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Recovering strong ground motion from performances of simple structures
A contribution to microzonation

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ABSTRACT: This paper analyses how the movement of simple structures can be used to obtain information on input strong ground motion. This information enable us to estimate: (i) upper and lower bounds of peak ground acceleration, (ii) direction of predominant direction of motion and (iii) sense of first motion.
Examples taken from the Azores earthquake of January 1st, 1980, illustrate the methodology referred. These examples provide useful and quite large amount of data points which, in complement of instrumental information, can be very helpful in different studies such as setting microzonation or defining source mechanism.

1. INTRODUCTION

Descriptions of damage inflicted to structures during earthquakes have been the main source of information for measuring the intensity of shaking at a given point. This is specially true for past earthquakes without any instrumental information and constitutes the basis of an intensity scale.

This information is a good indication of the overall behaviour of the structures, but unfortunatly it is quite difficult, generally seaking, to obtain further details on strong motion parameters from those damage patterns.

However, if one observes carefully the behaviour of some simple structures, it is possible to understand, in a more comprehensive way, the type of ground motion capable of causing the observed behaviour. In the literature on past events, some of historical dates, other quite recent, there is plenty of information refering the movement of blocks, either of translational or rotational nature, differential setlement between parts of the foundation, overturn of simple walls, obelisks, towers, chimneys, but also description of movement of more complex structures, such as church towers, ringing of bells, falling of some special appendages, sliding of retaining walls, etc..

Descriptions may include statements of witnesses, as they felt the earthquake motion, saw the movement of objects in the neighbourhood or even as they observed the passage of seismic waves or the oscillation of some structures. Human sensibility to ground motion is quite impressive and, if adequately used, can be of some interest as a complement of other types of information.

Data gathered from different sources of information refering to different sites and structures, can be used as an areal picture of the entire process of wave propagation.

Due to diversity and certain amount of data points, when plotted altogehter, these elements may show signs of consistency or dissimilarities on directions of predominance in the propagation and on values of peak ground motion parameters.

This information is essential to characterize the wave propagation from the fault (source mechanism) to the site. We observed quite interesting patterns in the example of Azores January 1st, 1980 earthquake.

Some of the material presented here can be found in more detail in Oliveira (1992 a).

1.1 *Historical background*

All the times experts always paid great attention to this type of movements as this reference is a must in the description of past events. Moreover, in a few cases they were used as basic data to obtain epicentral location and focal depths. In the late eighteen hundred, Mallet (1862) develop a theory to determine the hypocentre direction based on the orientation of main fissures in a damaged building. The intersection of several of these orientations should yield the hypocentre location. This reasoning was applied with certain success in several earthquakes such as the Neapolitan Earthquake of 1857 (Mallet, 1862) and the Central German Earthquake of March 6, 1872 (Grünthal, 1992). Cerero (1890) used similar arguments to study the Manila earthquake of 1880.

We are coming to the same basic idea but now we try to characterize the parameters of ground motion; later on, source mechanism and propagation. This data may be very relevant in places where no instrumental information is available and characterizes the near field movements.

We are testing the methodology with data of a recent earthquake where other sources of sismological information do exist, in order to gain the minimum confidence to apply the methodology to events without any seismological information.

The methodology proposed herein, beyond the observation of common features of wave propagation, emphasizes the behaviour of very simple reinforced concrete structures. These structures were selected on the basis of the following principles:

1. The structural behaviour is easily understandable from linear analysis.

2. The observed damage is relatively easy to relate to stress levels in some structural elements.

Based on these principles, upper or lower bounds on ground motion parameters may be derived. Currently, one structure gives only one of these parameters: the presence of a certain degree of damage informs on lower bound, whereas its absence informs on upper bounds.

But sometimes, the same structure can offer indications on both upper and lower bounds, if a given degree of damage is present at one element and another at a different location.

Depending on the location of the worst stressed elements in relation to the geographical coordinates, it is also possible to obtain information on the direction of predominant motion for certain frequency bands.

We have tried this methodology in the study of an Aqueduct in Lisbon under the 1755 earthquake and got quite interesting results (Oliveira, et al. 1991). However, the analysis of this single structure cannot be extrapolated with confidence due to lack of other points.

2. THE JANUARY 1ST, 1980 AZORES EARTHQUAKE

2.1 *General information*

The January 1st, 1980 Azores earthquake occured at 16h 42 m 38.6s with an epicentral location 38,75 N, 27°.75 W, a focal depth of the other h = 10 km and a local magnitude $M_l = 7.0$, Fig. 1. Fault plane solution from different authors (Bufforn et al. 1983, Correia et al, 1992) indicate a strike - slip left lateral, with a seismic moment $M_o = 2 \times 10^{26}$ din cm, a fault rupture with 70 km length, 9 cm of offset and a stress drop of 2.5 bar.

Grimison et al. (1988), using P and SH synthetics matching the recorded teleseismic, showed that the main event was the result of two shocks, the first one with larger amplitudes, both with 10 sec duration separated by 5 sec interval. However, while the 1st shock is in agreement with a WNW left lateral mechanism, the second shock indicates a thrust mechanism.

Instrumental information in the near-field is very scarce. The seismological stations in Angra, Horta and Ponta Delgada were all saturated at the first impulse. The only strong motion instrument, a SMA-1 Kinemetrics accelerometer, was located at Horta observatory at aproximately 80 km from epicentre and produced a 3-component record with peak accelerations of 53, 43 and 36 cm/s^2, respectively, for the NS, EW and vertical components, Fig 2a), Oliveira et al. (1984).

Even through the record is not of very high quality, it is possible to analise the 20 sec duration trace which ends with a particularly high single pulse.

The response spectra for each one of those components, Fig. 2b), shows that higher energy for the horizontal components are associated with periods 0.75 sec and 2 sec and for the vertical component in the band 0.2 to 0.4 sec. Particle orbits in the horizontal plane, Fig. 2 c), show polarization in the N-S direction for the frequency band 0.2 to 1.5 Hz and in the WNW-ESE for the frequency band 1.5 to 3.0 Hz.

In the near-field all other information comes from the performance of structures, descriptions of movement, etc. Before enumerating some of them, let's look at the overall information given by the isoseismal map, Forjáz (1980), Fig. 3a), showing that attenuation of seismic waves is not isothropic and the presence of islands increase the level of shaking. Detailed map of Terceira island, Fig. 3 b), shows that intensity geographical distribution is relatively symmetric in relation to an E-W axis, decreasing with distance to the epicenter and to the center of the island. An increase is shown around a NS central axis and anomalous high intensity spot is seen at the SE corner in S. Sebastião village. Intensity measures, obtained right after the earthquake are in good agreement with geographical distribution of damage and cost of repairs, Oliveira et al. (1992 c).

Another piece of great information, certaintly when analysing microzoning of a town, is the damage distribution in the town of Angra do Heroísmo, Fig. 4. This damage was assessed building by building (Carta de Danos, 1992), classifying the damage into 4 categories: no damage; slight damage; moderate damage; collapse. An observation of this map, indicates clearly that there are zones more strongly shaken, independently of the type of construction at stake, streets with heavier damage or even facades more prone to the shaking. This would certaintly depend on the direction of more intense motion and on how buildings organized in blocks resist to that motion.

One thing is commonly recognized by the population: other events in the past have caused higher shaking in the same locations as the present earthquake has evidenced, in such a way that people traditionaly know where to go if it starts shaking again.

Variability of shaking from point to point may be caused by local soil conditions but also by topographic and by incoherency on ground motion propagation, Pimentel et al. (1986).

2.2 *Descriptions of ground motion*

Descriptions of ground motion made by different people are very important to determine, in qualitative terms, the intensity of shaking, direction of motion and duration. There are many witnesses and reports which attest this statement. In relation to intensity, reports on how strong they felt the earthquake are common. Direction of incoming waves was referred by various persons which were able to describe in conclusive terms the way travelling waves were destroying the houses as the wave front progressed. Usually they were at a high location, with a good view of open space. In one case they report on waves reflecting at a certain cliff as sea waves at the shore line. Others refer the travelling waves in the field with certain speed and wavelength. In another report, an account of the movement of a church tower until collapse is described with great detail showing the number of cycles and the direction of motion.

Descriptions of frequency content and polarization of waves along the record is much more difficult to characterize. People do not recall precisely in which direction they felt the quake even through in few cases they try to explain the arrivals of P and S waves. An interesting account refers how the quake was felt when driving a car: one situation they thought of a flat tire; in other nothing happened. As it will be seen later on, this data is in agreement with the direction of preferencial movement.

As far as duration is concerned, there are many good examples obtained from the human behaviour during the quake. From the descriptions of what actions took place after the onset of the vibration, it is easy to deduce the duration of the most important part of shaking.

2.3 *Quantitative analysis of peak ground values*

Four reinforced concrete (RC), structures, Fig. 5, were selected as test objects to determine upper and lower bounds on peak values:

1. "Signal-house" in Monte Brasil and Praia da Vitória (Terceira island).
2. Hospital in Angra do Heroísmo.
3. Elevated water tower in Lajes Military Base.
4. Light-house in Topo (S. Jorge island).

The "signal-house" in Monte Brasil and Praia da Vitória were very simple structures, Fig. 6, which suffer no damage despite the small cross sections of the columns. Several tests were performed in this structure in order to characterize the material properties of the concrete and the reinforcing steel and a comparison between computed and measured frequencies of vibration matched within 10% error. Using linear analysis and a response spectrum similar to the one obtained in Horta, we obtained a peak ground acceleration of PGA = 30 cm/s^2 to induce slight cracking in the column sections. This indicates that the value 30 cm/s^2 is an upper bound on PGA for those locations.

The Hospital in Angra do Heroísmo, Fig. 7, suffered important damage at the soft-story in one of its three buildings. The top and bottom of most columns suffered extensive spalling of concrete. Dynamic analysis of this structure, considering the effect of infill brick walls above the 1st story has lead to a PGA = 144 cm/s^2 to cause significant damage in the columns. Consequently, this value represents a lower bound on PGA.

The Elevated water tower in Lajes, Fig. 8, is a Hintze structure with a 250 m^3 tank. At the time of the earthquake the tank was approximately at 50% full capacity. It suffered damage in the beams showing narrow cracks and spalling slight of the finishing mortar, and no damage in the columns. Dynamic analysis performed in this structure, considering the effect of water sloshing has led to an upper $PGA_{max} = 30$ cm/s^2 and a lower bound $PGA_{min} = 15$ cm/s^2. These values correspond to the limit states of damage in the columns and beams, respectively.

The light-house in Topo, at the shortest distance to the fault line, suffered quite heavy damage, not only in the tower itself but also in all surrounding buildings. The tower structure is a RC thick shell, Fig. 9, toped by a metalic lantern supporting the rotating light system. The most impressive damage consisted of an impact of the metalic structure against the surrounding RC pit. This impact was caused by the malfunction of the bolts holding the metalic structure to its foundation. Based on the stresses needed to cause the observed movement in the bolts, it was possible to estimate the approximate *moment* and consequently the ground motion at the base of the this structure using a very simple model to represent the light house. Deconvolution of movement lead to PGA_{min} in the interval 200 to 400 cm/s^2 and a frequency content in the band 2-4 Hz. The point of impact was also used as an indication of the predominant direction of motion.

For details of the damage description and dynamic analysis see Oliveira et al. (1992 b).

A comparison among the values obtained with the four structures above suggest, the following comments:

- Upper and lower bounds are quite stable.
- Values obtained agree in general with Mercalli Modified intensity assignments.
- In Angra do Heroísmo at 2 sites separated by approximately 2 km, (Monte Brasil and Hospital) the variation in PGA is 1:5. These values, which are in accordance with descriptions by witnesses, show that there are great differences in ground motion intensities probably due to soil and topographic characteristics. Further study at these sites should clarify these observations.
- In Praia da Vitória, the two sites under analysis (signal-house and elevated water tank) led to the same PGA bounds.
- In Topo the acceleration was by far the largest observed in this study.
- Correlation of PGA with assigned intensities, shown in Fig. 10, is quite good.

The behaviour of many other structures (not as single as the above ones) may also be used in assessing ground motion parameters.

One of them can inform on differential movement of relatively-close buildings, as is the case of a support pole used in the electric power network. Generalized damage was observed in these structures with two typical situations: electric pole pulled the masonry corner or electric wire were broken. To explain this effect a simple computation using the strength of the wires, indicate that at least a 2 cm differential movement between adjacent supports should have taken place. This value can be translated into a measure of wavelength associated with the propagation, after a few considerations on how buildings organized in blocks may behave.

2.4 *Direction of movement*

As already referred, there are several types of structures which can inform on predominant direction of movement. However, caution should be exercised in order to subtract the influence of the response of the structure. In fact, if a careful analysis of all elements is not made, conclusions may be completely wrong. We are going to give a few examples to illustrate the need for a clear analysis.

The first case refers the electric transformer house located at the wester-nmost point of Terceira island, where a diagonal crack clearly identifies the direction of movement. It is a square 3×3 m high brick masonry structure toped by a concrete 10 cm thick slab. An experimental test may indicate the PGA values for the formation of the observed cracks.

The second case refers to the fall of objects such as chimneys, decorative pieces at elevated locations, or direction of collapse of rural walls. All these elements contribute to the general knowledge of ground motion, but it is essentially to comprehend the response of the structure and the mechanics of connection between the structure and the element, before taking the conclusions. Distance from the vertical of the falling object to the impact point may also indicate particle velocity prior to the initiation of the fall. We estimated $v_{min} > 400$ cm/s as the largest value at the top of a 30 m church tower.

Horizontal displacement and rotations of rigid blocks of different sizes is also very common. This has been referred in many other earthquakes. Choffat et al. (1913) in studying the Benavente earthquake (Portugal) of April 23, 1909 have spotted translational and rotational movements in small obelisks in one cemetery, Fig. 11 a). The same was reported by Lopez-Arroyo et al. (1977) in the Friuli earthquake, Fig. 11 b), for the Trasaguis monument, and by Seebach (1873) during the March 6, 1872 Central Europe earthquake, Fig. 11 c).

Choffat and Bensaúde describe quite throughly various aspects of the movement and emphasize the behaviour of slender walls versus more rigid structures. They noticed the apparent incongruence in the direction of overturn of upper parts in those two types of structures and put forward this hypothesis as Captain Oom states: The aspect of the ruins shows that the ground moves from west to east. This shock causes overturn of all upper and heavy parts to the west and all the less solid walls to the east". We will comment on this interesting topic later on.

Azores earthquake is a good laboratory to observe and study this type of movements. We will look into two cases. The obelisk in the old cemetery of Angra do Heroísmo and a pyramid-like monument called Memória ("Memory").

The cemetery is located in a soft terrain to the north of Angra do Heroísmo in a zone of high damage, MMI $\simeq$ VIII. Many small obelisks of different sizes and constitutions are spread within an area of 100×50 m. Each one of them is made of several polished marble blocks, one on top of the others without any mortar in the separating surfaces. Heights of 1 to 3 m are very common. After the earthquake, several movements were observed:

- Overturn of upper parts occurred in few cases. Overturn of an entire slender structure took place due to the fact that there were small "strouts" at the first block not allowing the sliding of this block, Fig. 12.
- Sliding between blocks along the height of the obelisks is very often observed. In most cases "second mode" configuration prevail, Fig. 13. The direction of main deformation in the horizontal plane varies from structure to structure. However, there is a markedly tendency towards the NE direction.
- Rotation of upper blocks is very common. The degree of rotation varies from obelisk to obelisk. A maximum rotation of approximately 45^o was observed in one case, Fig. 14. There is a tendency of rotation always in the same direction.

The Memória is a square pyramide 23 m high with an approximate 6.5 m at the base. The structure is made of regular stone masonry in the outer parts and is infilled with irregular blocks. The botton part is hollow, supported by a 3 m deep foundation with well arranged stones, is embeded in a land fill with a retaining wall in the southern part. In the northern part, the access to the main platform is made by a stairway with an entrance gate with two lateral small columns with a capital.

Damage to this structure can be described as follows, Fig. 15:

- The upper block overturn to the north reaching an horizontal distance of approximately 8 m.
- The following third part seems rotated counterclockwise.
- The lower part of the structure is more damaged in the SE corner with the spalling of blocks.
- The capital of the western gate column rotated clock wise.
- The SE corner of the retaining wall collapsed (to the SE).

In presence of these signs, some of which seem contradictory, we proceeded to a more close observation and interpretation of the behaviour.

From pictures taken right after the quake to the four sides of Memória and to the capital, one can see that the rotation of the second third of the pyramid exhibits a translational component and that the rotation of the capital took place in relation to a certain fixed hinge. These movements can be explained by a translational input motion in the direction NNE-SSE. On top of these elements, the spalling to the SSE of stone masonry blocks in the lower portion of the pyramid and the collapse of the retaining wall, support the idea that the preferencial movement at Memória had an important component in the NW-SE direction with first motion to the north, Fig. 16.

The above finding fits quite well Capitan Oom's statement in which flexible structures exhibit damage in compression at lower levels on the opposite side of first motion and top elements overturn to the side of first motion. Stiff structures have a different behaviour, with overturning of top elements to the opposite side of first motion.

2.5 *Interpretation*

The direction of first motion felt at Memória is in total agreement with the shear wave pulse radiated by the left-lateral source mechanism obtained from teleseismic observation and fault alignment. In Fig. 17 we plotted the direction of first motion of other structures and objects for which it was possible to gather information. It is quite interesting to note that there is some consistency on the overall picture. The few exceptions to the main trend should be analysed separately in order to obtain a plausible explanation of the anomalous behaviour. One of them refers to the village of S. Sebastião (see section 2.1) where "first motion" was due the reflection at the border of an alluvial infill.

The trend of the first motion also agree with the horizontal polarization computed from the strong ground motion record, Fig.2. This polarization changes slightly for higher frequencies. This may be explained by a rupture model at the source, initiated at the focal location and propagating in both sides but essentially to the SE, in a total of 60 km. Considering an average rupture velocity of 2.5 km/s, this would indicate a rupture duration of 12 sec. Possibly and following Grimison model, the rupture would have taken place in two phases, the aftershock locations representing the stopping fault rupture. This mechanism could explain the larger PGA felt at Topo, 15 km away from the fault trace (second shock), the slight higher intensities observed in the southern cost of Terceira island and the hypothesis of a later strong push towards the end of the record.

The previous paragraph supports the idea that, at least, the source-mechanism and the site may contribute to anomalous behaviour in wave propagation.

3. MODELS FOR RIGID BLOCKS. A BRIEF REFERENCE

The behaviour of blocks under earthquake motion is a classic nonlinear problem which has always interested the spirit of mechanical oriented people. We already mentioned the pioniering work by Mallet last century. In more recent times, Muto et al. (1960) and Housner (1963) put forward the first principles that govern the rocking of rigid structures under seismic loads. The importance of the topic was again recognized lately for different reasons, and a number of papers were published since the eighties. Work by Yim et al. (1980), Spanos et al. (1984), Tso et al. (1989), Wong et al. (1989), Giuffré (1989), Psycharis (1990) and Andreaus (1990) are among the most recent published studies. Three more papers were presented at this 10th World Conference on Earthquake Engineering: Shenton III et al. (1992), Demosthenous et al. (1992) and Hogan (1992).

In this work several different situations were analysed such as rocking and sliding of a rigid block, computations of the probability of overturn as a function of ground motion amplitude and frequency content, for various slenderness ratios. Influence of vertical component and motions of 2 blocks were also analysed.

Very simple experimental work was done. In one case, Demosthenous et al. (1992), a small scale model of several blocks, ones on top of others, were subjected to sinusoidal base-input and quite interesting observations in relation to stability were made. This type of experiment can represent situations very similar to the ones described in parts of section 2:4 of the present paper, and give some important information to comprehend and quantify the input ground motion.

Even though great insight have been obtained with the papers referred herein, there still exist several observed features which are difficult to deal with. The most instriguing one is the large amplitude rotations observed in several obelisks. These rotations should be associated with higher frequencies input under some vertical component motion. Lower frequency rotational components of ground motion show very small amplitudes, at least as depicted from dense array networks (Oliveira et al. 1989). Other difficulties are linked to lack of knowledge on (i) the vertical component, on (ii), the coefficient of friction in the contact surfaces and on (iii) the existence of small asperities. As it was mentioned in 2.4, during the qualitative analysis of Memória performance, small perturbations may induce rotations which need no rotational component input.

In view of the above mentioned observations, it is strongly recommended that more experimental and analytical work is pursued in order to explain, in quantifying terms, the type of examples presented. Also an efficient measuring device is needed to trace the motion of each block, specially for the rotational components and the large amplitudes.

4. FINAL CONSIDERATIONS

The following final considerations should be stressed:

(a) Behaviour of simple structures can inform on several parameters of input ground motion and be used as a complement of instrumental information.

(b) Nonlinear analysis of other more complex structures such as masonry buildings, retaining walls, etc, could also inform on the basic ground motion parameters.

(c) All the elements referred in a) and b) are of great importance to microzonation and should be compared with other methods of analysis.

(d) In order to obtain ground motion parameter quantification from the movement of rigid structures, theoretical and experimental work should be performed. Shaking table tests with vertical and horizontal independent motion should be used to reproduce the behaviour observed in real structures and validate analytical models.

(e) Simple instrumental equipment based on the principles presented herein could be developed at very low cost and used world wide as a good measure of peak motion.

(f) Video-tape technology should be developed to record wave propagation and response of some structures as a mean to complement dense seismic array information and observe large displacement offsets.

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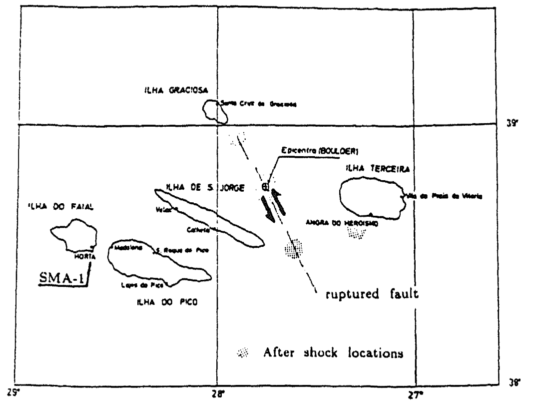

Figure 1 - Epicentral location of the January 1st, 1980 Azores earthquake. Presence of aftershocks (Hirn et al. 1980) indicates the existence of a NW-SW lineament (Forjáz et al. 1990).

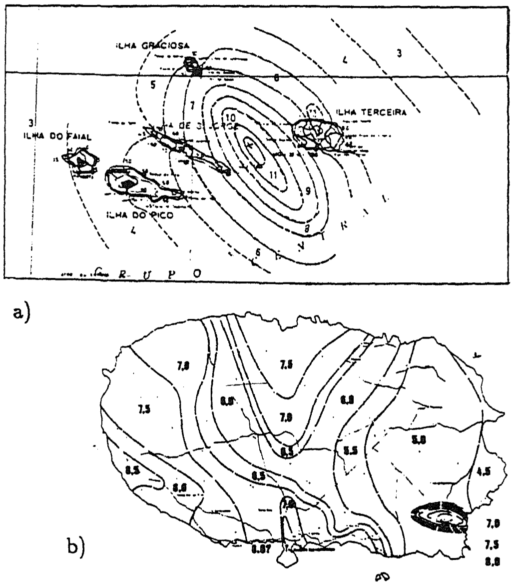

Figure 3 - Isoseismal map of the January 1st, 1980 Azores earthquake: a) Overall map; b) Terceira island details (after Forjáz 1980).

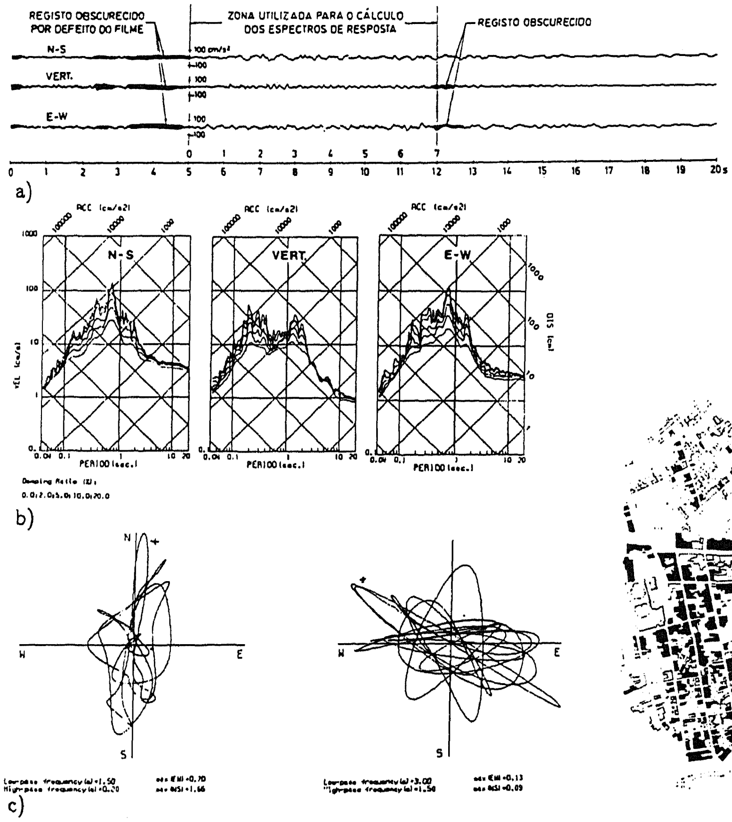

Figure 2 - Strong motion recorded at Horta observatory: a) time-history; b) response spectra; c) particle orbits in the horizontal plane.

Figure 4 - Distribution of damage in Angra do Heroísmo (after Carta de Danos, 1992).

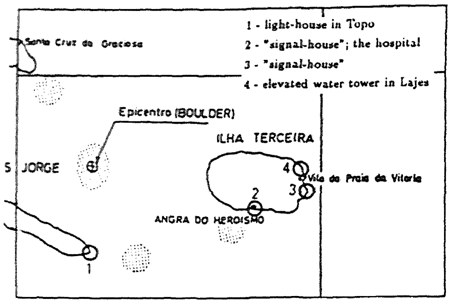

Figure 5 - Location of the four R.C. structures analysed.

Figure 8 - General view of the elevated water tower in Lajes.

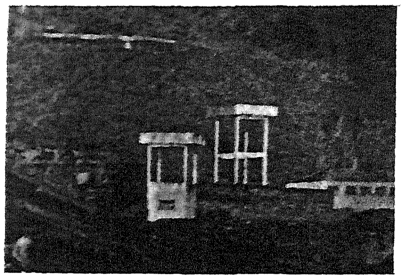

Figure 6 - General view of the "signal-house".

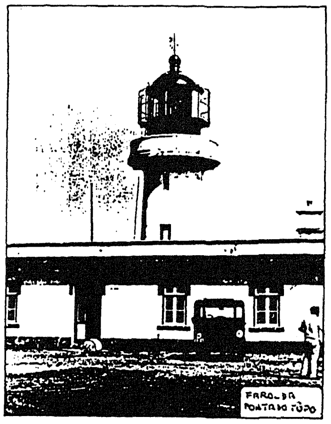

Figure 9 - General view of the light-house in Topo.

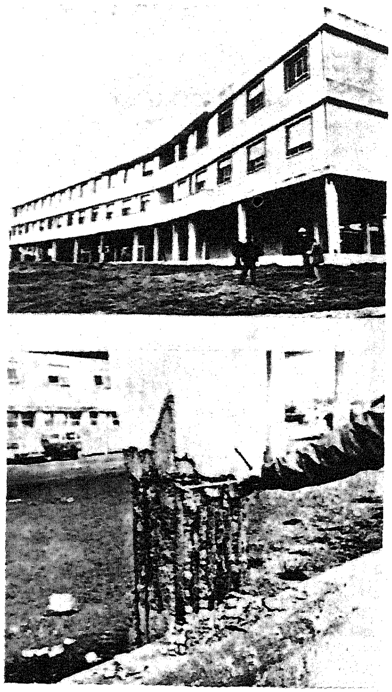

Figure 7 - General view of the hospital in Angra do Heroísmo. Damage to the columns in the soft-story.

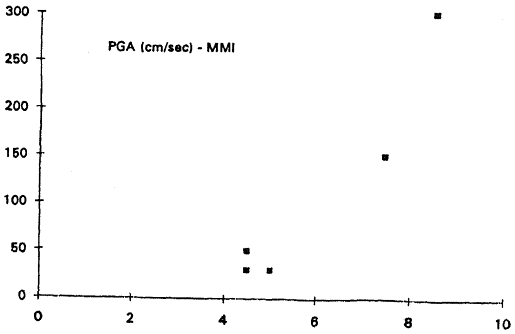

Figure 10 - Correlation between MMI and estimated PGA.

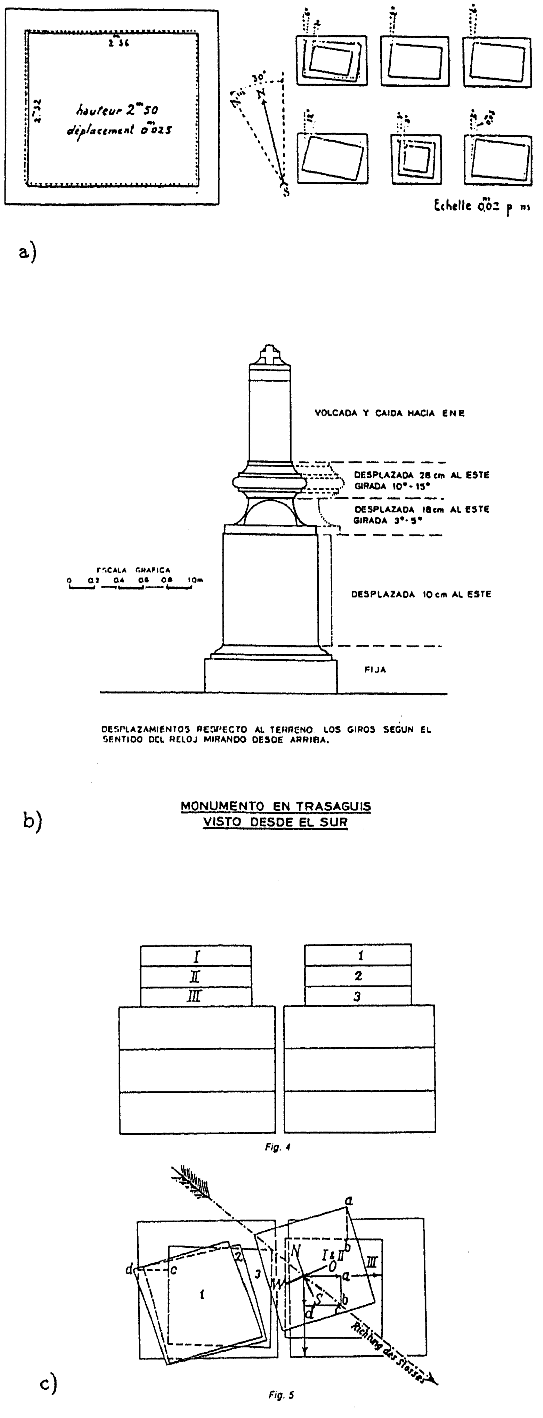

Figure 11 - Displacement and rotation observed in: a) Benavente earthquake of April 23, 1909 (after Choffat el al. 1913); b) Friuli earthquake (after Lopez-Arroyo et al 1982); c) Central European earthquake of March 6, 1872 (after Seebach, 1873).

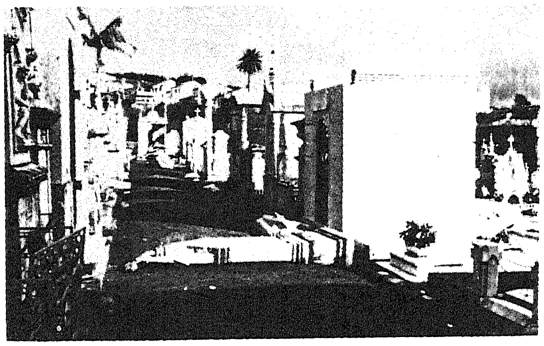

Figure 12 - Overturn of a slender structure at Angra do Heroísmo cemetery due to the existence of small "strouts".

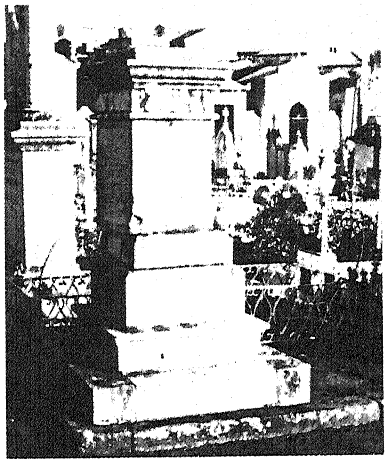

Figure 13 - Sliding of blocks in a "second mode" configuration.

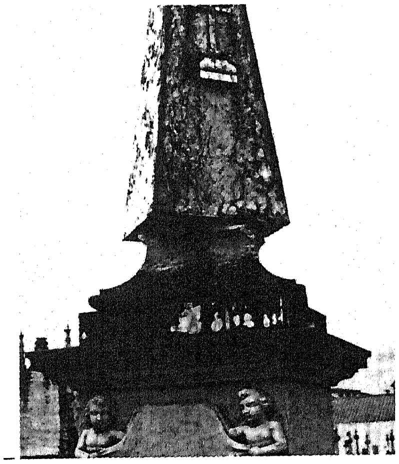

Figure 14 - Rotation of upper block.

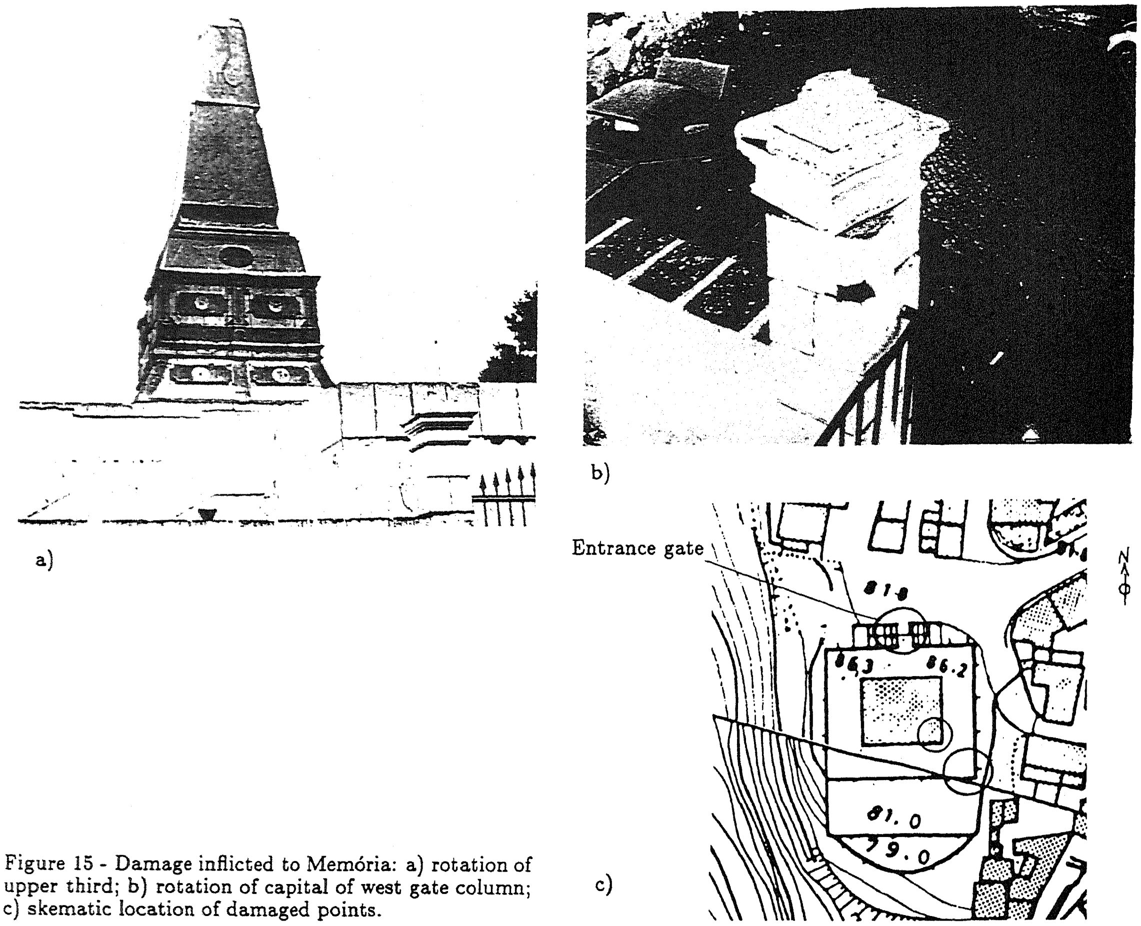

Figure 15 - Damage inflicted to Memória: a) rotation of upper third; b) rotation of capital of west gate column; c) skematic location of damaged points.

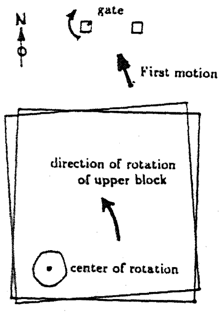

Figure 16 - Sketch of input motion to Memória.

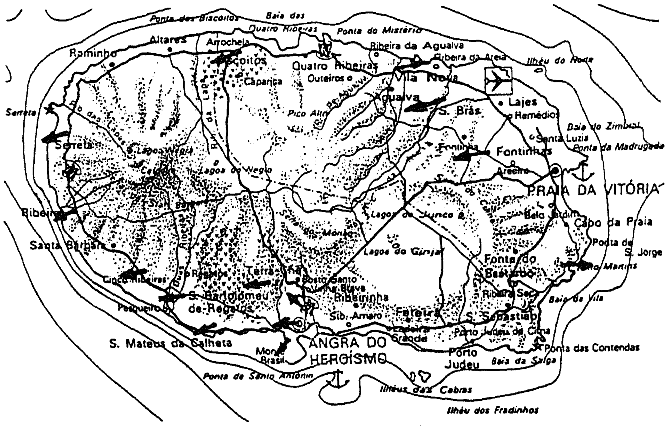

Figure 17 - Global interpretation of direction of 1st motion as recovered from movement of simple objects.