One-Dimensional Multilayer Velocity Model for Porto dos Gauchos/MT

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This paper was prepared for presentation at the 8th International Congress of The Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 14-18 September 2003.

Abstract

In this paper is presented a 1D velocity model for the seismogenic area of Porto dos Gauchos/MT (PG), got from two calibration explosions of a local seismographic network installed around the epicentral area located at the northern part of the Intra-cratonic Parecis Proterozoic Basin (Siqueira & Teixeira, 1993). It is one of the most active seismic areas in Brazil, in terms of magnitude and seismic frequency; and presented the largest magnitude already observed in the country (m_b = 6.2 on 01/31/1955) (Berrocal et. al, 1984) ;and on 03/10/1998 occurred the second largest magnitude in the area (m_b = 5.1). After that, more than 2,400 seismic events have already been recorded, fifteen of them have magnitude over 3.5.

From this model was possible to localize the explosions with accuracy up to 20 m (only readings with of the P phase) and of 110 m (with readings of the P and S phases). The obtained model consists in a ratio V_p/V_s of 1.82 and three layers with thickness of 0.3 km (Vp = 3.88 Km/s), 2.0 km (Vp = 5.88 Km/s) and 15 km (Vp = 6.20 Km/s) laid over an infinite half-space.

Introduction

The accuracy of an earthquake hypocentral location depends on, strongly, of two factors: quality of the data and the velocity model employed at the location. As quality of the data it should be understood digital records in triaxial stations, well calibrated, with accurate clocks and installed around the epicentral region. As the model employed, it must be realistic, representing in the most accurate possible way, the velocity structures of the area surrounded by seismographic network stations.

The criteria's of optimization do not always explain the model quality; it just express the accuracy of the location related to the adopted model; a low RMS (Root Mean Square) value of the residual just shows that the location was optimized in relation to the adopted model. Hence, if the model is bad the resulting location will be bad too.

A good velocity model can be obtained from geological information of the study area and the geophysical information derived from controlled seismic sources (Kissiling, et al., 1995). The model for Porto dos Gauchos was obtained from the accomplishment of two calibrations explosion of a seismographic network with ten stations, one vertical component and nine three components stations installed around the PG seismogenic area.

The validity of the model was checked running the Hypocenter location program with the found model (Lienert, 1994). The explosion 1 was located with an accuracy of 40m (using readings of P phase only) and 240m (with readings of the P and S phases); the explosion 2 with accuracy of 20m (readings of P phase only) and 110m (with readings of the P and S phases).

In this paper will be presented the 1D model obtained for Porto dos Gauchos/MT and an updated summary of the seismicity of the area which complement the work of Barros et all, 2001.

Summary of the Seismicity of Porto dos Gauchos in period 1998 - 2002

During the last five years of uninterrupted seismographic monitoring of the Porto dos Gauchos area, more than 2,400 seismic events were detected, 15 of them with magnitudes larger or equal to 3.5 m_R (Fig. 1).

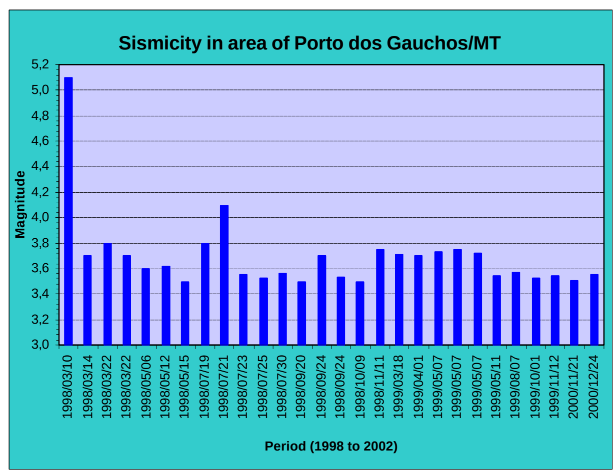

Figure 1 - Aftershock activity in Porto dos Gauchos with magnitude above 3.5, in period from mar/1998 to Dec/2002.

In spite of the uninterrupted monitoring of the Porto dos Gauchos seismic area, the functioning of the stations was very irregular and, therefore, most of the events (1,739) was registered by only one station, according to Figure 2. From the total of the seismos registered, only 120 were well located. Three different location techniques were used: graphic method (triangulation), azimuthal method (three component stations) and interactive method. From all of the located events, only those events with RMS ≤ 0.1, recorded by four or more stations, were selected, which are plotted in Figure 3.

Nº of stations	1	2	3	4	5	6	7	9
Nº of events	1739	279	92	26	24	7	1	1

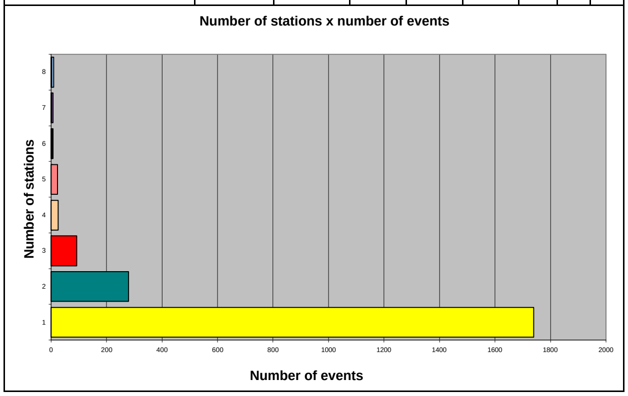

Figure 2 - Demonstrative graphic of number of events registered by one or more stations in period from 03/10/1998 to 12/12/2002.

Seismographic network calibration

The establishing of a velocities model for Porto dos Gauchos was an extremely hard task. Several models were tested and all of them provided satisfactory results in terms of RMS value of the residue. However, it was noted that the resultant location did not establish any trend for the seismicity, as it was expected, presenting a great dispersion in spatial distribution of the epicenters, creating many doubts concerning to the validity of the model. It proves that it is not always that a good fit of the data means that the best solution was found in terms of real-land, just that the solution is optimum for the adopted model. That is why it was necessary to perform the calibration of Porto dos Gauchos Local seismographic Network - PGLSN.

Calibration explosions of the PGLSN

Two calibration explosions were performed, whose location is presented in Figure 3. The first explosion was done on 12/09/2002 at 09:54:02.33h (GMT) and recorded by seven stations (experiment 1), and the second on 12/13/2002, at 01:55:54.28h (GMT), recorded by nine stations (experiment 2). In both cases 200 kg of dynamite were used in 40 m of depth holes, which 10 of them were covered with rubble, in first experiment, and with concrete in the second. Tables 1 and 2 and figures 4 and 5 show, respectively, the data of the explosions and their records by the PGLSN.

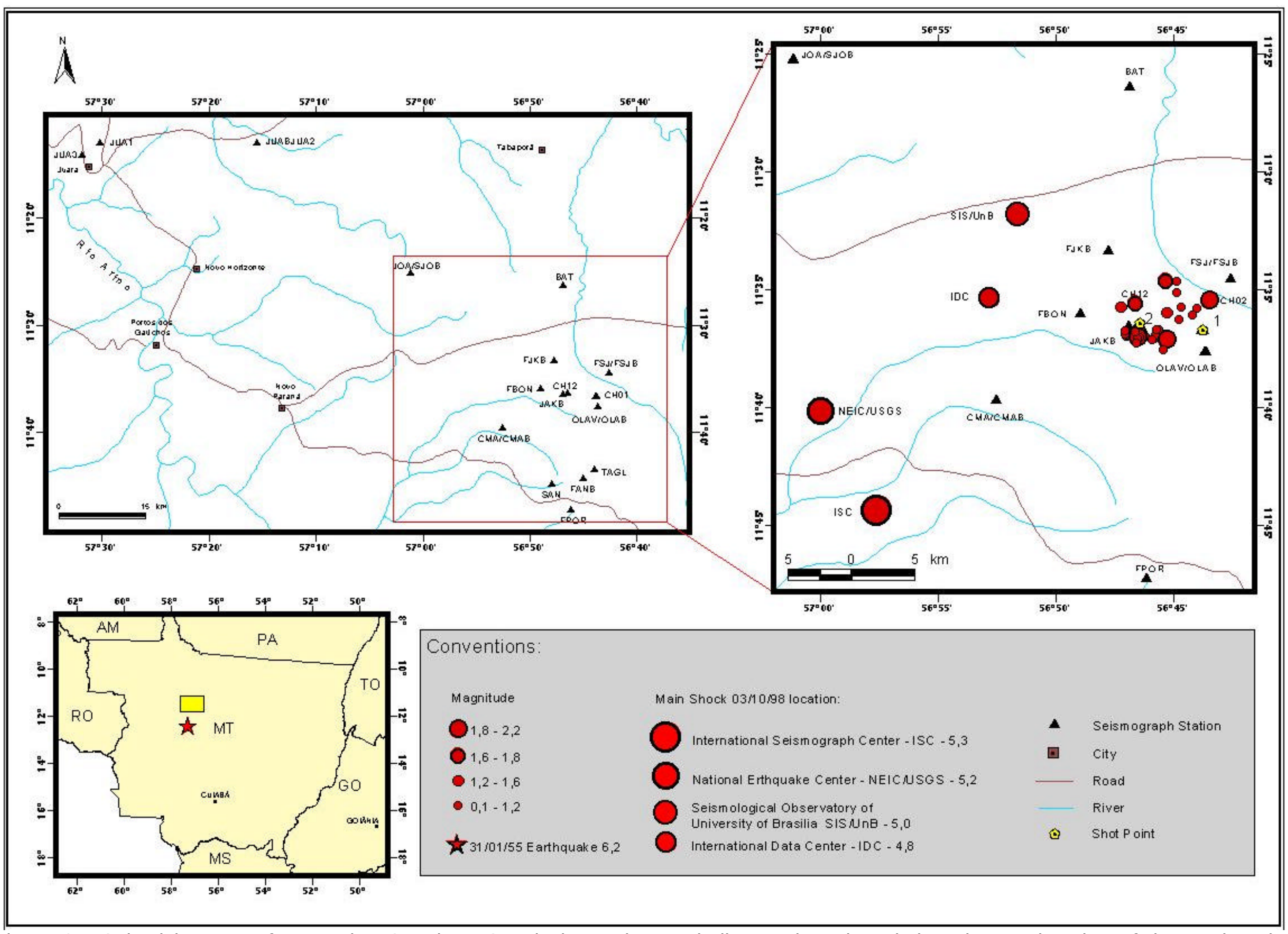

Figure 3 - Seismicity map of Porto dos Gauchos. Star in beneath map indicates the telesseimic epicenter location of the earthquake January/1955. Left map indicates the location of all stations of the Seismographic Network and the right map shows the seismos location, using the 1D model defined in this work and the network used in the experiments. The location of the 10/03, 1998 mainshock by different international agencies are also showed.

Table 1 - Location data of experiment 1 indicating the recorder stations. The distances (in degrees and km) are from the shot point in relation to each station and the azimuth is from the shot point to each station, measured in relation to the North. The first three channels were recorded at 200 sps, at ViSies System; channel 00 is the time code, channel 01 recorded the instant of the explosion (when a wire connected to fuse placed in bottom of hole was broken by the explosion), channel 02 is the recording of the signal detected by a short period vertical seismometer installed at 153 m from the shot point.

Station	Lat (S)	Long (W)	Dist (°)	Dist (km)	Azim (°)	B-Azim (°)	Observation
CH00	ViSeis System clock synchronized by satellite						
CH02	11.61185	56.72932	0,000	0,000	0,000	0,000	Short period 1C
CH01	11,61175	56,72792	0,001	0,153	85,8556	265,856	Shot point
OLAB	11,62700	56,72600	0,015	1,713	167,809	347,808	Broad Band 3C
JAKB	11,60900	56,78100	0,051	5,639	273,166	93,207	Broad Band 3C
FBON	11,60000	56,81500	0,085	9,426	277,976	97,994	Short period 3C
CMA	11,66100	56,87500	0,151	16,774	251,093	71,122	Short period 3C
BAT	11,43900	56,78000	0,179	19,883	343,867	163,877	Short period 3C
SJOB	11,41900	57,05100	0,374	41,587	300,793	120,858	Broad Band 3C

Table 2 - Location data of experiment 2 indicating the recorder stations. The distances (in degrees and km) are of the shot point in relation to each station and the azimuth is from the shot point to each station, measured in relation to the North. The interruption of the signal at the station CH11 (channel 12 of ViSeis System) indicates the exact moment of occurrence of the explosion. Channel 12 (CH12) is the recording of the signal detected by a short period vertical seismometer installed at 36 m from the shot point.

Station	Lat (S)	Long (W)	Dist (°)	Dist (km)	Azim (°)	B-Azim (°)	Observation
CH00	ViSeis System clock synchronized by satellite						200 SPS
CH11	11,60717	56,77383	0,000	0,000	0,000	0,000	Shot point - 200 SPS
CH12	11,60717	56,73350	0,000	0,036	90,000	270,000	Short period 1C - 200SPS
JAKB	11,60900	56,78100	0,007	0,807	255,486	75,487	Broad Band 3C - 100 SPS
FBON	11,60000	56,81500	0,041	4,555	280,013	100,021	Broad Band 3C - 100 SPS
OLAB	11,62700	56,72600	0,051	5,653	112,812	292,803	Broad Band 3C - 100 SPS
FJKB	11,55533	56,79500	0,056	6,175	338,064	158,069	Broad Band 3C - 100 SP
FSJ	11,57500	56,70883	0,071	7,924	53,352	243,339	Short period 3C - 100SPS
CMA	11,66100	56,87500	0,113	12,524	241,634	61,654	Short period 3C - 100SP
BAT	11,43900	56,78000	0,167	18,595	357,927	177,928	Short period 3C - 100SPS
SJOB	11,41900	57,05700	0,335	37,213	303,942	123,998	Broad Band 3C - 100 SPS

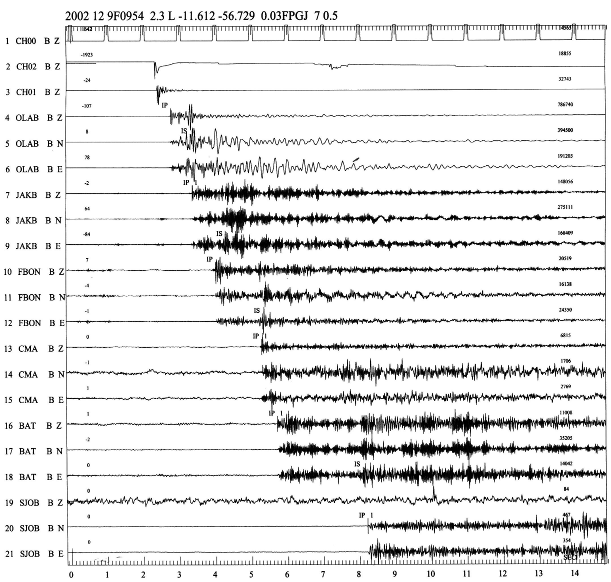

Figure 4 - Record of experiment 1 at the PGLSN stations. Only 15 seconds of signal are showed. In the first three channels are, respectively, the time code (CH00), the instant of the explosion (CH02) and the record of the explosion at 153 m far from the shot point. These channels were recorded in ViSeis System, at 200 sps. The other channels are the N-S, E-W and vertical seismograms, in this order, at the other stations of the Seismographic Network. The interruption of the signal in CH02 channel indicates the exact moment of the explosion.

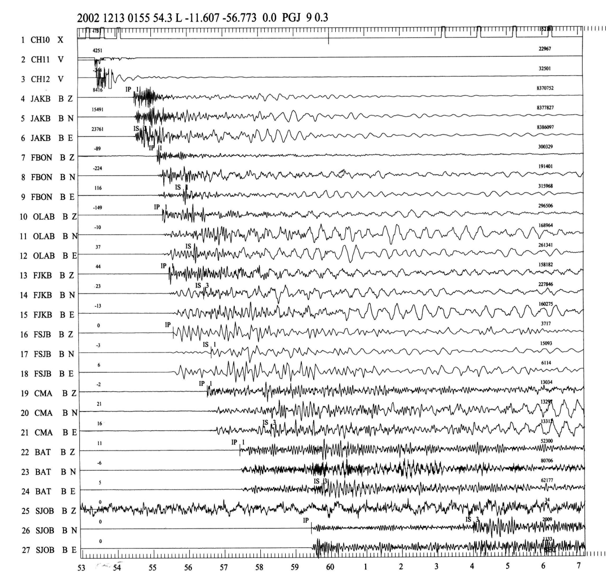

Figure 5 - Record of experiment 2 in the PGLSN. Only 14 seconds of data are showed. At the Station CH11 (channel 2 of the ViSeis System) is indicated the exact instant of occurrence of explosion, rupture moment of the wire connected to fuse cord installed at the bottom of the hole; in the channel 12 (CH12) the record of the explosion detected by a short period vertical seismometer, installed at 36 m far from the shot point.

Acquirement of the 1D velocity model

Analyzing the records of the two explosions, it was possible to extract two important information for the location of Porto dos Gauchos hypocenters; first is the relation between the velocities of the compressional (V_p) and shearing (V_s) waves, i. e, the relation V_p/V_s, and the second is the velocity structure for the area surrounded by the seismographic network. In the first case, the least-square method was used in order to establish, from the arrival time of P and S waves at each station, the ratio V_p/V_s and, in the second, using the seismic ray theory and arising the travel times x distances curves, the velocities of the first layers were derived and the respectives thickness. On the following two sections it will be explained the adopted procedures in two cases.

Determination of V_p/V_s ratio

Using the observational data conjunct, related to the arrival times of the P and S waves at each station of the network (tables 1 and 2), the plot (T_s - T_p) x (T_p) was done (Fig. 6), where T_p and T_s are the travel times of P and S waves phases, respectively.

It can be easily showed that the slope of the straight (T_s - T_p) x (T_p) is equal to [(V_p/V_S)-1], (Barros, 2003). In Figure 6 is shown graphic (T_s - T_p) x (T_p) for all observations together, whose slop is 0,8 ± 0,03. Table 3 shows results for individual plots.

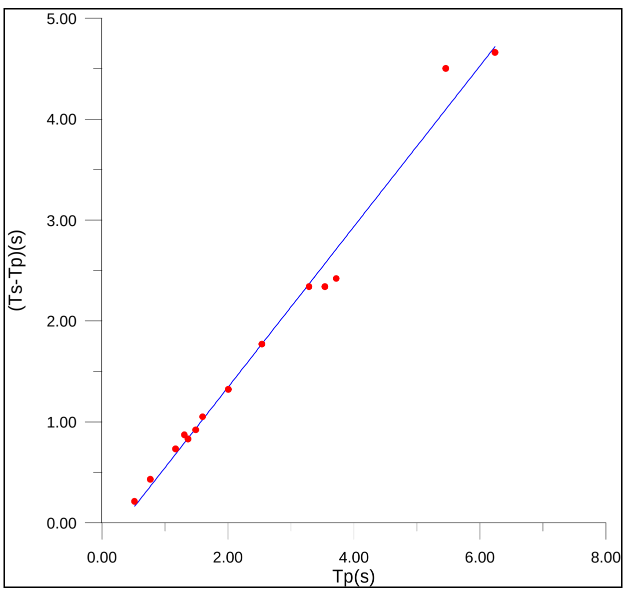

Figure 6 - Wadati Diagram with conjunct data of the two explosions.

Table 3 - Results of the Wadati Diagram for the two explosions (Vp/Vs= 1,81 STD = 0,06 e N=2)

Y	M	D	h:ms	T_o	Stations Quantity	$V_{P/}V_S$	RMS	Curr.
2002	12	09	09:54:02,4	09:54:02,4	6	1,77	0,09	0,997
2002	12	12	01:55:54,3	01:55:54,4	8	1,85	0,12	0,995

The intersection point in Figure 6 of the straight with the axis (T_p) is equal to origin time of explosion (T_0). It occurs because if (T_s - T_p) = 0 the epicentral distance is zero, i. e, we are in epicenter and in this case, T_p is equal to the origin time (T_0).

Testing different values of V_p/V_S ratio to locate the explosions, with V_p/V_S varying between 1.70 and 1.90, it was verified that the best result in terms of RMS values, focus depth and location error, was obtained for V_p/V_S = 1,82.

Determination of the velocity structure

The velocity structure, i. e, the thickness of the layers and the respective compressional P wave velocities can be determined in a geophysical experiment with controlled source by a plot of the distances from the source to the different record stations and their respective travel times. From that graph can be obtained two important informations: the velocity that the P waves travel in each layer and its respective thickness as we can see in the following.

The simplest version of a layered model is that consisting of a layer above an infinite half-space, as showed in Figure 7. The travel time for this case can be determined using simple trigonometric relations.

$$T_r = \frac{\Delta}{V_2} + \frac{2h_1}{V_1}\cos\theta \qquad (1)$$

where T_r is the travel time of a seismic Ray following the ACDB trajectory with V_2 velocity on path CD.

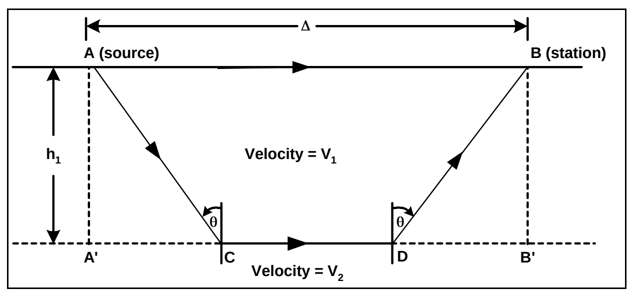

Figure 7 - One homogenous layer above an infinite half-space.

Figure 8 is a plot of travel time x distance for the case of Figure 7, of a thickness of layer h_1 over an infinite half-space.

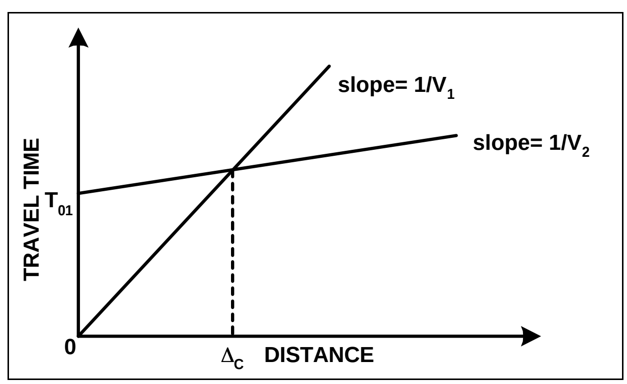

Figure 8 - Travel time x distance curve for case of a layer over an infinite half-space.

The critical distance, Δ_C, of Figure 8 is the shorter distance from the source in which the refracted wave will appear on surface. It is known as *offset*. A receiver placed in a distance shorter than the critical distance will not detect the refracted wave.

In our case, it is more useful to consider the critical distance for refraction, i. é, the distance beyond which there is a refracted arrival. In Figure 7, the minimum refracted path is such that CD = 0. Thus, the critical distance is given by:

$$\xi_1 = 2h_1\tan\theta \qquad (2)$$

The first curve branch corresponds to direct wave, whose slope is $1/v_1$, and the second refers to refracted wave and has a slope of $1/V_2$.

The intersection of that two curves projected on axis X gives the critical distance, i. e, the distance in which the refracted wave is observed before than the direct wave.

For the multiple layer case over an infinite half-space, as Figure 9 shows, the equations for travel time and for critical distance (Lee & Stewart) are:

$$T_k = \frac{\Delta}{v_k} + 2\sum_{i=1}^{k-1} \frac{h_i\left(v_k^2 - v_i^2\right)^{1/2}}{v_i v_k} \qquad (3)$$

$$\xi_k = 2\sum_{i=1}^{k-1} \frac{h_i v_i}{\left(v_k^2 - v_i^2\right)^{1/2}} \qquad (4)$$

The equation (3) shows that the time versus distance relation for a wave refracted along the top of the k^{th} layer has a linear form with slop equal to $1/V_k$. A important information that can be obtained from the travel time curve is the vertical interception points, T_{0i}, although having no sense, it can be used to determine the layers thickness.

$$h_1 = \frac{T_{01} v_2 v_1}{2\sqrt{v_2^2 - v_1^2}} \qquad (5)$$

$$h_2 = \left[T_{02} - \frac{2h_1\sqrt{v_3^2 - v_1^2}}{v_3 v_1}\right] \cdot \frac{v_3 v_2}{2\sqrt{v_3^2 - v_2^2}} \qquad (6)$$

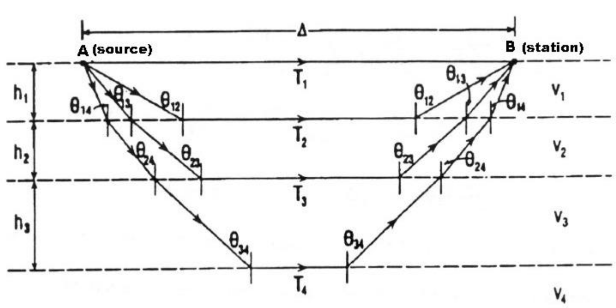

Figure 9 - Multiple layers over an infinite half-space.

Table 4 - Distances and travel times data for P and S waves related to experiment 1, obtained from the seismogram of explosion 1 (Fig. 4).

Station	Distance (km)	Tp (seg)	Ts (seg)	(Ts - Tp) (seg)
CH 01	0,000	0,000	-	Shot point
CH 02	0,153	2,39	-	
OLAB	1,713	2,77	3,20	0,43
JAKB	5,639	3,37	4,20	0,83
FBON	9,426	4,01	5,33	1,32
CMA	16,774	5,29	7,63	2,34
BAT	19,883	5,72	8,14	2,42
SJOB	41,857	8,24	12,90	4,66

Table 5 - Distances and travel times data for P and S waves related to experiment 2, obtained from the seismogram of explosion 2 (Fig. 5).

Station	Distance (km)	Tp (seg)	Ts (seg)	Ts - Tp
CH 11	0,000	-	-	Shot point
CH 12	0,006		-	
JAKB	0,807	54,52	54,73	0,21
FBON	4,5655	55,17	55,90	0,73
OLAB	5,653	55,31	56,18	0,87
FJKB	6,175	55,49	56,41	0,92
FSJB	7,924	55,60	56,65	1,05
CMA	12,524	56,54	58,31	1,77
BAT	18,595	57,44	59,78	2,34
SJOB	37,213	59,46	63,90	4,50

Using the data of tables 4 and 5 and the set of equations, were determined the velocities and the respective thickness of the layers, resulting in the velocity model shown in Table 6.

Table 6 - Resulting velocity model.

Depth	Velocity (km/s)	
	V_p	V_s
0,00	3,88	2,13
0,30	5,93	3,26
2,00	6,20	3,41
15,00	6,78	3,73

Checking the model

The calibration of the seismographic network was performed with controlled sources, i. e, knowing their locations in space and time. The shot points coordinates were determined by a GPS of 30 m accuracy. The origin time of the explosions was measured by inner clock synchronized by GPS of the ViSeis recorder (digital recorder of 24 bits resolution with up to 8 channels), which registered the time code, the explosion instant and the resultant signal detected by a short period vertical seismometer, installed at 153 m (first explosion) and at 36 m (second explosion) from the shot points, respectively.

Knowing the source coordinates, as well as its origin time, you can easily test the model validity; you run the location program, verifying if the obtained results is coherent with their real temporal and spatial locations of the sources (Table 7).

Table 7 - Model validity observational results.

Experiment		Explosion 1	Explosion 2
Source temporal and spatial location	Lat.	-11.61185	-11.60717
	Long	-56.72932	-56.77383
	Depth	33m	40m
	O. T.	09:54:02.33	01:55:53.42
Result of the location program with P wave readings	Lat.	-11.612	-11.607
	Long	-56.729	-56.774
	Depth	1.2km	1.2km
	O. T.	09:54:02.35	01:55:54.28
	error	40m	20m
Result of the location program with P and S wave readings	Lat	-11.609	-11.606
	Long	-56.731	-56.773
	Depth	300m	100m
	O. T.	09:54:02.35	01:55:54.26
	Error	240m	110m

The error indicated in Table 7 is the real error, obtained by plotting on map the explosion epicenters and comparing them to those obtained from the location program. As you can observe (Table 7), the error is bigger in explosion 1 than in explosion 2, it occurred because two stations of the seismographic network (FSJB and FJKB) presented functioning problem at the time of the explosion 1. Unfortunately, the FPOR Station did not operate during the performing of the two explosions.

The program was run, varying the ratio v_p/v_s from 1.70 to 1.90 and the best result was obtained on 1.82.

Station correction

The results of the Table 7 were obtained making station corrections, got from the differences between the residues in each station and the global average of the residues of all stations. It was verified that the application of these corrections improved the location accuracy. For the explosion 1, with P phase reading, the error without correction was 800 m and with readings of the P and S phases the error is 800 m. For the explosion 2, these errors are, respectively, 200 and 500 m.

Conclusions

The realization of two calibration explosions allowed to obtain a good 1D velocity model for the Porto dos Gauchos/MT seismogenic area. The model was tested comparing the obtained results in the Hypocenter location program (running the model) with the real positions of the source and their respective origin time. The best results were obtained with only readings of P phases. It can be explained because the S phases of explosion was not very clear, especially in closer stations.

The obtained model, despite the fact that it has been tested for artificial sources, it is also valid for natural sources, because shot points were located in the area of the most of epicenters and were registered, among others, by OLAB, FSJB, FJKB, CMA and BAT stations, which have recorded most of natural events.

It was noted that locations using station corrections improved too much the accuracy of the location, correcting structural anomalies present in path of the seismic rays.

Acknowledgments

The authors express their most sincere gratefulness to all those people that contributed to the accomplishment of this paper, especially those that contributed with their job during the execution of the services related to the two calibration experiments: Darlan P. Fontenele, Reny C. Macedo, Daniel L. da Silva and Antonio E. Neves and the staff from SDF-Serviços de Desmonte e Furação de Rocha Ltda ME, José O. da S Lucas and Ronan F. Lemos Filho. Finally, we would like to thanks Pedro F. de Andrade, Kate T. de Sousa, Zilá das G. O. Rodrigues for the electronic edition and maps preparations.

This study has been supported by the Seismological Observatory of the University of Brasilia.

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