Revista Brasileira de Geofísica
RBGf
Brazilian Journal of Geophysics

Revista Brasileira de Geofísica (2006) 24(1): 81-89

ISSN 0102-261X
www.scielo.br/rbg

COMPARATIVE TESTS OF SEISMIC SOURCES AND GEOPHONES AIMING AT SHALLOW REFLECTION SEISMIC INVESTIGATION IN URBAN AREAS

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Recebido em 24 outubro, 2005 / Aceito em 23 fevereiro, 2006
Received on October 24, 2005 / Accepted on February 23, 2006

ABSTRACT. Pseudo walkaway noise tests were accomplished in study area in São Paulo city, Brazil, in order to evaluate the potentiality of seismic reflection technique in shallow geological/geotechnical investigation in urban environment, where there is usually the presence of different types as well as intensities of noises and the paved surface. Data acquisition was conducted with a 24 channel seismograph with 24 bit A/D converter, 28 Hz and 100 Hz geophones, as well as sledge hammer and seismic rifle as sources. The best results were obtained with: (i) 100 Hz geophones with 0.18 m spike and hammer source with steel plate; (ii) 100 Hz geophones coupled through clay on asphaltic coverage with hammer source applied on asphalt. Laboratory tests were also accomplished in shake table in order to evaluate geophone responses when they were coupled with different types of clay. Tests indicated clay employment is a good alternative to couple geophones, notwithstanding kaolinitic clays are less indicated.

Keywords: seismic reflection, seismic sources, shallow geophysics, geophones, seismic in São Paulo city.

RESUMO. Visando avaliar a potencialidade do emprego da sísmica de reflexão na investigação geológico-geotécnica rasa em ambientes urbanos, nos quais normalmente há a presença de ruídos de diferentes tipos e intensidades, assim como de superfícies pavimentadas, foram realizados diversos ensaios de análise de ruídos (*pseudo walkaway noise test*) em uma área teste na cidade de São Paulo, Brasil. Na aquisição dos dados foram empregados um sismógrafo de 24 canais com conversor A/D de 24 bit, geofones de 28 Hz e 100 Hz e fontes sísmicas do tipo marreta e rifle sísmico. Os melhores resultados foram obtidos com: (i) geofones de 100 Hz com ponteira de 0,18 m e fonte marreta com placa de metal; (ii) geofones de 100 Hz acoplados através de argila na cobertura asfáltica com fonte marreta aplicada sobre asfalto. Também foram realizados ensaios de laboratório em mesa vibratória para avaliar as respostas dos geofones quando acoplados com diferentes tipos de argila. Os testes indicaram que o emprego de argilas é uma boa alternativa para acoplar os geofones, sendo as argilas cauliníticas as menos indicadas.

Palavras-chave: sísmica de reflexão rasa, geofones, fontes sísmicas, geologia da cidade de São Paulo.

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INTRODUCTION

Since the 1990s in great Brazilian urban centres, an expressive increase of civil works focused in infrastructure needs is happening, and, following a worldwide tendency, they have been concentrated in underground infrastructure and facilities such as road tunnels, overflow retention reservoirs, pipelines, power lines, etc.

Aiming at elaborating design-build projects and executing the previously mentioned works a good geological knowledge is necessary such as spatial distribution of geological strata and thicknesses, as well as recognition and positioning of geological structures.

In this context, shallow seismic reflection presents a great application potential, once it allows mapping structures continuously, interpolating subsurface geological information obtained from drilling at discrete locations (Hunter et al., 1984; Jeng, 1995; Steeples & Miller, 1990).

However, urban environment presents several aspects that damage or hamper the acquisition as well as the analysis of seismic data, as restricted operation space and altered superficial strata (earth embankments and asphaltic coverage), likewise background noise associated to power lines and shake noise from the traffic.

Those factors are contributed so that seismic reflection does not be considered yet an effective investigative method for building practitioners in Brazilian urban centres. (Prado et al., 2001).

In order to investigate the accuracy and potentiality of shallow seismic reflection method in the described conditions, several pseudo walkaway noise tests were accomplished in a densely occupied area of São Paulo city. Another assay was also accomplished as comparative tests in controlled laboratory conditions for evaluating the spectral content of seismic signal by using clay in geophone coupling.

Results of acquisition, carried out with different types of geophones and sources, as well coupling conditions are presented.

We discuss the results of comparative tests among geophones of different frequencies and plant in soils and on asphaltic coverage through spikes and clay. Geophone responses obtained from tests in shake table are also discussed.

LOCATION AND GEOLOGICAL CONTEXT OF STUDY AREA

The study area is located in Western São Paulo city, in the left margin of Pinheiros River (Figure 1). The choice of this place was conditioned by several factors: i) existence of geological information from nearby boreholes; ii) possibility to do simultaneous acquisition on asphaltic coverage and soil; iii) to be placed in a typical urban space, with heavy traffic of vehicles and people.

The geology of this area consists of tertiary sediments of Itaquaquecetuba Formation from São Paulo Sedimentary Basin, which settles on Precambrian basement. PP1 well description located close the acquisition area provides the following information about main lithofacies: (1) sands until 25 m depth; (2) conglomerate from 25 m to 35m; (3) sands from 35 m to 52 m; (4) clays from 52 m to 80 m; (5) granite-gneisse basement.

METHODOLOGY

Initially, 1D geological model was obtained, analysing information from PP1 well (Figure 2a); synthetic seismograms were generated from this model by using Triseis algorithm of Seismic Unix software (Stockwell & Cohen, 1998) in order to estimate the reflection travel time from the interfaces (Figure 2b).

Following, several pseudo walkaway tests were executed. The tests were made using 28 Hz and 100 Hz geophones, both coupled to soil with spikes of 0.1 m and 0.18 m length, and fixed with clay in paved area (Figures 3a, 3b). On soil, two types of sources were used: (1) 12-caliber rifle (Figure 3d), fired in holes of approximately 0.4 m deep; (2) sledge hammer of 6 Kg (Figure 3c) impacted on steel plate. Hammer was used on pavement with impacts on plate and directly on asphalt. Table 1 presents parameters and geometry employed in these tests.

Table 1 – Pseudo walkaway tests acquisition parameters.

Number of chanels	24
Minimum offset	0,5 m
Maximum offset	72 m
Receiver spacing	0,5
Geophone type	28 Hz and 100 Hz
Source type	12-caliber rifle and Sledgehammer - 6 Kg
Coupling	Spike (0,10 m and 0,18 m), Kaolinitic clay
Sample rate	0,25 ms
Recording time	200 ms
Pre A/D low cut filter	3 Hz

The main objective of these field tests was to compare responses of different geophones, in different coupling situations and with wave generation of several seismic sources, and starting from this study finding to establish equipment and ideal parameters to improve the quality and resolution of shallow seismic reflection.

The comparative study was based on the analysis of amplitude spectra obtained by different test conditions, as well as on final results of seismogram processing.

Since these first results, a second field test was carried out aiming at checking previous results in a more controlled envi-

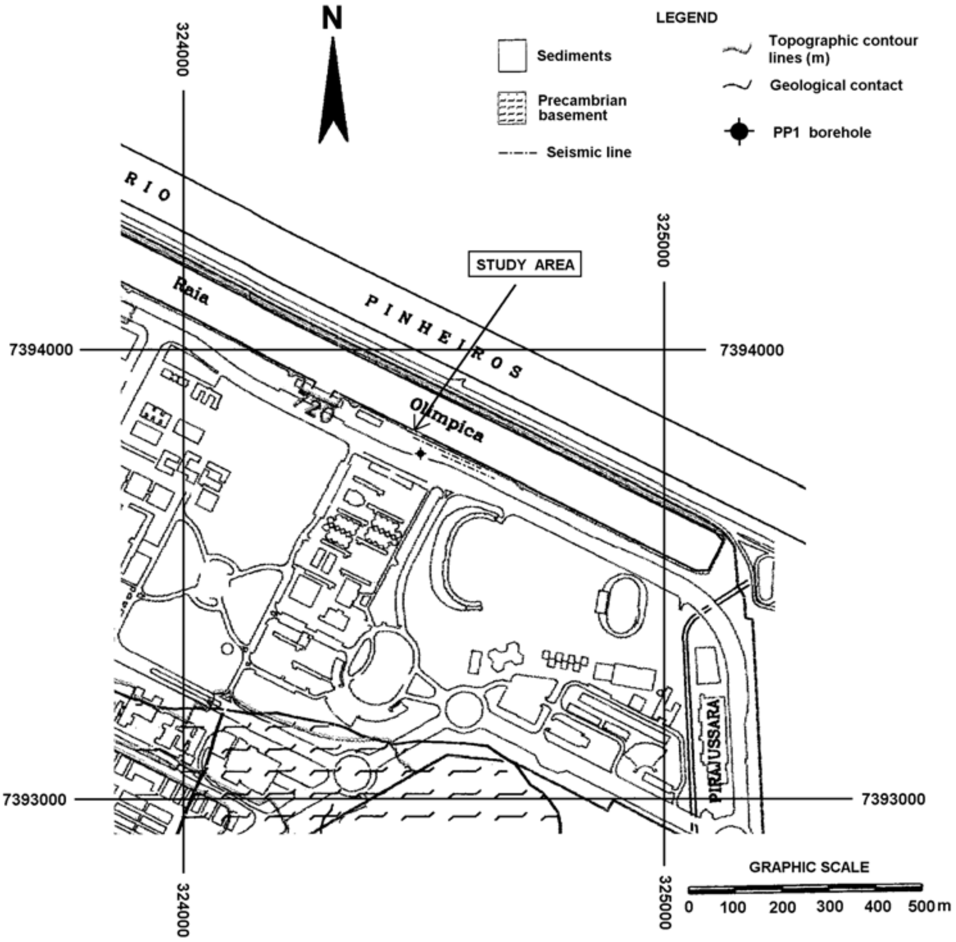

Figure 1 – Site map showing seismic test line, wells and local geology (adapted from Iritani, 1993).

ronment in which geophone parameters (frequency and coupling) were tested simultaneously by the same energy generation. For that, a walkaway test was made with five parallel linear arrays, with 0.4 m equidistant one each other, and 4 geophones each one (1 m spacing). All arrays were connected to the same seismic cable and acquisition system. New records were acquired with variations of sources, geophones and coupling, concurrently, with minimum offsets of 20, 40 and 60 meters (Figure 4).

Besides field tests, tests with geophones were also done under controlled laboratory conditions, in order to evaluate their responses using different clay mineral for coupling.

The experiment (Figure 5) was constituted by APS Dynamics Inc shake table (APS Electro-six model) positioned at a massive block of concrete, Entelbra audio generator (ETB511 model), APS Dynamics Inc Power Amplifier signal amplifier (124 model), OYO seismograph (DAS-1 model), Tectronix oscilloscope (TDS220 model), four 100 Hz geophones, and three different clay samples (Table 2). A tray, specifically projected for this experiment, was fixed to shake table. This tray allowed fixing rigidly one of the four geophones, along with reproducing a similar surface of paved area via small rugosities (Figure 6).

Laboratory tests were executed as following: i) firstly, 4 geophones were rigidly fixed to the table, and simultaneously submitted to the same shake signal to attest the equivalence among their responses (Figure 6a); ii) subsequently one of them was used as reference for an ideal coupling (rigidly fixed to the table), and the other ones coupled with three different clay samples (Table 2). 02-geophone was coupled by using 01-Sample; 03-geophone by using 02-Sample; and 04-geophone, 03-Sample (Figure 6b); iii) The shake table was submitted to a sinusoidal excitation with a frequency bandwidth from 80 Hz up to 120 Hz (in 5 Hz steps), characteristic of shallow seismic field test previously got done;

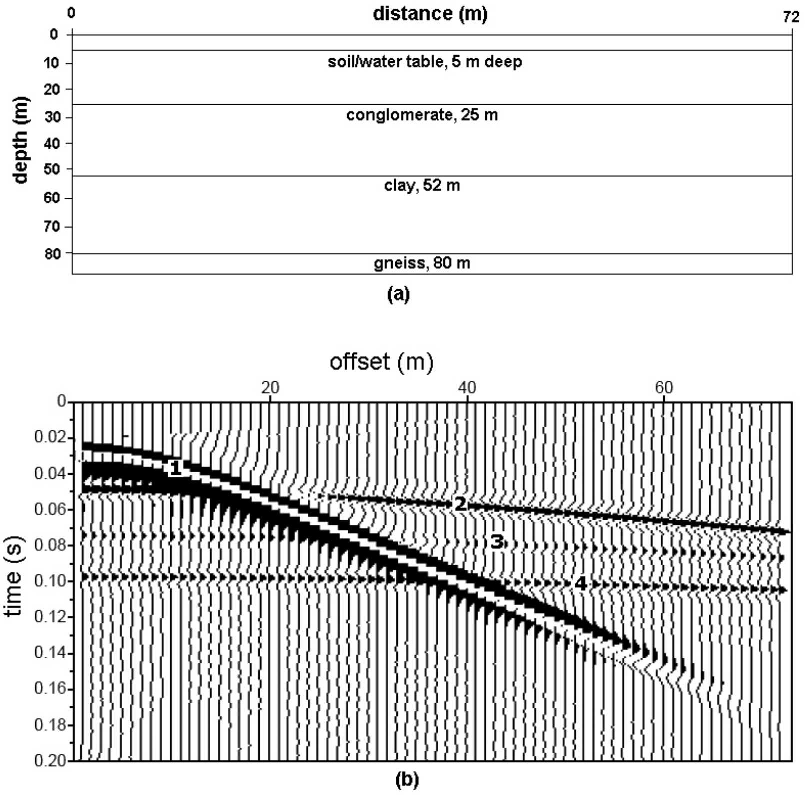

Figure 2 – (a) Geological model generated from PP1 log; (b) synthetic seismogram generated from the geological model. Event 1: interface soil/water table, 5 m of depth, V_{int} = 0.4 km/s (interval velocity); event 2: top of conglomerate, 25 m of depth, V_{int} = 1.7 km/s; event 3: top of clay, 52 m of depth, V_{int} = 2.1 km/s; event 4: basement, 80 m of depth, V_{int} = 2.4 km/s.

iv) simultaneous records were made with oscilloscope and seismograph.

The same clay samples were submitted to mineralogical analysis by X-Ray difratometry (Table 2). Results indicated the clay from 01-Sample was predominantly kaolinitic (90-95%) differently to the two other ones that contained a considerable amount of smectite and illite (up to 55%).

Table 2 – Mineralogical Analysis of clay samples originated from X rays difratometry.

Sample	Clay mineral	Semiquantification (%)
Sample 01	Kaolinite	90 – 95
	Illite	3 – 5
	Smectite	< 2
Sample 02	Kaolinite	50
	Smectite	35 – 40
	Illite	10 – 15
Sample 03	Kaolinite	60 – 65
	Illite	20 – 25
	Smectite	< 15

An analysis was also made to establish the moisture content of these samples. The moisture content was determined as the rate between water weight and dry solid material weight expressed in percentage. Results are presented in Table 3. It is possible to observe the found contents were relatively similar, although the largest value (24%) was associated to more kaolinitic sample (01-Sample).

Table 3 – Moisture content of clay samples.

Sample	Moisture content (%)
Sample 01	24,64
Sample 02	19,25
Sample 03	23,30

RESULTS

After the acquisition of first *in situ* data, the initial processing had as objective to identify the reflections in the seismograms and to compare them with synthetic seismograms generated since information from PP1 well.

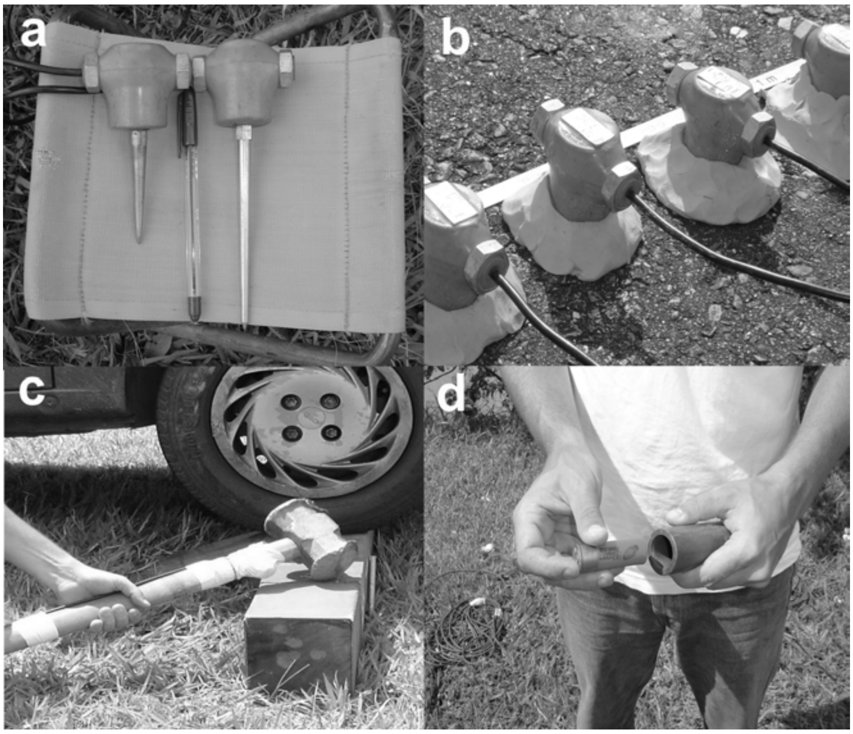

Figure 3 – (a) Geophones with spikes of 0.1m and 0.18m (b) geophones coupled through clay; (c) sledge hammer of 6 Kg; (d) 12' seismic rifle.

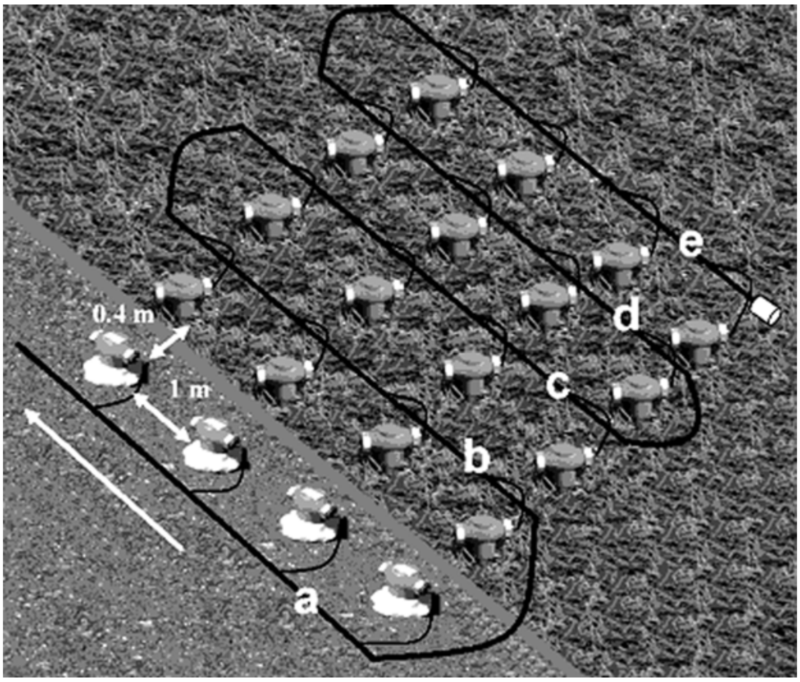

Figure 4 – Outline illustrating the type of array used in the second comparative field test: (a) 100 Hz geophones coupled through clay; (b) 100 Hz geophones with spike of 0.18 m; (c) 100 Hz geophones with spike of 0.1 m; (d) 28 Hz geophones with spike of 0.18 m; (e) 28 Hz geophones with spike of 0.1m.

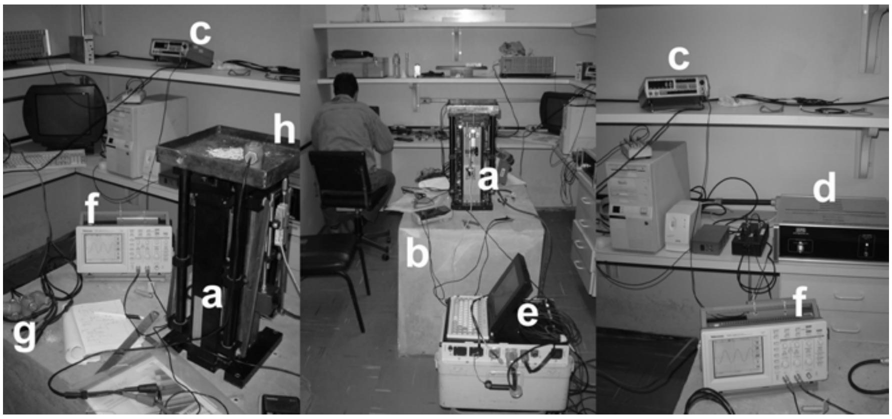

Figure 5 – Design of shake table test: (a) APS Dynamics Inc. shake table (APS Electro-six model); (b) massive block of concrete; (c) Entelbra audio generator (ETB511 Model); (d) APS Dynamics Inc. Power Amplifier signal amplifier (124 model); (e) OYO-1 seismograph; (f) Tectronix oscilloscope (TDS220 Model); (g) four 100 Hz geophones; (h) geophone "tray".

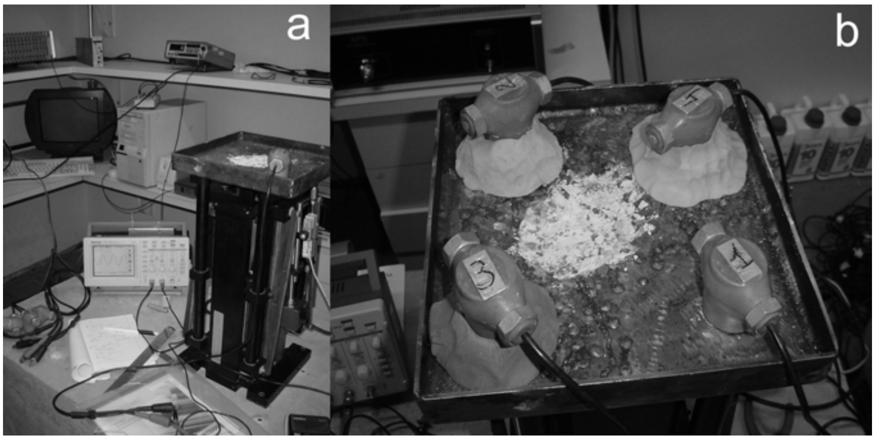

Figure 6 – (a) Geophone rigidly fixed to table and submitted to shake signal; (b) 01-geophone used as reference of an ideal coupling (rigidly fixed to the table), and the other ones coupled with 3 different clay samples. 02-geophone coupled by using 01-Sample, 03-geophone by using 02-Sample, and 04-geophone by using 03-Sample.

Processing challenge was to preserve the high frequency contents and to enhance shallow reflections from "noisy" events such as direct wave, refractions, ground roll, and airwave.

Initially passband frequency filters were applied. Several bandwidth and different slopes were tested, with no satisfactory results to an increase in signal/ noise ratio.

F-k filter was applied in order to eliminate events associated to ground roll and airwave, taking care to extend the fan reject zone to spectrum part associated to spatial aliasing of airwave.

Finally, applying an AGC gain, final seismogram was obtained, presenting three evident reflection events in 50 milliseconds, relative to the top of conglomerate; 75 ms, associated to the top of clay; and 100 ms, related to the basement (Figure 7).

Figure 8 presents responses of four geophones that were fixed to the shake table and simultaneously submitted to an input signal programmed by audio generator. As suggested by data, all responses are equivalent. It can be also observed in Figure 8b – generated from oscilloscope measurements – and in Figure 8c – generated from traces recorded in seismograph – 01-geophone, with ideal coupling, has a frequency distribution similar to three geophones coupled to different clays. However, the record obtained with 02-geophone (red line), coupled predominantly with kaolinitic clay (01-Sample), presents a decrease of energy.

CONCLUSIONS

Comparative analysis of all seismograms from walkaway tests after processing, showed the best results were obtained with:

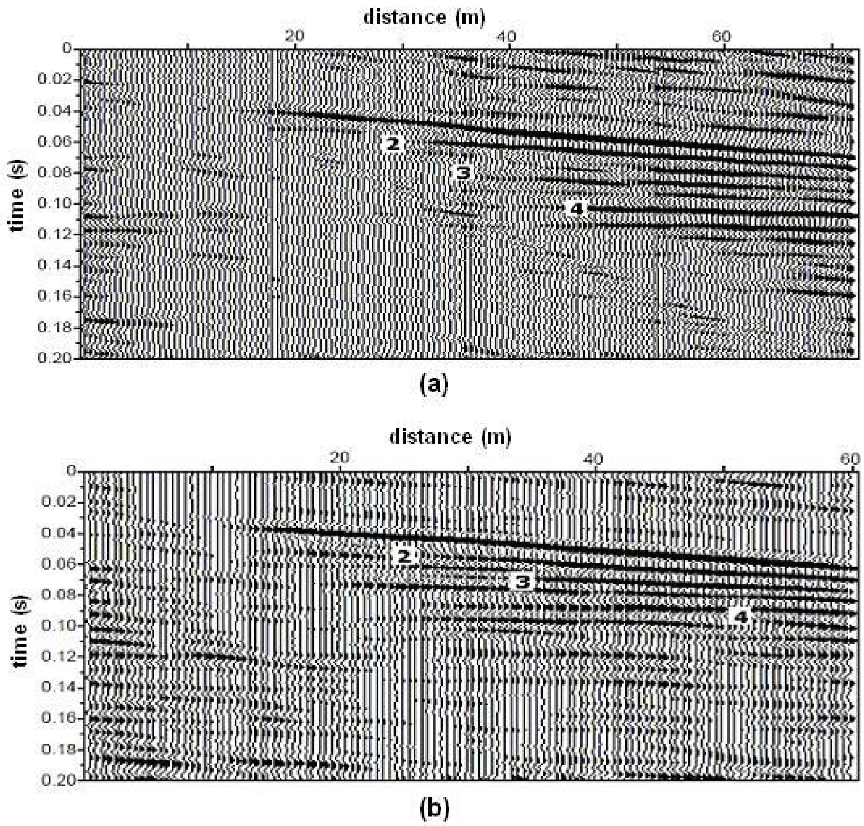

Figure 7 – (a) Seismogram recorded with 100 Hz geophones coupled through spikes of 0.18 m on soil by using sledge hammer impacted on steel plate; (b) record obtained with 100 Hz geophones coupled through clay on asphaltic pavement by using hammer impacted on steel plate. The events interpreted starting from the analysis of synthetic seismogram generated since the description of PP1 well (Figure 2). Event 2: top of conglomerate, 25 m of depth, V_{int} = 1.7 km/s; event 3: top of clay, 52 m of depth, V_{int} = 2.1 km/s; event 4: basement, 90 m of depth, V_{int} = 2.4 km/s.

(i) 100 Hz geophones with spike of 0.18 m, and hammer source with steel plate; (ii) 100 Hz geophones coupled through clay on asphaltic coverage with hammer source applied on asphalt.

Analyses of amplitude spectra for the second field experiment indicated: (1) increase of length spike (from 0.10 m to 0.18 m) did not improve the signal/ noise ratio (Figure 9a); (2) 100 Hz geophones coupled through clay on pavement achieved an equivalent result to geophones coupled with spikes on soil, since their amplitude spectra were analogous (Figure 9c); (3) 100 Hz geophone had its higher energy response in band of frequencies from 30 Hz up to 120 Hz, differently to 28 Hz geophone that showed an accentuated fall in its spectrum of approximately 20 db between predominant frequency ($\sim$20 Hz), and the highest frequencies ($>$ 60 Hz), which explains the worst quality of acquired data by using 28 Hz geophones (Figure 9b); (4) results obtained with hammer applied on pavement and in plate on pavement were equivalent to those ones obtained with hammer applied in plate on soil (Figure 9c); (5) data obtained from laboratory tests suggest that clay is a good alternative to couple geophones, notwithstanding kaolinitic clays are not the most appropriate. According to Souza-Santos (1989) clay mineral from kaolinitic group with 30-60% of moisture content passes to liquid state (liquidity limit), differently, for example, of clay mineral of smectite group that remains in plastic state even when moisture content is near or higher than 60%. It can be conclude although the three samples (particularly 01-Sample and 03-Sample) have presented similar moisture content (Table 3), predominantly kaolinitic clay (90-95% – 01-Sample) had an inferior performance (larger attenuation of induced energy) at the moment of the tests due to its mechanical properties. Obviously, it is necessary to observe other samples with different clay mineral contents in order to obtain an embracing conclusion.

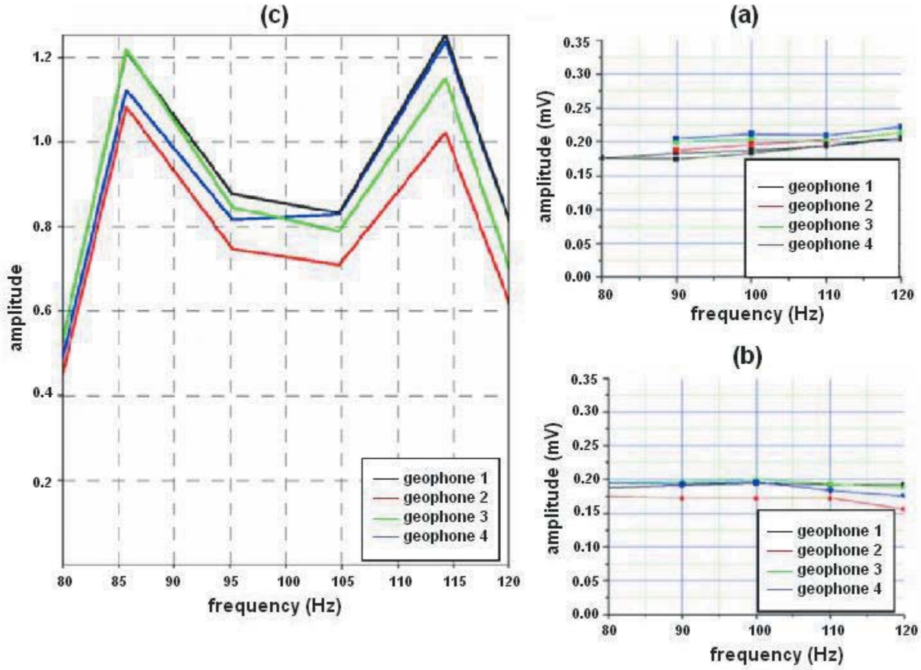

Figure 8 – Spectra obtained from records in comparative experimental tests in laboratory: a) responses of 01, 02, 03, 04-geophones rigidly fixed to table, and simultaneously submitted to the same shake signal; b) responses of 02, 03, 04-geophones coupled through clay, and of 01-geophone with ideal coupling measured directly in oscilloscope; c) responses of 02, 03, 04-geophones coupled through clay, and of 01-geophone with ideal coupling recorded in seismograph.

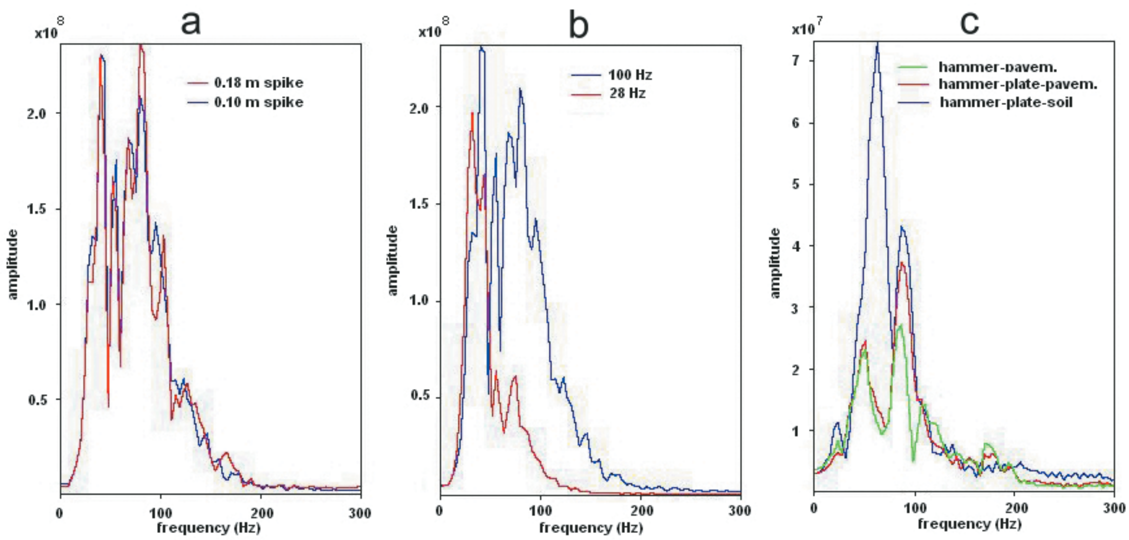

Figure 9 – Spectra of field records obtained with different types of geophones, sources and coupling conditions: (a) 100 Hz geophones with spike of 0.18 m and 0.1 m, sledge hammer source; (b) 100 Hz (10 impacts) and 28Hz (1 impact) geophones, hammer impacted on steel plate; (c) 100 Hz geophones coupled with spike of 0.18 m, and hammer impacted on steel plate (blue), and coupled through clay on pavement with impact directly on pavement (green), and on steel plate (red).

ACKNOWLEDGMENTS

The authors would like to thanks CNPq (Conselho Nacional de Pesquisa, Brasil). We are also grateful for comments from two anonymous reviewers that helped clarify the manuscript.

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