# PREDICTION OF SEISMIC IMPACT IN A METROPOLITAN AREA BASED ON HAZARD ANALYSIS AND MICROZONATION -METHODOLOGY FOR THE TOWN OF LISBON-

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## SUMMARY

The evaluation of the seismic impact of future earthquakes in the metropolitan area of Lisbon aiming at (i) determination the areas of higher risks and (ii) quantification of losses in terms of death toll and damaged buildings, requires the development of different tasks, the most important ones dealing with hazard, microzonation, building vulnerability and population distribution along the day. The social economic impact is also considered.

The present paper describes the main parameters connected to each one of the tasks above and proposes a model for prediction of earthquake losses in a consistent basis. Finally, an illustrative exemple taken from data in the Lisbon region is made.

## INTRODUCTION AND OBJECTIVES

In historical times, the town of Lisbon was struck by the occurrence of important earthquakes, (Ref.1). The 1755 Lisbon earthquake destroyed a large portion of the town, causing 5-10% victims and a tremendous impact that last for the remaining eighteen century. The study of this quake (Ref.2), based on description of damage of several hundred monumental buildings showed remarkable differences in damage distribution throughout the town, Fig. 1. The February 28, 1969 North Atlantic earthquake, not causing a great deal of damage, Fig. 2, created a disruption on the everyday life and also showed differences of intensity of shaking in the town.

Mitigation of seismic risks in a metropolitan area in case of future earthquakes requires the evaluation of zones of higher risks and estimation of global human and material losses.

The detailed study of the most important earthquakes has given a first estimate of seismic impacts (extend of damage) as a function of the magnitude, type, epicentral distance and of the existing buildings at the date of occurrence. Studies of tectonics, propagation of seismic waves, local geology and topography, enable us to improve the definition of seismic actions in the different areas of the town. Mapping of construction throughout the town and the definition of a vulnerability function (year and type of construction, number of stories, etc.) allows the quantification of material losses; the distribution of the population during the day informs on the human and social impacts at different hours.

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## GEOGRAPHICAL DISTRIBUTION OF SEISMIC INTENSITIES

To obtain a microzonation map of Lisbon associated with a certain probability of occurrence, the following aspects were considered: 1) More than 120 earthquakes were felt in the Lisbon area since the 11th century, (Fig. 2), among which 9 of them caused important damage, Table I. These events give great insight into occurrence plus attenuation models and serve to test seismic disaster scenarios. 2) Identification of tectonic structures that can generate earthquakes important to the town, (Ref.3). Two main situations were studied as they represent the most common cases, Fig. 3. The Gorringe structure generates large interplate earthquakes which are felt in Lisbon with long duration and predominance of low frequency waves and the local interplate faults generating moderate earthquakes which are felt in Lisbon with short duration or impulsive type, and predominance of high frequence content. 3) From local explosions, the model of the upper crust, the attenuation of surface waves and the existence of differentiated spectral behavior of soils, were derived for the region of Lisbon. Fig. 4 reveals that waves attenuate with $R^{-1.9}$ and natural frequencies of vibration vary from 2.5 Hz to 6.0 Hz (Ref.4). 4) A detailed study of surface geology, (Ref.5), at a scale 1:10 000 allowed the identification of 5 categories of soils and their location.

The first two items above referred were essential to determine hazard curves for Lisbon, Fig. 5, its basis being presented in a separated paper, (Ref.6). This Figure, showing the contributions of the offshore and the onshore quakes, represents also the return periods of the large earthquakes felt in Lisbon. Items 3) and 4) were used as elements for establishing differential behavior of soils in Lisbon, (Ref. 7). The concept of acoustical impedance was used together with noise measurements and historical descriptions. Fig. 6 presents the upperbound estimation of MM intensity of shaking for the Gorringe scenario. Four other seismic scenarios were thouroughly studied, too.

Even though these results correlate well with the observed effects (earthquake of 1755, 1969 and the very recent slightly felt Jan 24, 1983, Ref.8), further studies on soil and topographic influences should be pursued.

## BUILDING PERFORMANCE DURING EARTHQUAKES. POPULATION AT STAKE

The behavior of existing buildings during earthquakes is very difficult to predict and depend upon a great number of parameters. Buildings of different types, ages, number of stories and material properties exist in the metropolitan area of Lisbon. Furthermore, buildings in Lisbon are laterally supported by each other with discontinuities in height and in plan. The existence of a first floor transition to accomodate wide open spaces is very common. They may be located in a flat zone or at a steep street and may be in a good or bad structural condition due to lack of repairing.

With the objective of characterizing structurally the construction of Lisbon, a survey was initiated last year (Ref.9). About 20 parameters, among which are the ones above referred, are analysed in this enquiring. A small sample of enquires which are made from the outside of the buildings by teams of expertises will be subjected to confirmation of actual structure. The buildings selected will be analysed according to the present knowledge of earthquake engineering and vulnerability curves derived. In some cases additional testing such as measurement of frequencies of vibrations might be used. Important, dangerous or special structures which knowledge and behavior is essential to disaster prepardness are always studied in detail.

It is expected that by the end of 1984 the survey will be completed and a gene ral formulation to assess building vulnerability will be determined. A pilot study for a small area of the town is now under way and results briefly referred in the following sections of this paper.

For the time being the buildings in Lisbon were typified into 5 categories A to E, Table II. Vulnerability curves were subjectively assigned to each category based on type of construction, natural period of vibration (no. of stories plus type) and on statistics obtained from 13 recent earthquakes, Table III. Some statistics show that, without further developed studies, the percentage of victims and injuries varies tremendously and is difficult to correlate with building damage.

For reasons of applicability of this study, the metropolitan area of Lisbon (county) was divided into 23 units showing some kind of homogeneity in building and population morphology. Each one of these units areas is considered as having uniform characteristics. Building survey will give the exact geographical distribution of category A to E.

In a separate study, (Ref. 10), population evolution along the day has been determined for the 23 different unit areas of the town, Fig. 7. Periods $0-7^{30}$, $7^{30}-9^{30}$, $9^{30}-18$, 18-20 and 20-24 hours were considered.

## BASIS FOR THE SEISMIC IMPACT MODEL

The mathematical model to analyse the seismic impact is development along the following: a) Lisbon is divided into 23 unit areas ($j = 1,23$); b) 5 classes of buildings ($i = 1,5$) with $n_i$ stories; c) 4 seismic source of earthquake generation-scenarios ($k = 1,4$) each one associated with a certain probability distribution of occurrence $F_k(.)$; d) 6 classes of intensity due to microzonation reasons ($\ell = 1,6$); e) 5 periods during the day ($m = 1,5$).

If: $S_{j,k,\ell}(\omega)$ is the response or power spectrum in unit j, soil $\ell$, due to source k; $V_{i,j,k,\ell}$ is the mean vulnerability for $S_{j,k,\ell}(\omega)$ in buildings of class i with $n_i$ stories and plant area $a_{pi}$; $N_{i,j}$ is the no. of buildings of class i in unit j; $P_{j,m}$ is the no. of persons in unit j during the period m; $C_{i,j}$ is the value of construction per $m^2$ as a function of class i and location j (more correctly, $C_{i,j}$ depends in order factors such as utilization and social and economical functions); $A_j$ is the area of unit area j; $a_{\ell,j}$ is the area of class of intensity $\ell$ in unit j.

The following functions can be obtained for unit j and source k (Ref. 11):

$$\text{ILF (Individual Loss Function)}\ i,j,k = C_{i,j}\ a_p\, n_i\, N_{i,j} \sum_\ell V_{i,j,k,\ell} \frac{a_{\ell j}}{A_j}$$

$$\text{GLF (Global Loss Function)}\ j,k = \sum_i \text{ILF}_{i,j,k}$$

$$\text{AP (Affected Population)}\ j,k,m = \sum_i \sum_\ell V^P_{i,j,k,\ell} \frac{a_{\ell j}}{A_j} N_{i,j} \cdot P_{m,j}$$

Where $V^P_{i,j,k,\ell}$ is taken as percentage of population affected as a function of vulnerability $V_{i,j,k,\ell}$ (for instance if $V_{ijk\ell} > 50\%$, $V_{ijk}P_\ell \sim 1$). To compare different damage in different units the Density of Losses (DL) and the Density of Population Affected (DPA) are more appropriate.

$$DL_{j,k} = GLF_{j,k} \Big/ \sum_i C_{i,j}\, a_{ni}\, N_{ij} \quad ; \qquad DPA_{j,k} = AP_{j,k,m} \Big/ P_{m,j}$$

The influence of all seismic sources is obtained by the convolution:

$$GLF_j = \int GLF_{j,k}\, dF_k$$

To illustrate the model, an application was made for 3 unit areas under seismic scenario of Gorringe Table IV: the first two, Alcântara and Olivais are representative, respectively, of old and new construction areas; Baixa is an area with flutuations of population of order 1:8 along the day.

According to the distribution of intensities shown in Fig. 6 it was possible to establish the non-homogeneous behavior within each unit and evaluate the risk function defined above. For each unit, the ratios of different building categories as well mean no. of stories were estimated be urban experts, (Ref.12); a rough estimation of the total no. of buildings was made proportional to the 0-7.30 population distribution; the mean area per building was assigned to each category according to the evolution of living standards with time; finally the estimation of C was made taking into consideration the volume of transactions and services related to the 1976 statistics.

## FINAL REMARKS

The model developed in this paper constitutes a very usefull tool for disaster planning and is a basis to direct retrofiting policies of old towns. The results presented in Table IV are just an exemple for illustration. Definite considerations will be available only after the conclusion of the building survey. An analysis of uncertainties in the different tasks of this presentation will also be studied in such a way that final risk estimations (DL and DPA) are associated to confidence limits. It can already be referred that the largest uncertainties come from the evaluation of intensities of shaking throughout the town and from vulnerability functions.

To implement the estimation of intensities (microzonation), it is strongly recommended the installation of a network of 6 to 10 ground motion instruments that can record microseisms and large earthquakes. Vulnerability functions can only be implemented if detailed analytical studies and observation on real buildings are made.

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TABLE I - List of important earthquakes causing damage in Lisbon after the 14th century

| DATE | PROBABLE EPICENTRAL LOCATION AND MAGNITUDE | TYPE OF EARTHQUAKE | MAXIMUM MM INTENSITY IN LISBON | DAMAGE DESCRIPTION | DAMAGED AREA |
|---|---|---|---|---|---|
| 1344 July-Aug. | NE of Lisbon in a radius of 30 km ($M_L$ ~6.5) | Local - II Related to the NE-SW fault trend | VII - VIII | Damage to houses and churches. Numerous victimes | Lisbon and surrondings |
| 1356 Aug, 24 | 200 to 300 km SW of Lisbon in the main fracture zone Azores-Gibraltar ($M_L$ ~ 7.5) | Global - I Great duration; one year of after shocks | VII - VIII | Great damages to houses and churches. Numerous victimes | Algarve, Spain Lisbon and surroundings |
| 1512 Jan, 28 | Area of Lisbon ($M_L$ = 5-6) | Local - I May have been a landslide | VII | 200 houses destroyed and 2000 people killed | Lisbon North |
| 1531 Jan, 26 | 10 to 20 km NE of Lisbon in the lower Tagus fault ($M_L$ = 6.0) | Local - II Related to the NE-SW fault trend; 2 large impulses; large amount of fore and aftershocks; tsunami due to landslide | VIII - IX | Great damage to houses, old churches. One land - slide. Reduced number of victimes due to foreshock activity | Lisbon and surrounding in a 100 km diameter |
| 1597 July, 22 | Area of Lisbon - | Local I Most probably was a landslide | VII | 110 houses in 3 streets pushed in a landslide | Lisbon West |
| 1755 Nov, 1 | 150-200 km SW of Lisbon near the main fracture zone Azores-Gibraltar | Global - I Great duration; many after shocks; Great tsunami | VIII - IX (Variations of 3 MM Degrees in town) | Great damages to houses and churches. 5 to 10% population killed | Algarve, Lisbon and surroundings, Spain, Marrocos |
| 1909 April, 23 | 30 km NE of Lisbon in the tower tagus fault. ($M_L$ = 6.0) | Local - II Impulse type; large amount of after shocks | VI | Slight damage to chimneys | Area of 20 km from Benavente in the Lower Tagus Valley |
| 1941 Nov, 25 | 1000 km W of Lisbon north of the main fracture zone-Azores-Gibraltar | Global - II Great duration | V | Felt only | All coast of Portugal with great attenuation inland |
| 1969 Feb, 28 | 250 km SW of Lisbon in the main fracture zone, Azores-Gibraltar ($M_L$ = 7.8) | Global - I 30 sec duration with a peak acceleration of 0.05g; small tsumani; no aftershocks | VI | Some damage to masonry chimneys, minor structural crack | Algarve, Lisbon and surroundings |

BUILDING CATEGORY

A - Masonry stone buildings prior to 1880, in bad shape. Freq >3Hz

B - Masonry stone buildings prior to 1880 with horizontal ties and in good shape. Freq >2.5Hz

C - Brick masonry tall buildings constructed during 1880-1940. Floors are in wood. Freq > 2Hz

D - Dual Structures with masonry resistant walls + RC slabs or RC moment resistant frames heavily infilled with non-resistant brick walls. Freq > 2.5Hz

E - Modern RC buildings designed for same lateral load. Freq.< 2.0Hz

TABLE II - Typification of buildings in Lisbon. Vulnerability functions

| | A | B | C | D | E |
|---|---|---|---|---|---|
| VII | 0.15 | 0.08 | 0.10 | 0.06 | 0.03 |
| VIII | 0.50 | 0.25 | 0.30 | 0.20 | 0.10 |
| IX | 0.80 | 0.50 | 0.60 | 0.40 | 0.20 |
| X | 1.00 | 0.70 | 0.85 | 0.60 | 0.40 |

TABLE IV - Evaluation of seismic impact for three zones of Lisbon

| UNIT AREA | BUILDING CATEG. | $N_{ij}$ | $n_i$ | $a_{pi}$ ($m^2$) | ILF $x10^3$ | GLF $x10^3$ | AP (inhab) | DL | DPA |
|---|---|---|---|---|---|---|---|---|---|
| ALCÂNTARA | A | 108 | 3 | 180 | 29.2 | | $v^P > 50\%$ 2835 | | $v^P > 50\%$ 0.13 |
| Popul. 22 600 | B | - | - | | - | | | | |
| Estimated | C | 442 | 4 | 150 | 104.4 | 187.0 | | 0.23 | |
| Buildings 774 | D | 108 | 4 | 130 | 15.6 | | $v^P > 80\%$ 2712 | | $v^P > 80\%$ 0.12 |
| $C_{ij}$ = 1.85 units | E | 116 | 6 | 100 | 67.0 | | | | |
| OLIVAIS | A | - | - | | - | | $v^P > 50\%$ 1125 | | $v^P > 50\%$ 0.05 |
| Popul. 60 800 | B | - | - | | - | | | | |
| Buildings 1232 | C | 370 | 2.5 | 150 | 77.9 | 227.1 | | 0.20 | |
| | D | - | - | 130 | - | | $v^P > 80\%$ 87 | | $v^P > 80\%$ 0.004 |
| $C_{ij}$ = 1.25 units | E | 862 | 9 | 100 | 149.2 | | | | |
| BAIXA | A | - | - | | - | | $v^P > 50\%$ 22154 | | $v^P > 50\%$ 0.98 |
| Popul. 12 600 | B | 274 | 5 | 180 | 956.6 | | | | |
| Buildings 238 | C | 3 | 5 | 150 | 10.5 | 975.7 | | 0.53 | |
| $C_{ij}$ = 7.33 | D | 3 | 5 | 130 | 6.1 | | $v^P > 80\%$ 35 | | $v^P > 80\%$ 0.002 |
| Units | E | 3 | 5 | 100 | 2.5 | | | | |

TABLE III - Summary of building damage produced in 13 past earthquakes

| EARTHQUAKE | MMI | DEATH | INJURED/DEATH Severe injured | INJURED/DEATH Total | DAMAGE Monum. | DAMAGE Masonry | DAMAGE R Conc. n< 5 | DAMAGE R Conc. n>5 |
|---|---|---|---|---|---|---|---|---|
| CARACAS | VI-VIII | $136/10^6$ | 0.6 | 6 | Mean | Mean | Low | 1.43% collapse (VIII) Mean |
| FRIULI | VIII-IX | 1% localy 4.5% | | | " | " | | |
| MONTENEGRO | IX | | 1.7 | 12 | | 27% 0.25 g causes 50% collapse | | 2% collapses |
| MANÁGUA | VIII-IX | 2.2% | | 5 | | severe | moderate | |
| IMPERIAL COUNTY | VII | 0 | - | - | | slight | | few |
| AGADIR | IX | 33% | | | | severe | | moderate |
| ROMÉNIA | VII-VIII | 0.12% | | 5 | | large | | 15% of damaged buildings collapse large |
| EL ASNAM | IX | 4% | | | | | | brittle failure |
| GUATEMALA | VII-IX | 0.4% | | 5 | moderate | large | | few |
| SUL ITÁLIA | VII X | $74/10^6$ | | 2.5 | | | | 2 buildings collapsed |
| AÇORES 1980 | VII-VIII | 0.1% | | | large | large | | few |
| LISBOA 28/2/1969 | VI | - | - | - | no | slight | | - |
| GRÉCIA 1981 | VIII | | | | large | moderate | | |

American Statistics of death (dwelling.-Calif)

| | | |
|---|---|---|
| VII | $10/10^6$ | $20/10^6$ |
| VIII | $150/10^6$ | $300/10^6$ |
| IX | $500/10^6$ | $1000/10^6$ |

$\frac{\text{Injured}}{\text{death}} = 4:1$

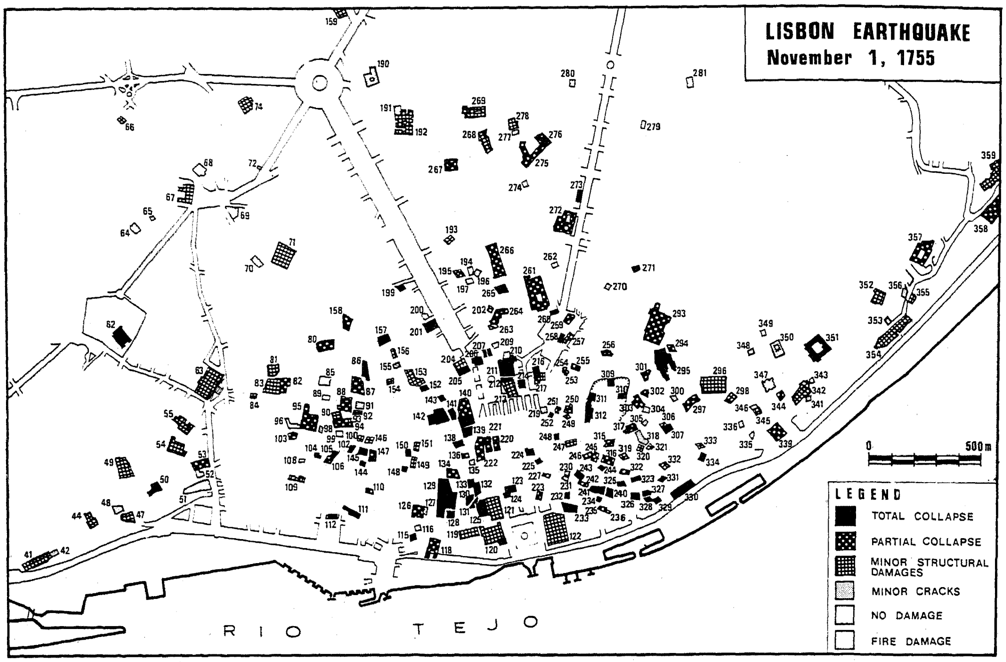


Fig. 1 - Damage distribution in the town of Lisbon during the 1755 earthquake upon a recent study (Ref. 2)

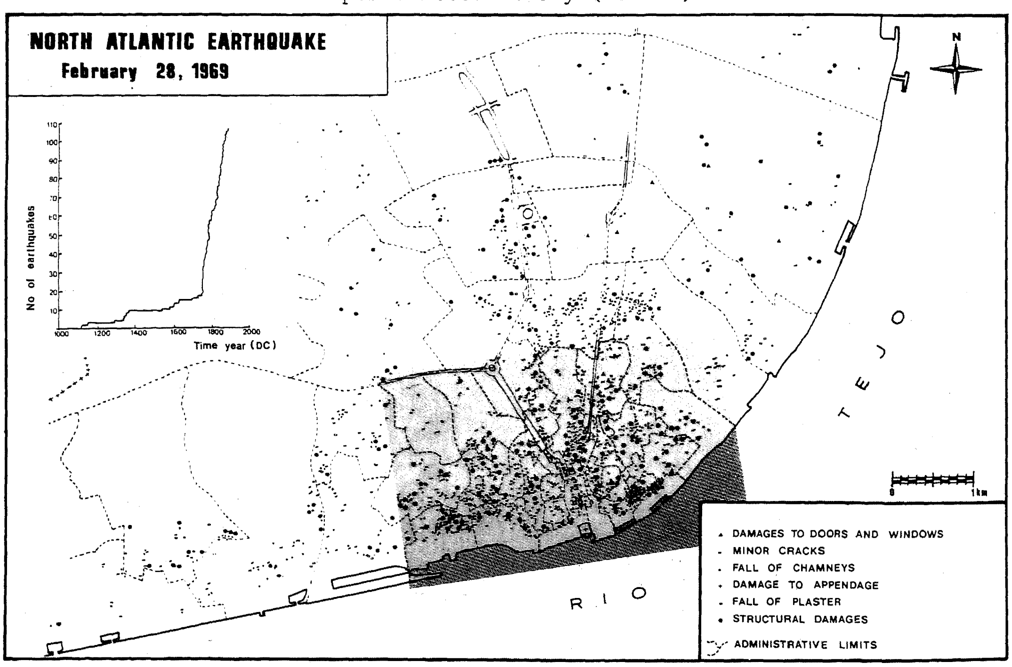


Fig. 2 - Minor damage inflicted in Lisbon during the February 28, 1969 North Atlantic earthquake. No. of earthquakes felt in Lisbon since 1000 DC

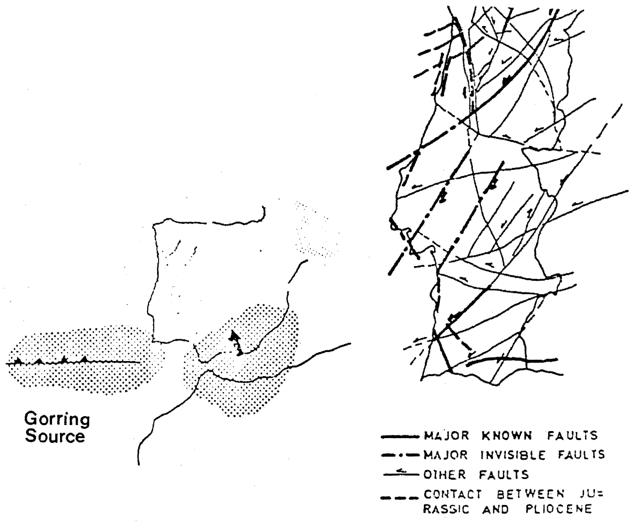


Fig. 3 - Tectonic environment. Main structures affecting Lisbon

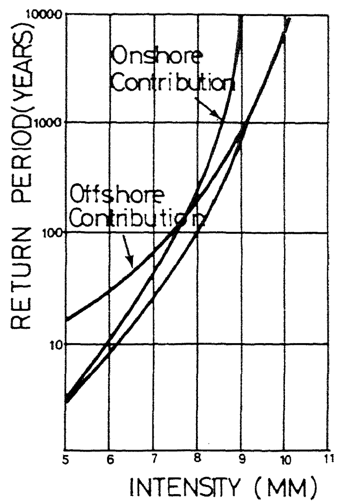


Fig. 5 - Seismic hazard for Lisbon

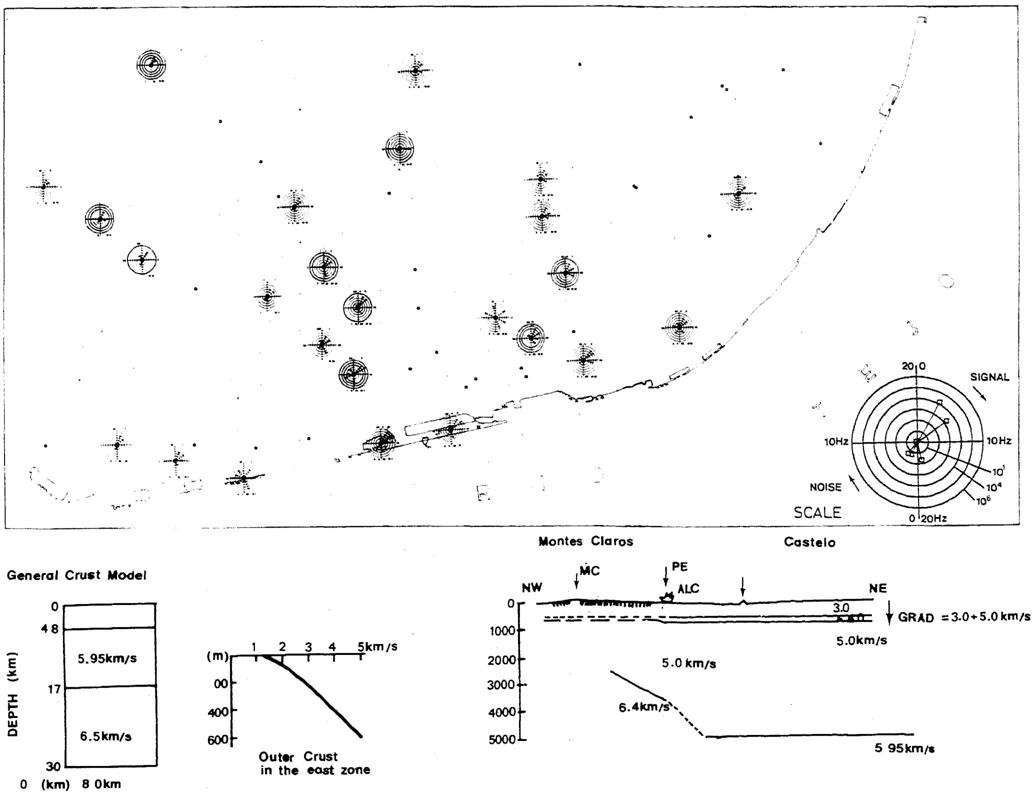


Fig. 4 - Model of the local upper crust in the region of Lisbon and spectral attenuation

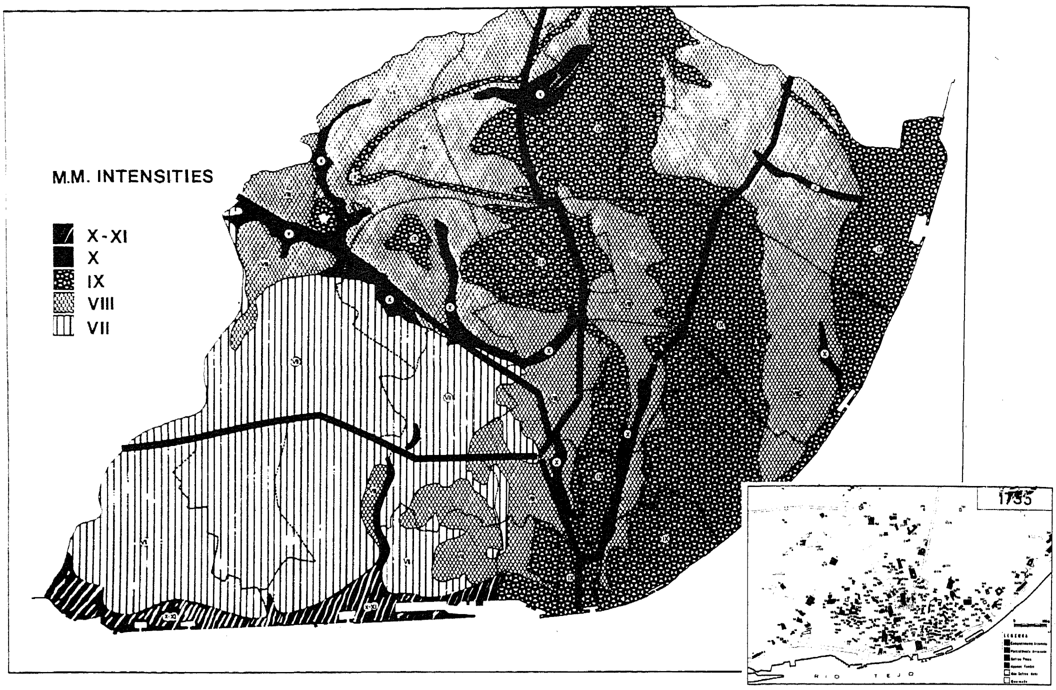


Fig. 6 - Estimation of MMI in Lisbon for the Gorringe scenario - upper bound

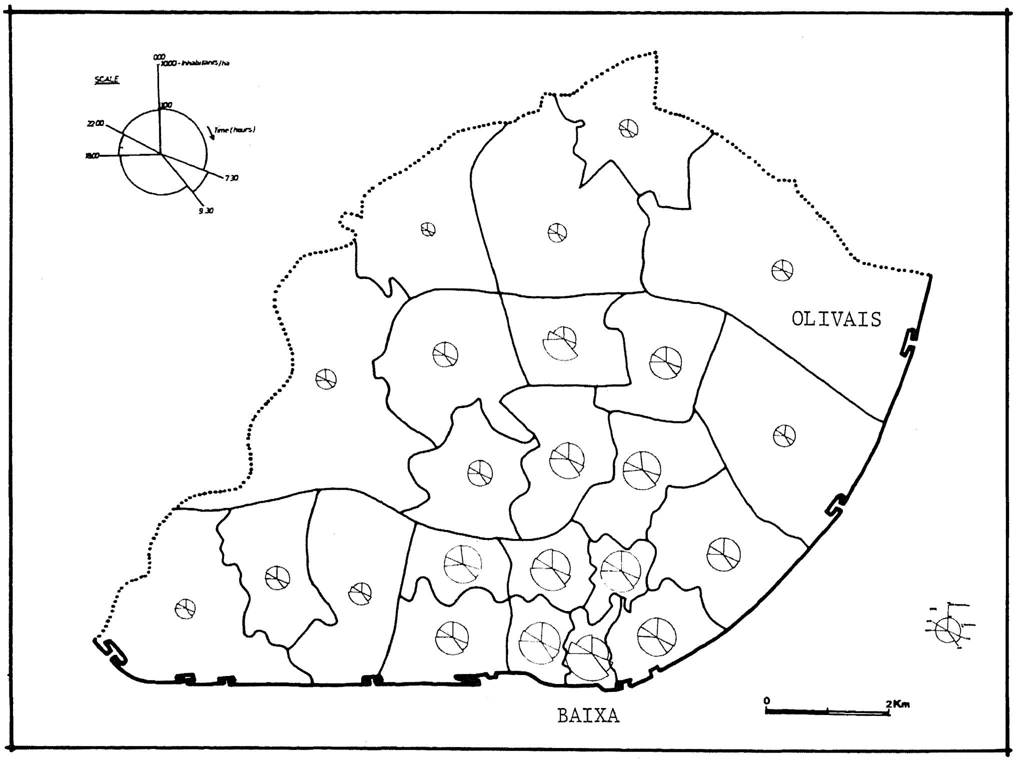


Fig. 7 - Population evolution along the day for the 23 unit areas of Lisbon after (Ref. 10)