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Considerations on the Diffuse Seismicity Assumption in Stable Continental Regions (SCR)

Jorge D. Riera[1] **and Ignacio Iturrioz**[2]

[1]PPGEC, Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brasil
[2]PROMEC, Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brasil

Correspondence should be addressed to Ignacio Iturrioz, ignacio@mecanica.ufrgs.br

Abstract It is well known that seismic activity is much higher along inter-plate boundaries, decreasing perceptibly in intra-plate regions. Although a few locations in so-called Stable Continental Regions (SCRs) around the globe, like the New Madrid area in the USA, have been subjected to earthquakes with magnitudes above $M_w = 8$, the largest events in most SCRs do not exceed about 7, and their prediction for engineering purposes presents great difficulties on account of the scarce available evidence on seismic activity in intra-plate regions. The situation led in the last two decades to the extensive studies promoted by EPRI. In view of the difficulty to identify seismogenic sources in most SCR areas, the assumption of diffuse seismicity is often accepted in Seismic Risk Analysis of Nuclear Power Plants (NPP) in SCRs, like the South American Plate, used in this paper as an illustrative example. There are few objective criteria known to the authors to accept or reject the hypothesis that the currently used uniform seismicity model is acceptable in any given location, which led to the generalized adoption of the view that an active fault does not exist until its existence can be confirmed by other means. In the paper the authors examine available seismic data for two 500 km radius circular areas in the South American SCR, subjecting the hypothesis of a uniform (diffuse) seismicity to a critical assessment. In addition to an evaluation of parameters applicable to both areas and to preliminary estimates of the differences, a proposal is advanced to define, on the statistical evidence provided by recorded sesimic events, specific seismogenic sources. The possible influence of the approach on the final outcome of risk assessments is finally discussed.

Keywords *Diffuse Seismicity; Stable Continental Regions; Seismic Risk; Fractal Dimension*

1. Introduction

It is well known that seismic activity is much higher along inter-plate boundaries, decreasing perceptibly in intra-plate regions. Although a few locations in so-called Stable Continental Regions (SCRs) around the globe, like the New Madrid area in the USA, have been subjected to earthquakes with magnitudes above $M_w = 8$, the largest events in most SCRs do not exceed about 7, and their prediction for engineering purposes presents great difficulties on account of the scarce available

evidence on seismic activity in intra-plate regions. The situation motivated extensive research on the topic, which resulted in the well known EPRI (1994, 2006) reports and to the consolidation of the notion of SCR.

In view of the difficulty to identify seismogenic sources in most SCR areas, the assumption of diffuse seismicity is often accepted in Seismic Risk Analysis of Nuclear Power Plants (NPP) in those locations, like the South American Plate, used in this paper as an illustrative example. However, there are few objective criteria known to the authors to accept or reject the hypothesis that the currently used uniform seismicity model is acceptable in any given site, which led to the generalized adoption of the questionable view that an active fault does not exist until its existence can be confirmed by other means.

In the paper the authors examine available seismic data for two 500 km radius circular areas in the South American SCR, subjecting the hypothesis of a uniform (diffuse) seismicity to a critical assessment. In addition to an evaluation of parameters applicable to both areas and to preliminary estimates of the differences, a proposal is advanced to define, on the statistical evidence provided by recorded seismic events, specific seismogenic sources. The possible influence of the approach on the final outcome of risk assessments is finally discussed.

2. Fractal Dimension

Beauval *et al.,* (2006) argue that Seismicity is a complex phenomenon that may nevertheless be quantified using fractal concepts. In fact, fault networks and epicentral distributions are known to have fractal properties (Goltz, 1998). Thus, a natural way to analyze the spatial distribution of seismicity is to determine the fractal dimension (*D*-value). This *D*-value is an extension of the Euclidean dimension and measures the degree of clustering of earthquakes. In a two-dimensional space, *D* can be a decimal number and ranges from 0 (point) to 2.0 (uniform distribution in space). Beauval *et al.,* (2006) aimed at characterizing the bias in probabilistic hazard estimates resulting from the incomplete knowledge of the degree of clustering of the "true" seismicity distribution. The fractal dimension considered in their study is the correlation dimension (Grassberger and Procaccia, 1983). Although the assessment of the diffused seismicity assumption presented in this study does not follow the approach described by Beauval *et al.,* (2006), the concepts are useful in the interpretation of the ensuing results.

Synthetic seismicity distributions were generated by Beauval *et al.,* (2006) over the source zone, increasing the clustering of the seismicity from a line ($D \approx 1.0$) to a uniform distribution over the area ($D \approx 2.0$). Surfaces with a fractal dimension *D* were generated in accordance with the detailed description in Turcotte (1997). A uniform distribution of seismicity over the source zone (i.e., $D = 2.0$) results in identical acceleration values inside the source zone. Distributing the seismicity in a non-homogenous manner obviously leads to a non-homogenous estimation of hazard at the sites; the closer the site is to the high seismicity densities the higher is the hazard estimated at this site. The impact *I* on probabilistic hazard is defined as the difference between the acceleration calculated for a spatially uniform seismicity. A_{unif} and the estimated one *A*, normalized by the uniform value and expressed in percentage:

$$I = [(A_{unif} - A) / A_{unif}] \times 100 \qquad (1)$$

Therefore, positive impacts correspond to sites where the assumption of uniform distribution of seismicity results in an increase of the hazard.

3. Seismicity of South-Eastern Brazil

In the following assessment, the south-eastern region of Brazil located within the 1200 km square area shown in Figure 1 will be considered.
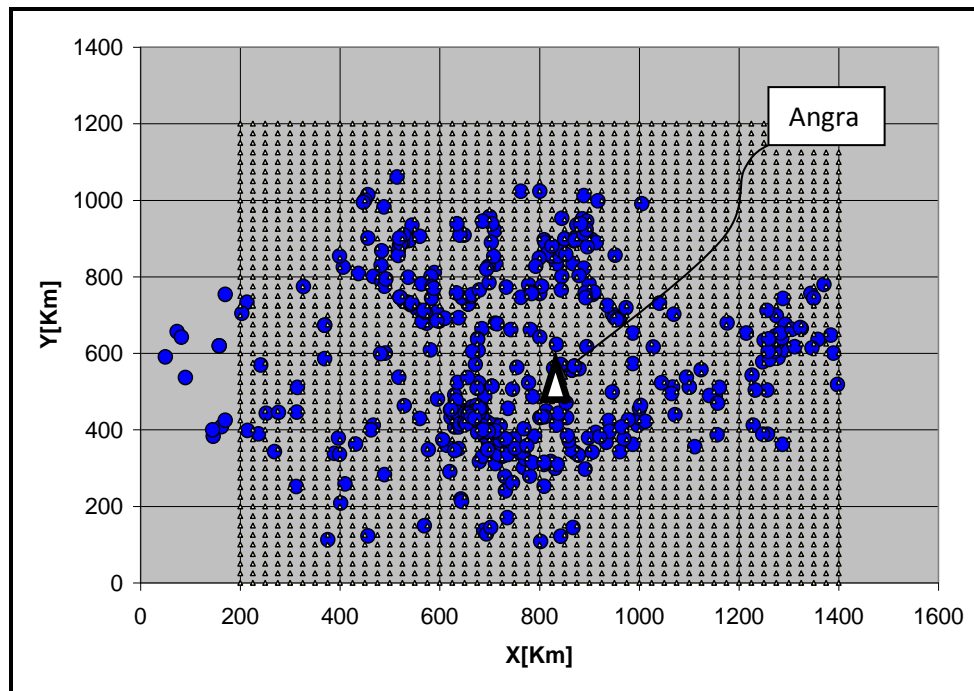

Figure 1: In Blue Circles the Seismic Events are indicated. In Little Triangle Point are Indicate the Poles. And the Big Black Rinagle Indicate the Position of Angra. The Seismic Event Position and the Nodes Localization (Events Registred From 1961 to 2011) 50 Years. The Origin of Coordinates is in (22 S, 52W). The ANGRA Position is (The Big Black Triangle), (23,008S,44,45W)

Figure 2: Distribution of Epicenters of Seismic Events ($M_w ≥ 2$) Occurred in the 50 Years Period between 1961 and 2011 within the Square Region Shown in South-Eastern Brazil. The Big Triangle at (23.08° S, 44.45° W) Shows the Site of the Angra dos Reis NPP (CNAAA)

The epicenters of seismic events with moment magnitudes $M_w \geq 2$ are indicated by circles, while the site of the Angra dos Reis NPP is shown by the big triangle in Figure 2. Actually the catalog available (Berrocal, 2011) contains information on events with epicenters in a somewhat smaller and irregular region, with magnitudes specified in the body wave m_b scale and is presently being updated to include all events in a 1200 km diameter area. For present purposes moment magnitudes were determined by means of the equation:

$$M_w = 1.157 \, m_{b\_obs} - 0.84 \tag{2}$$

The magnitudes of seismic events was plotted in Figure 3, which also shows the locations of nodal points, spaced 25 km in a regular grid that will be used to assess the spatial distribution of seismic activity. It should be underlined that the focal depth z is not known for most events in the catalog, but all seismic events are considered shallow ($z \leq 20$ km) (Berrocal, 2011). The next step in the analysis consists of determining the number of events with epicenters within circles of increasing diameter, centered at the nodes of the grid, in the 50 years period under consideration. This index is shown in Figure 4 (left column) for circles of radius equal to $R = 10$, 20 and 50 km, respectively. The right column of the same Figure shows plots of the sum of the magnitudes, rather than the simple sum of the number of events, which provides an alternative yet similar view of the seismic activity.
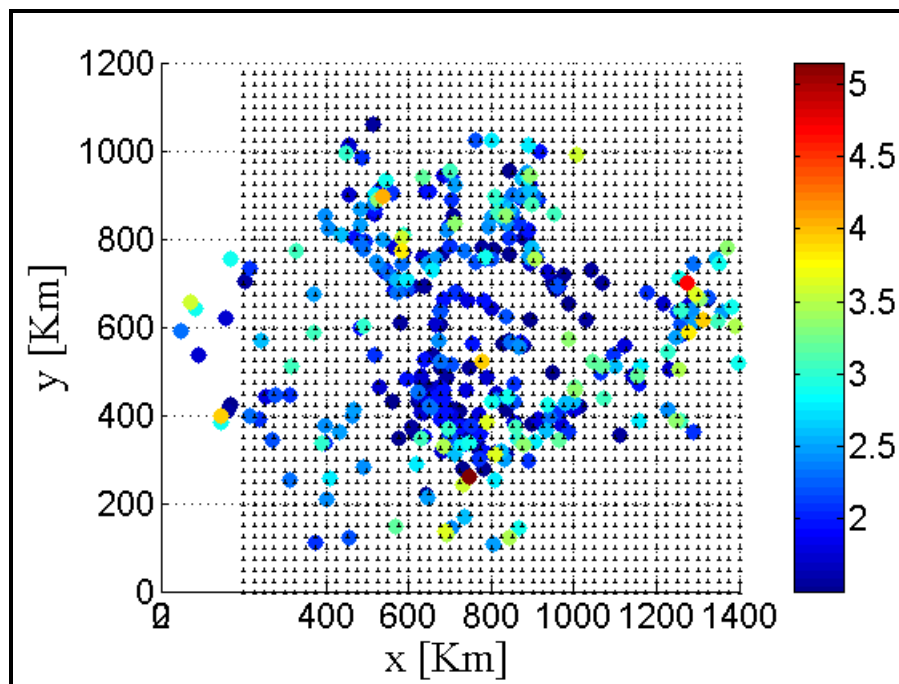

Figure 3: Magnitude M_w of Seismic Events Shown in Figure 1. The Small Triangles Indicate the Locations of Observation Nodes in the Grid

It may be seen that as the radius increases the picture tends to present a more uniform color. Obviously, for a radius of a few hundred kilometers, the entire region tends to be characterized by a uniform color that corresponds to the average number of events per unit area in the time interval considered. Moreover, as Figure 5 illustrates, the records of about the first half of the period under consideration are incomplete. Only the last two decades of record may be regarded as including all events in the range $M_w \geq 2$.
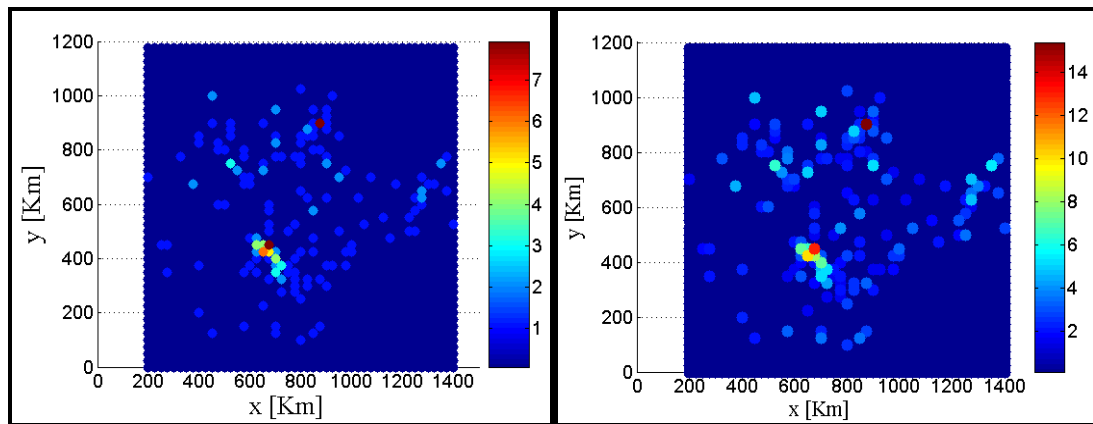
Radius of Circles Centered at Nodes of Grid: R= 10 km
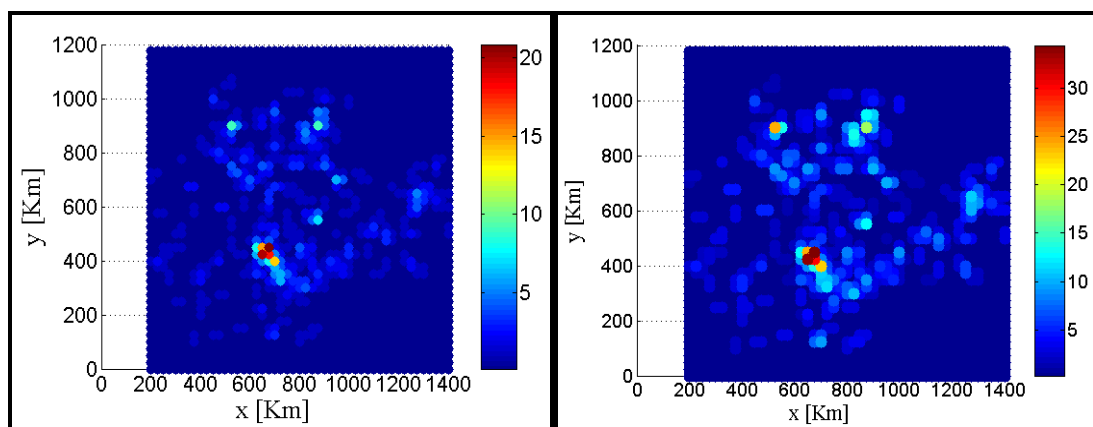
Radius of Circles Centered at Nodes of Grid: R= 20 km
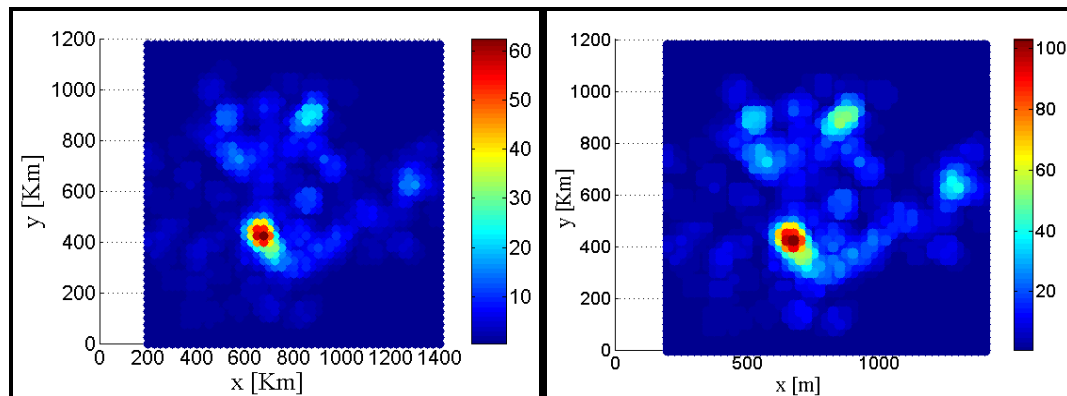
Radius of Circles Centered at Nodes of Grid: R= 50 km

Figure 4: *Distribution of Epicenters of Seismic Events within the PPS Region in Brazil, in the 50 Years Period between 1961 and 2011. (Left) Number of Events in Circular Regions of Radius R and (Right) Sum of Magnitudes of Events within Each Circle*

The preliminary studies suggest that, with the exception of the small region centered approximately at coordinates x= 700 km, y= 400 km (Figure 4), the assumption of uniformly distributed seismicity may be acceptable for the PSS in south-eastern Brazil. In fact, the ratios between the peak amplitudes within this higher activity region and the mean amplitude attain values close to 10, that is, one order of

magnitude higher, which is proposed as a valid indicator to identify a specific seismic source, but the contribution of this source appears to be insufficient to alter the initial assumption of uniform seismicity.
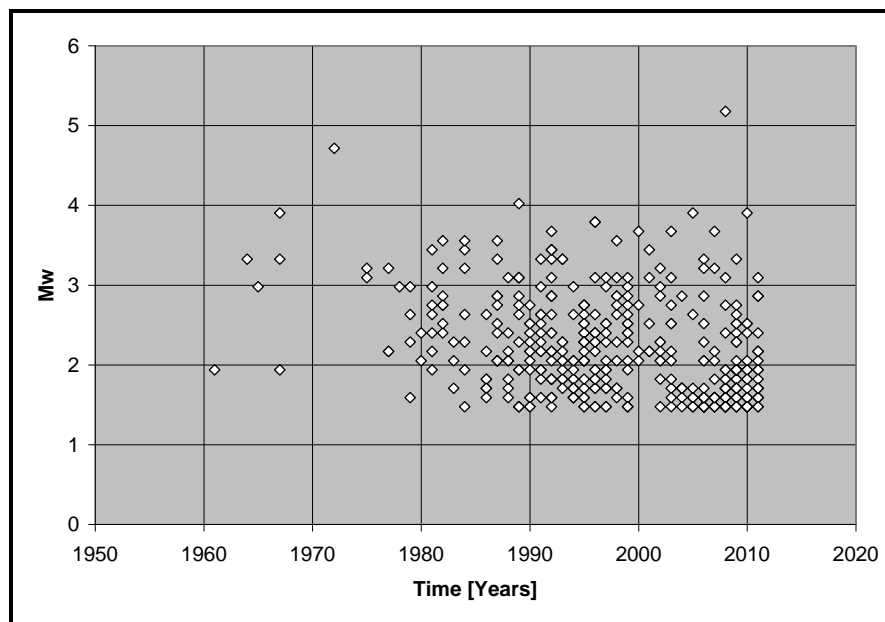

Figure 5: Distribution in Time of Seismic Events Recorded in the Data Base, Showing the Influence of New Seismological Stations that Entered Into Operation after 1980

In a region with uniform seismic activity, assuming that Poisson`s model is valid, the expected value v of the number of seismic events that occur in a time unit (year) with epicenter in an area unit (1 km^2) is constant. Hence, the expected number n of events in a circular area of radius R, in N years, results:

$$n = v \, \pi \, N \, R^2 \qquad\qquad (3)$$

Considering only events of magnitude $M_w \geq 2$ in the data base, it follows that in the South-American SCR, coefficient v is less than 4×10^{-5} / ano×km^2, value that decreases rapidly when larger cut-off magnitudes, such as $M_w \geq 3$ or $M_w \geq 4$ are adopted in the analysis. Taking natural logarithms of both sides of equation (3):

$$ln(n) = ln(v \, \pi \, N) + 2 \, ln(R) \qquad\qquad (4)$$

It follows that in a region with uniform seismic activity the relation between $ln(n)$ and $ln(R)$ must be linear, with a slope equal to 2. This slope coincides with the fractal dimension D discussed in Section 2. Figure 5 shows a plot of $ln(n)$ for all nodal circles in the region, for each radius considered in the analysis ($R = 10, 20, 50, 100, 200, 300$ and 500 km), as well as the mean value for each radius, indicated by the white squares.
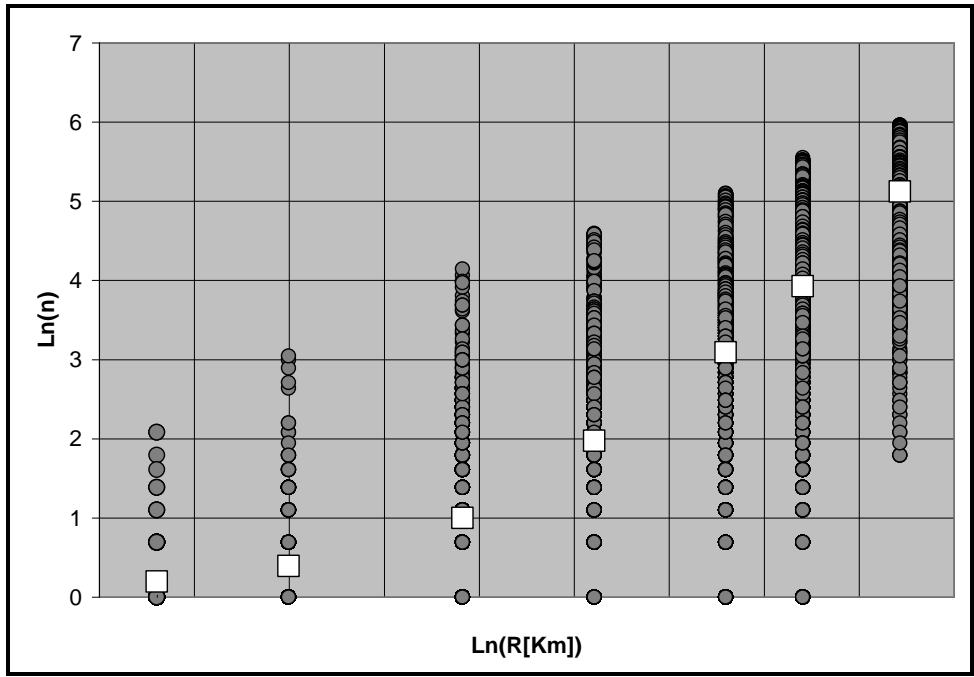
Figure 6: Relation between the Natural Logarithm of the Number of Events and the Logarithm of the Radius R of Circles Centered at the Nodal Points of the Grid. The White Squares are the Mean Value for each Radius Considered in the Entire Region. With R= 10, 20, 50, 100, 200, 300, 500 Km

As an initial step in the assessment of the available data, the evolution of the mean value of $\ln(n)$ for each radius will be examined first. As shown by the plot in Figure 7, it seems clear that the relation is not linear in the entire field of variation of R. It was then assumed that linear equations, of the form (4), are valid for small and for large values of R, with the boundary ξ_C between both ranges to be determined. The transition is modeled by the logistic function $f[\ln(R)]$. Setting $\xi = \ln(R)$, the adopted relations are:

$$Log\ N(\xi) = [(a_1 - b_1\xi)\ f(\xi) + [(a_2 - b_2\xi)\ [1 - f(\xi)] \tag{5}$$

In which:

$$f(\xi) = \exp[-(\xi - \xi_C)/0.2]\ /\{1 + \exp[-(\xi - \xi_C)/0.2]\} \tag{6}$$

Figure 7 presents a plot of equations (5) and (6) fitted to the mean values of $ln(n)$ shown in Figure 6 by means of a non-linear regression analysis. Adopting by trial and error a location parameter of the logistic function equal to $\xi_C = 4.2$, leads to the coefficients $a_1 = -1.0796$, $b_1 = -0.5339$, $a_2 = -6.9635$ and $b_2 = -1.9218$. The last coefficient, applicable to large R, is close to 2, thus suggesting a *uniformly distributed seismicity*, but the authors are not aware of any criteria to accept or reject such hypothesis. Coefficient $a_2 = -6.9635$ on the other hand, implies a mean frequency of seismic events in the region under consideration equal to $v = 6 \times 10^{-6}$ / ano×km², which is too low and confirms, as suggested by Figure 5, that the data base is incomplete.
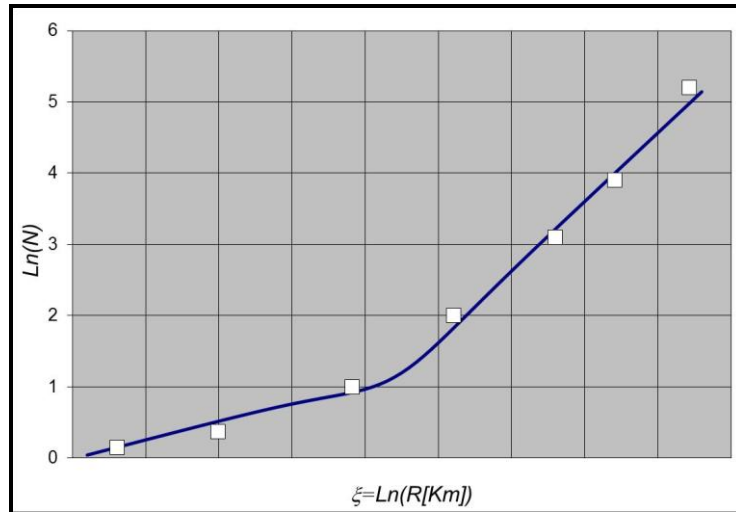
Figure 7: *Plot of Equations (5) and (6) Fitted to the Mean Values of ln(n) Shown in Figure 6, Yielding $a_1 = -1.0796$, $b_1 = -0.5339$, $a_2 = -6.9635$, $b_2 = -1.9218$. The Location Parameter of the Logistic Function is $\xi_C = 4.2$. With R= 10, 20, 50, 100, 200, 300, 500 Km*

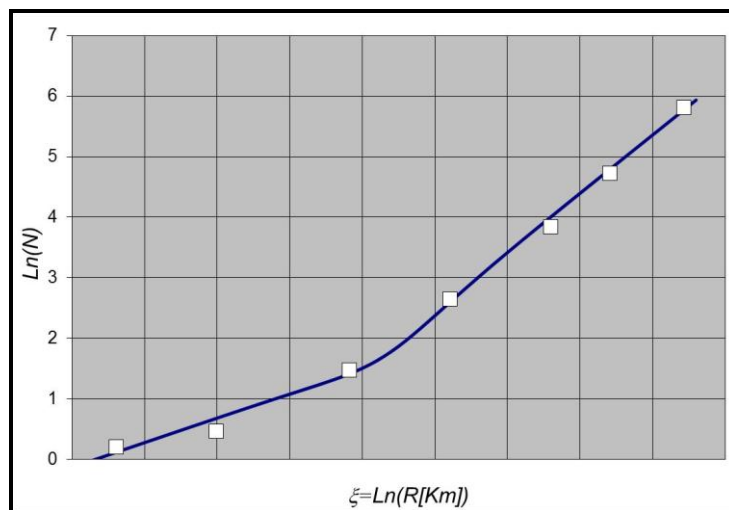The standard error in the adjustment is $s = 0.151$, and the correlation coefficient $r = 0.9983$

Figure 8: *Plot of Equations (5) and (6) Fitted to the Mean Values of ln(n) Corrected for Incompleteness, Yielding $a_1 = -1.7614$, $b_1 = -0.8158$, $a_2 = -6.1685$, $b_2 = -1.9212$. The Location Parameter of the Logistic Function is $\xi_C = 4.2$. With R= 10, 20, 50, 100, 200, 300, 500 Km. The Standard Error in the Adjustment is $s = 0.157$, and the Correlation Coefficient r= 0.9987*

A correction of the number of events was introduced, assuming that the number of missing events in the record decreases with their magnitude, resulting in the function presented in Figure 8, which also shows a plot of equations (5) and (6) fitted to the mean values of $ln(n)$ corrected for incompleteness, yielding $a_1 = -1.7614$, $b_1 = -0.8158$, $a_2 = -6.1685$, $b_2 = -1.9212$. The location parameter of the logistic function is also $\xi_C = 4.2$. In this case the coefficient $a_2 = -6.1685$ corresponds (see equation 3) to $v = 1.33 \times 10^{-4}$ / ano×km^2 which is compatible with the original data set. It is clear that, in addition to the geometry of the sources in the region, ξ_C is influenced by the size of the data set, since for a *finite* total number of events in the data set, the mean number of seismic events within circles of radius R will tend to zero as R decreases. The interaction between R and v, as well as the influence of statistical errors, require further study, which are currently in progress, in order to establish the existence of relevant specific sources in the region, as an alternative to the uniform seismicity model.

4. Seismicity of Rio de la Plata Region

The epicenters of both historical and instrumentally recorded seismic events within a 600 km radius circle centered at the site of Atucha NPP in Argentina are indicated in Figure 9 (Ambrosini *et al.*, 2006). The region is part of the South-American SCR shown in Figure 10 and hence might share some common features with the Brazilian PSS examined in Section 3. There are increasing difficulties to perform for the region shown in Figure 10; a similar analysis, because the available data base does not contain information for small magnitude events ($M_w \leq 3$). However, some preliminary results are described next, which should be considered with additional care for the reasons previously mentioned.
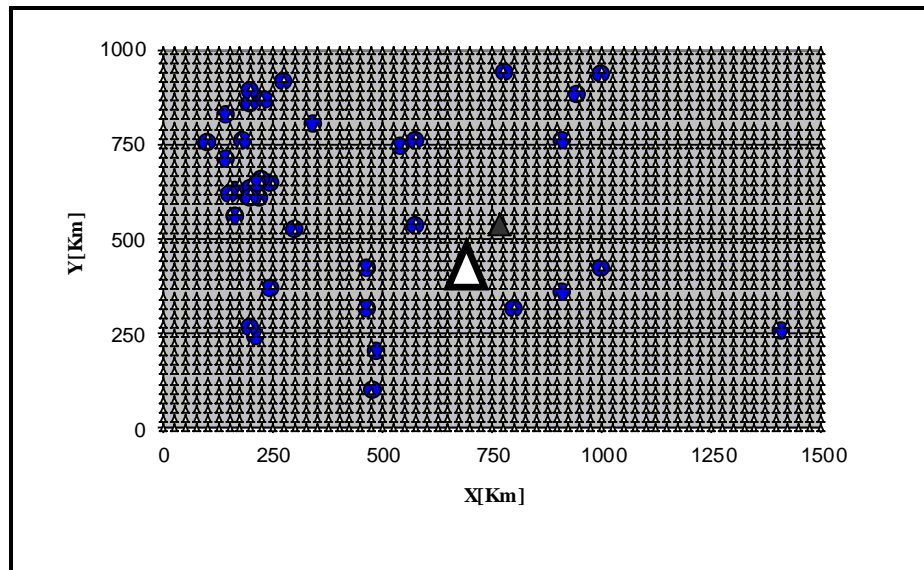

Figure 9: *Epicenters (circles) of Seismic Events Registered in the Region under Consideration around Atucha NPP (Big Triangle at 33.96S, 59.3W) between 1964 and 2008. In Small Triangle Points are Indicate the Poles of the Adopted Grid. The Origin of Coordinates is at (29.55 S, 52.60W)*
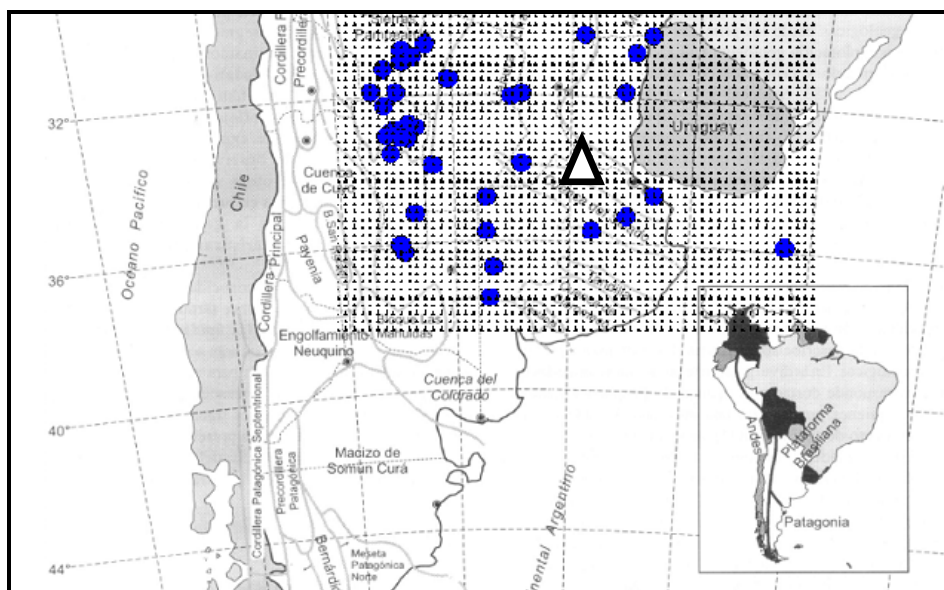

Figure 10: *Distribution of Epicenters of Seismic Events ($M_w \geq 3$) Registered Between 1964 and 2008 within the 1000 km × 1500 km Region around Atucha NPP, Indicated by Big Triangle at (30.45° S, 53.5° W) in the Figure*

Figure 11 shows the moment magnitudes M_w of the events, estimated from the magnitude scales indicated in Ambrosini *et al.,* (2006) data set, while Figure 12 shows the number of seismic events ($M_w > 3$) in the 44 years period between 1964 and 2008 in circular regions of radius R= 100 km around nodes of the observation grid. Curves for smaller radius are not meaningful since they simply tend to reproduce the locations of individual epicenters, and thus cannot be directly compared to assess seismic activity with the figures presented in Figure 4 for the PSS region in Brazil. Nevertheless, an area of higher concentration of events is clearly shown around coordinates x≈ 200 km, y≈ 600 km.
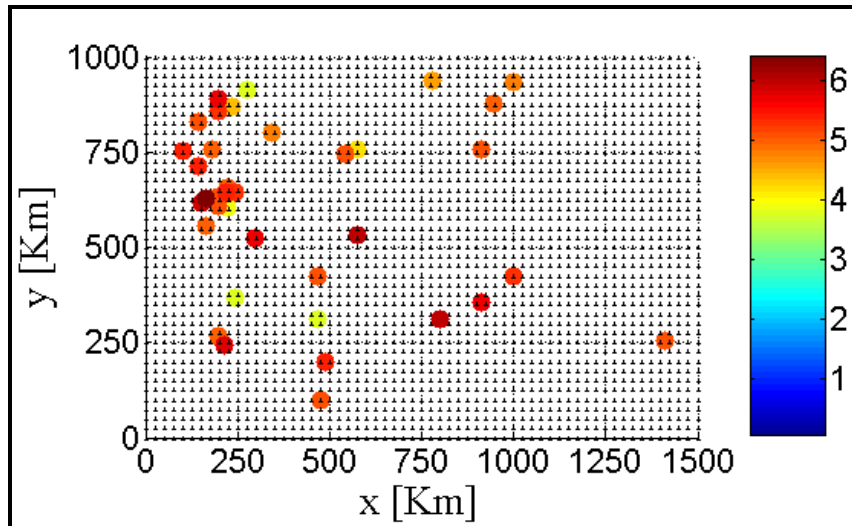

Figure 11: *Magnitude M_w of Seismic Events Shown in Figure 9. The Small Triangles Indicate the Locations of Observation Nodes in the Grid*
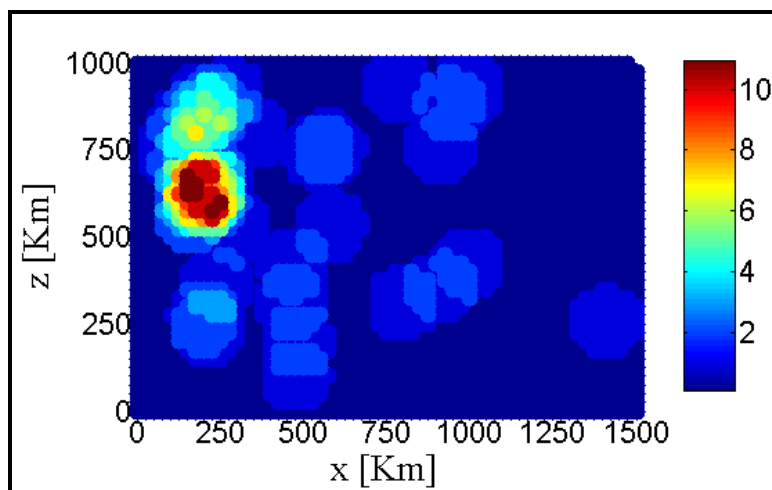

Figure 12: *Number of Seismic Events ($M_w > 3$) in the 44 Years Period Between 1964 and 2008 in Circular Regions of Radius R= 100 km around Nodes of the Observation Grid*
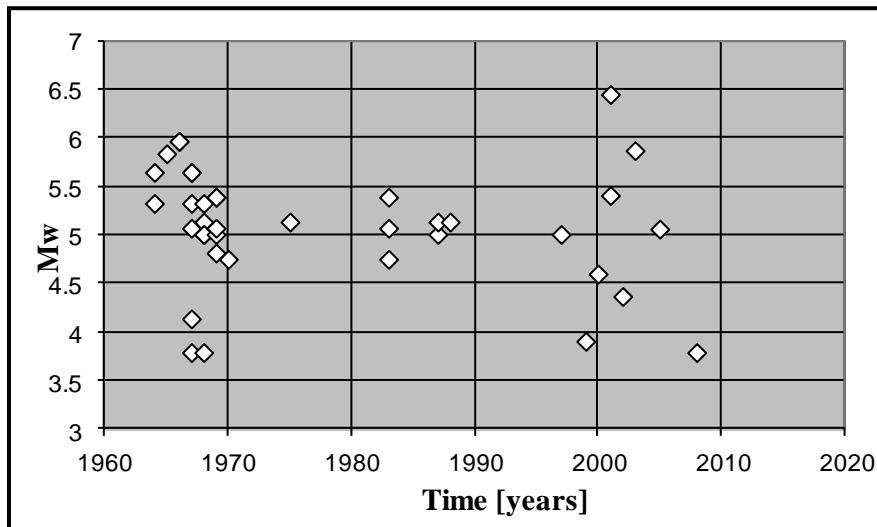
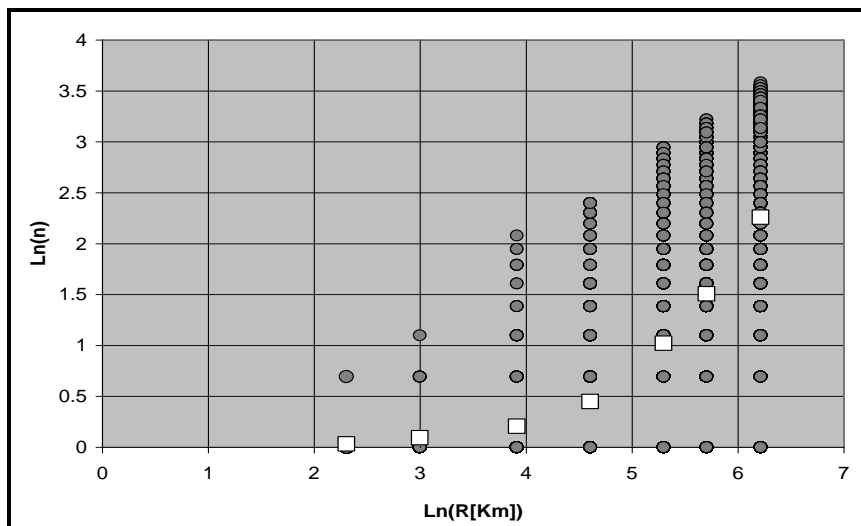**Figure 13:** *Distribution in Time of Seismic Events in the Data Base*

Figure 14: *Relation between the Natural Logarithm of the Number of Events and the Logarithm of the Radius R of Circles Centered at the Nodal Points of the Grid. The White Squares are the Mean Value for Each Radius Considered in the Entire Region. With R= 10, 20, 50, 100, 200, 300, 500 Km*
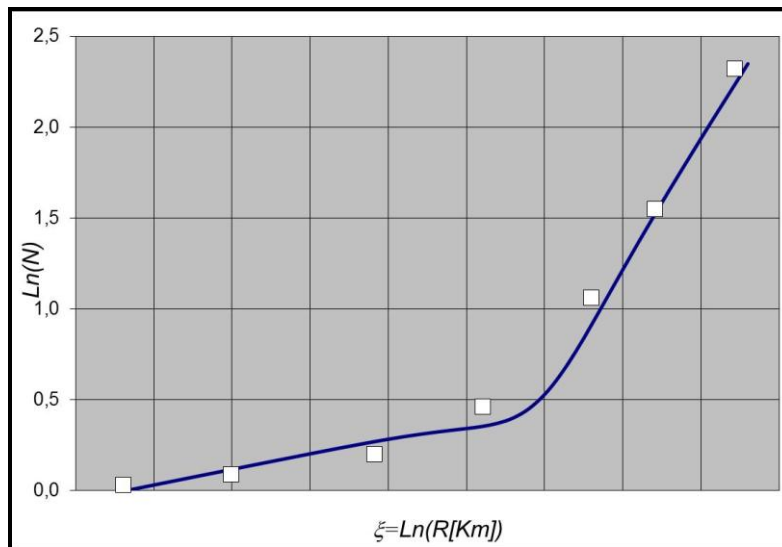
Figure 15: *Plot of Equations (5) and (6) Fitted to the Mean Values of ln(n) Shown in Figure 14 for the Region around Atucha NPP in Argentina, Yielding $a_1 = -0.4007$, $b_1 = -0.1726$, $a_2 = -6.1537$, $b_2 = -1.3500$. The Location Parameter of the Logistic Function is $\xi_C = 5.0$ and the Dispersion 0.05. With R= 10, 20, 50, 100, 200, 300, 500 Km. The Standard Error in the Adjustment is s=0.063, and the Correlation Coefficient r=0.9983*

Figure 15 shows a plot of equations (5) and (6) fitted to the mean values of *ln*(*n*) shown in Figure 14 for the region around Atucha NPP in Argentina which, with the restrictions mentioned previously related to the differences in the data bases, present a possibly relevant difference with the plots of Figures 7 and 8, applicable to Brazilian PSS. In the latter, the slope b_2 is close to -2, value that would apply in a uniform (distributed) seismicity model. In the first case, on the other hand, is only -1.35, suggesting the existence of a localized seismic source within the region that would invalidate the assumption of uniform (distributed) seismicity.

Additional studies are presently under way directed to the development of quantitative criteria to accept or reject the hypothesis in question.

5. Influence of the Diffused Uniform Seismicity Assumption on Risk Assessments

It is generally unclear whether the assumption of diffused uniform seismicity in the SCR region under consideration should lead to conservative estimates of the seismic hazard at the site of interest or not. This fact has been established in the studies of Beauval*et al.,* (2006), which do not exhaust the subject, leaving the question in want of an answer, short of examining all possible models.

It is herein suggested that an initial step would be to develop a criteria to accept or reject the model, for which purpose preliminary results were presented.

6. Conclusions

A preliminary evaluation of the uniform seismicity assumption usually adopted in seismic hazard analysis of structures in SCR sites is presented in the paper. The procedure may also be useful to identify specific seismogenic sources in the region under study.

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