectonic environment, several alternative distributions of final probability distribution functions, $G_Y(y)$ were used and the information integrated altogether as $P(Y_a > y) = \Sigma P(Y_a > y/A_i)\,\omega i$, where $G_Y(y) = 1-P\,(Y > y)$, A_i is alternative i in a number of n and ω_i the weight assigned to each one.

Fig 9 presents the annual probability distribution functions (p.d.f.) for a_{max} for three typical sites in Portugal. 10 different alternatives were used to compute the mean values $\bar{Y}$ and $\bar{Y} \pm 2\,\sigma_y$. Equal weights were used. Fig 10 present the 1000 years hazard maps for the entire country in terms of a_{max}, v_{max} and d_{max}. Regional variations of 1: 3.5 in a_{max} correspond to 1: 2 in d_{max}.

FINAL CONSIDERATIONS

1 - The quality of model analysis is greater than the quality of data. With the available data it is impossible to reduce furthermore the uncertainties (point estimations) on the final hazard p.d.f. 2 - Extrapolation up to 100 years mean return periods can be made without great errors; uncertainty increases for the lower risk levels. Beyond the 1000 year, uncertainties are too large for being of any usage. 3 - Historical seismicity help improving the accuracy for extrapolation up to 1000 year only. Based on geotectonic evidence it will possible to extend even further these extrapolations.

4 - The method of using areas for seismic sources instead of line sources, dilutes the seismicity, decreasing the overall hazard in points near the fault trace but increases in points located far-away. 5 - In an intermediate region there is a certain dependency on distant earthquakes as compared to nearby earthquakes. Design should consider separatly the influence of both mechanisms. One simple parameter is seen inadequate for analysis at intermediate environment.

REFERENCES

1 - Oliveira, C.S. (1977) "Sismologia e Risco Sīsmico. Aplicações em Portugal", Relatōrio LNEC, Lisboa.

2 - Oliveira, C.S. (1979) "O Risco Sīsmico em Portugal e sua Influência na Segurança Estrutural da Construção", Tese LNEC, Lisboa.

3 - Ribeiro, A. (1979) "Personal Communication"

4 - Yegulalp, T.M.and Kuo, J.T. (1974) "Statistical Prediction of the Occurrence of Maximum Magnitude Earthquakes", Bull. Seis. Soc. Am., (64) 2.

5 - Oliveira, C.S. (1979) "Comparative Seismic Hazard Studies for the San Francisco Bay Region" Proc.2nd U.S. Nat. Conf. Eart. Eng.,Stanford, U.S.A.

6 - Cornell, C.A. and Merz, H.A. (1975) "Seismic Risk Analysis of Boston", J. Struct. Div, ASCE, (101), ST10.

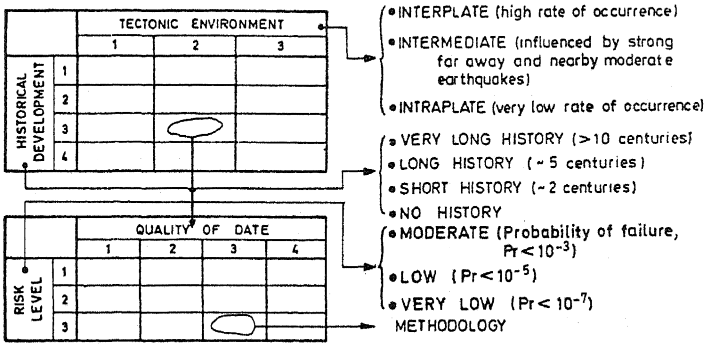


Figure 1 - Flow chart for methodology of analysis.

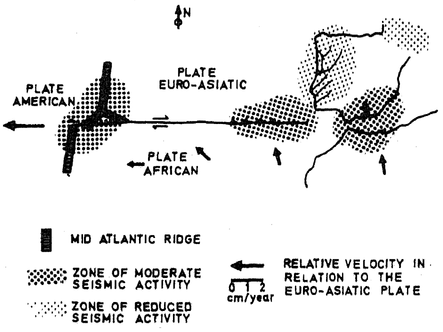


Figure 2 a) - Major regional geotectonic structures affecting Portugal.

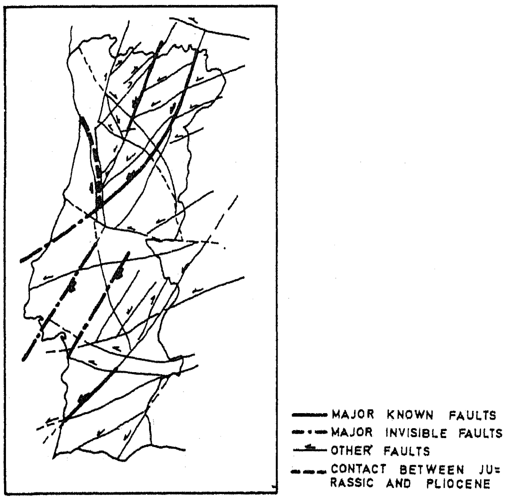
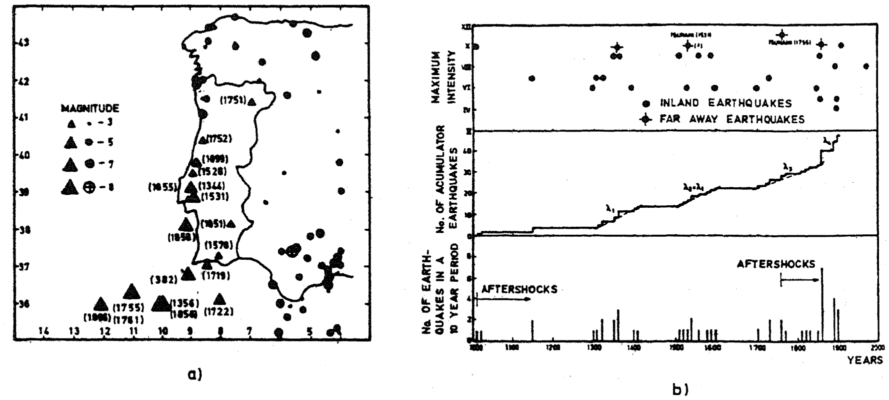


Figure 2 b) - Probable main fault lines in the continent.

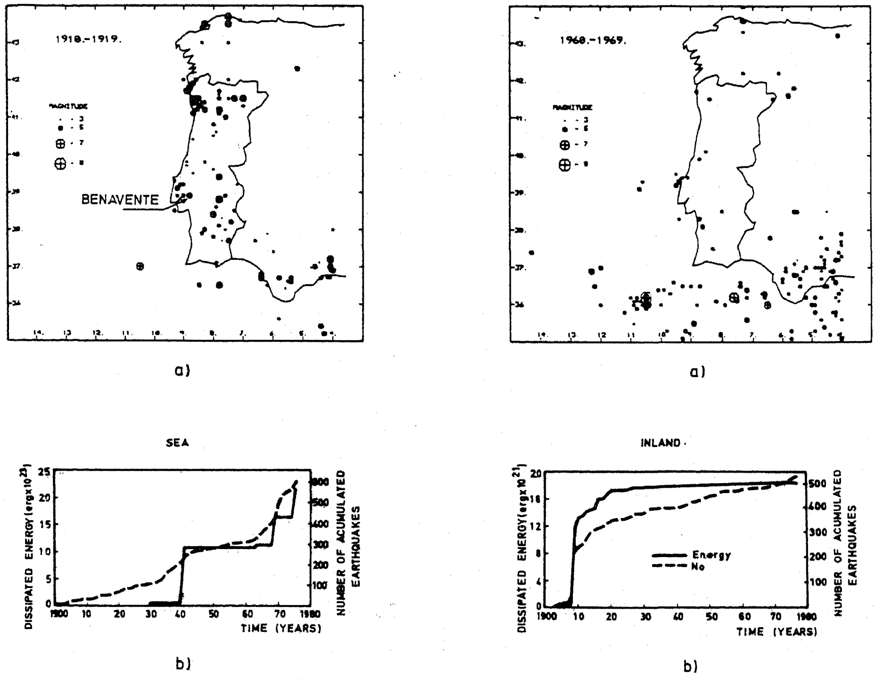


a)

b)

Figure 3 - Historical seismicity (up to 1900);

a) preliminary epicentral location and magnitude; b) time analysis.



a)

a)

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Figure 4 - Instrumental seismicity;

a) epicentral locations and magnitude of earthquakes occurred during two different decades;

b) time analysis in terms of dissipated energy

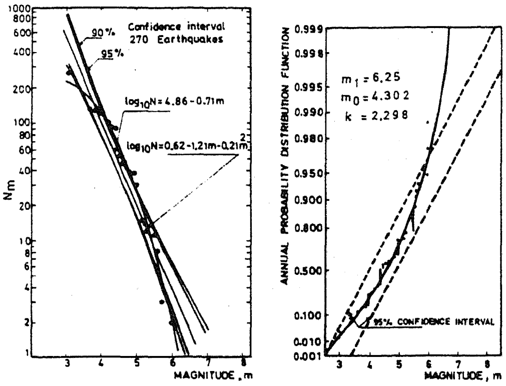


Figure 5 - Probability distribution of magnitude using the entire sample or the yearly maximum events (earthquakes occurred in land)

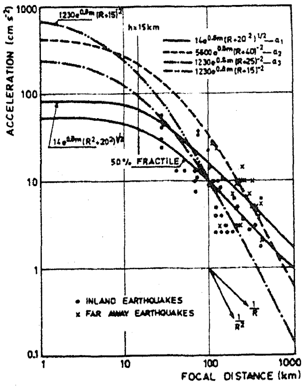
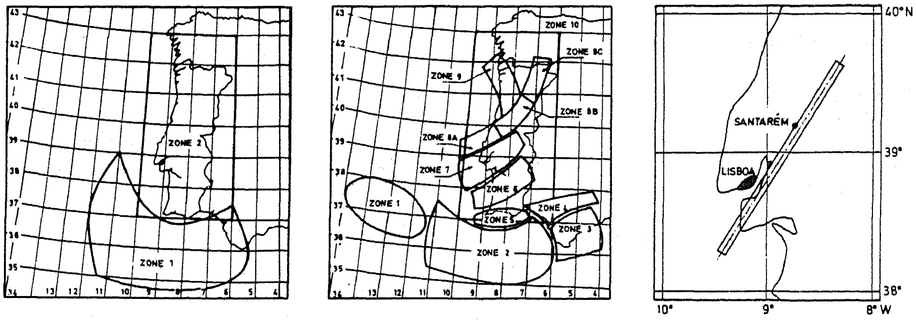
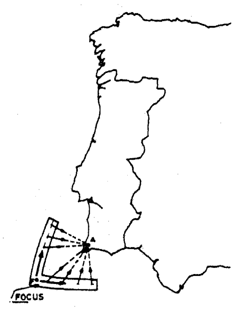


Figure 6 - Attenuation curves obtained from data on isosseismals ($M_L = 6$). Comparison with other proposed curves.



a) b) c)



d)

CASES	ZONE	β_1	β_2	α_{m_0}	m_0	m_1	OBSERVATIONS
2 Zones	1	-1.04	0.0	1.13	3.0	8.75	
	2	2.79	-0.49	3.90	2.8	7.0	
10 Zones	1	3.00	-0.47	0.21	3.5	8.5	
	2	-0.92	-0.03	1.54	3.5	8.5	
	3	0.30	-0.18	1.00	3.0	7.0	Spanish data
	4	-0.05	-0.06	0.50	3.0	7.5	
	5	-0.50	0.001	0.30	3.0	7.0	
	6	1.12	-0.26	0.62	3.0	7.0	
	7	1.43	-0.30	2.23	3.0	7.0	
	8	1.60	-0.35	0.35	3.0	6.5	
	9	2.75	-0.47	0.41	3.0	6.5	
	10	-1.22	-0.001	0.67	3.0	5.5	
1755 Zone	-	-0.50	0.001	0.005	7.0	8.75	

e)

Figure 7 - Earthquake source-areas considered: a) two zones; b) 10 zones; c) Benavente fault-source; d) 1755 fault-source; e)seismic characteristics for the different models.

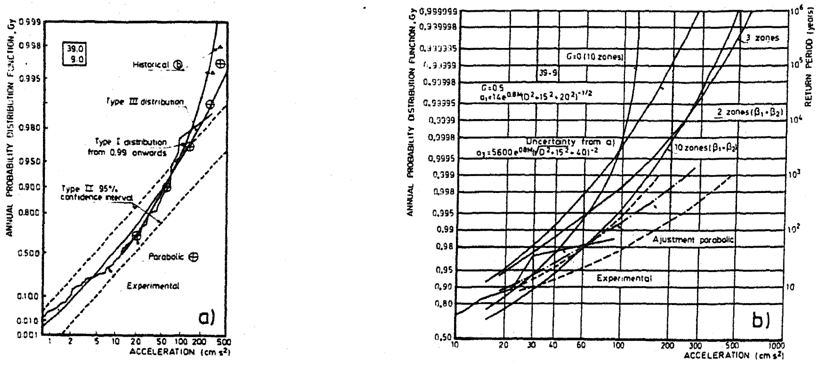


Figure 8 - Comparison between experimental and analytical methods.

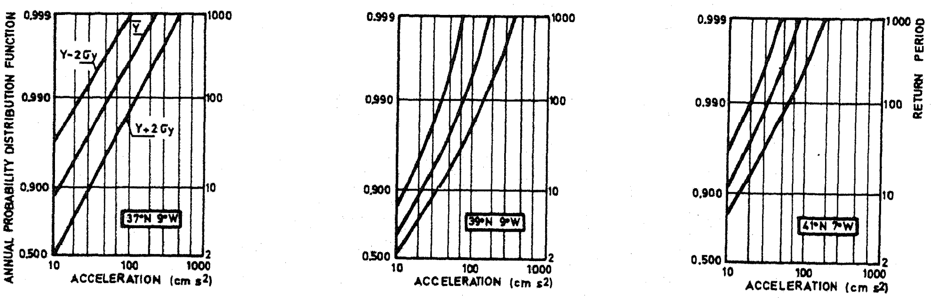
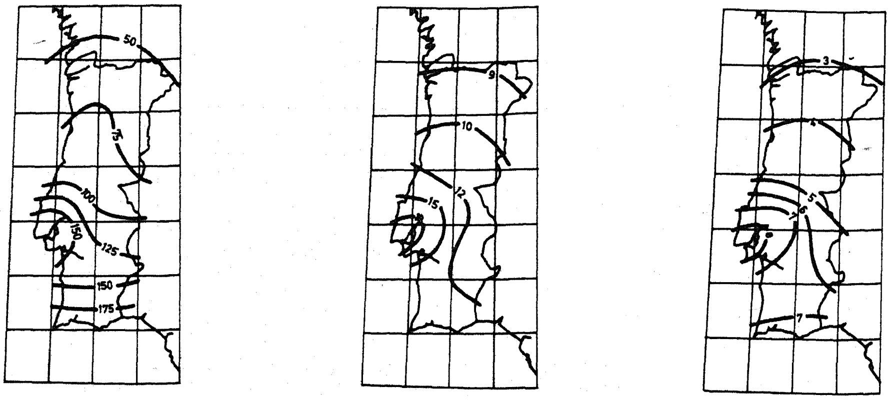


Figure 9 - Annual probability distribution function of peak acceleration obtained from a weighted superposition of several alternatives



Peak acceleration (cm/s²)

Peak velocity (cm/s)

Peak displacement (cm)

Figure 10 - Hazard maps for Portugal (1000 year return period)