Local soil conditions and earthquake damage in the town of Aiquile - Bolivia

Donniez géotechniques et dégâts matériaux causés par un séisme dans la ville d'Aiquile - Bolivie

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ABSTRACT: This paper presents an evaluation of the seismic response of soil deposits in the town of Aiquile (Bolivia), during the earthquake of May 1998, which registered a magnitude of 6.8 in the Richter scale. In-situ tests including electrical resistivity, standard penetration (SPT) and the spectral analysis of surface waves (SASW) were performed after the earthquake. A provisional microzonation map of the area is proposed.

RÉSUMÉ: Cet article présente des analyses de mesures sismiques dans les sols de la ville d'Aiquile (Bolivie) prises lors du tremblement de terre de mai 1998, le quel a enrégistré a niveau de 6.8 dans l'échelle de Richter. Les résultats d'essais de pénétration standard (SPT), résistivité et propagation d'ondes superficielles (SASW) exécutés apnées le séisme sont aussi présentés. Une carte provisoire de répartition en zones est proposée.

1 INTRODUCTION

The present article describes briefly the work carried out for the development of a microzonation map for the town of Aiquile.

The earthquake caused significant destruction, 86 people were killed. To be precise, about 520 constructions from a total of 1130 suffered major damage and had to be rebuilt.

Several tests were performed in the area such as the standard penetration (SPT), electrical resistivity test, spectral analysis of surface waves (SASW) and the classification of all soil samples collected.

Seismic microzonation is actually a multidisciplinary work involving branches of applied science such as engineering geology, seismology and geotechnical engineering. However, due to the lack of appropriate information, emphasis is placed upon geotechnical issues.

2 EARTHQUAKE AND STRUCTURAL DAMAGE

2.1 *Earthquake characteristics*

An earthquake with a magnitude $M_S = 6.8$ stroke the town of Aiquile on May 1998.

An intensity of VII on the MMI scale, a distance to the epicenter of 60 km and a focal depth of around 13 km were reported by the San Calixto observatory.

Table 1 shows some seismic records near the area of study. One may notice that earthquakes of considerable magnitude have been periodically taking place. The area can be classified as seismically active.

Table 1. Last seismic events in the area.

Date	Magnitude*
October, 1925	5.2
September, 1958	5.9
February, 1976	5.2
May, 1998	6.8

* Cabre et al. (1989)

2.2 *Earthquake damage*

The town of Aiquile was conformed in general by low rise constructions (up to 3 levels).

The quality of construction varying from poor, in the outer areas, to good, in the center.

Just after the earthquake a field inspection was carried out by a team of San Simon University with the aim of evaluating the level of damage.

The results are summarized in figure 1. It clearly shows a regular pattern of damage distribution.

The darkest zone reflects the most affected area, houses totally destroyed, surrounded by a less damaged belt and even farther the damage was minor or unnoticeable (yet the construction quality was mainly poor).

Figure 1. Actual structural damage pattern (DISU, UMSS)

3 GEOTECHNICAL INVESTIGATION

3.1 *Field testing*

The objectives of the geotechnical characterization were to identify the soils present and to estimate the shear wave velocity.

The standard penetration test and the electrical resistivity were useful to outline the stratigraphy.

The SASW, a non-destructive method, was employed to estimate shear wave velocity (V_S) profiles. Sixteen tests were performed at points spread all over the area of study (Fig. 3).

The general configuration of the SASW test is shown in figure 2. Surface waves are generated by applying a dynamic load at the ground surface. The propagation of the surface waves generated is monitored by two receivers or geophones.

The impact of a hammer was used here as source. A symmetrical arrangement was adopted (e.g. the distance from the source to the near receiver is equal to the distance between receivers).

The receivers, Mark L-4A with natural frequency of 1 Hz., were placed consecutively at spaces of 0.5, 1, 2, 4, 8 and 16m. For each spacing, 3 or more signal outputs were averaged from the left and from the right side.

A dynamic signal analyzer, HP 35670A, was used to record the motions at the receivers and finally, the data was transferred to a computer for further interpretation.

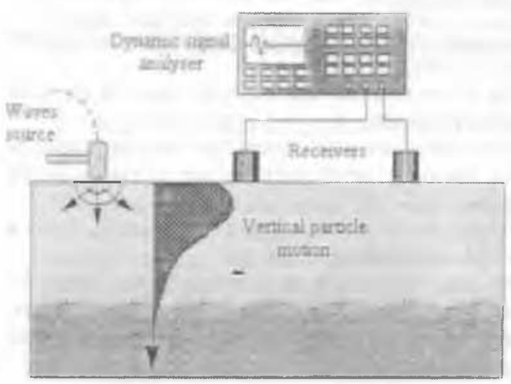

Figure 2. SASW field test configuration

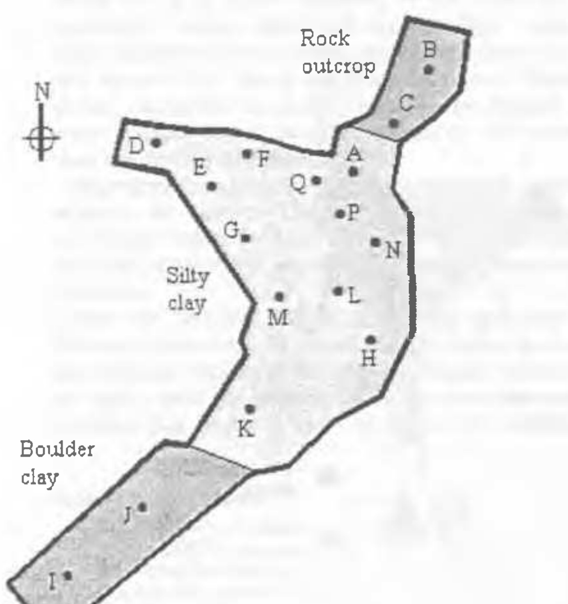

Figure 3. SASW tests location and Geotechnical characterization

Table 2. Average shear wave velocity in-situ

Testing line	Shear wave Velocity [m/s]	Testing line	Shear wave velocity [m/s]
A	200.7	I	992.4
B	1210.5	J	528.1
C	942.1	K	348.8
D	267.7	L	404.2
E	248.7	M	345.4
F	349.5	N	279.8
G	171.2	P	160.8
H	413.3	Q	157.2

3.2 *Geotechnical characterization*

The area was subdivided into three zones according to the subsoil conditions.

Figure 3 describes the geotechnical characterization of the area an the location of the SASW tests. Moreover, table 2 summarizes the average shear wave velocities estimated for each testing point.

To the north, a rock outcrop was found. The measured shear wave velocities (V_S) reach values over 1000 m/s. Samples could not be extracted due to the hardness of the material.

In the center of the town the subsoil corresponds to a clayey and silty clayey deposit of soil, with variable and undetermined maximum depth. The shear wave velocity (V_S) varies from 160 to 400 m/s. Table 3 shows the physical indexes of soil samples extracted and figure 4 shows a typical profile.

Finally, to the south, a stiff and deep deposit of boulder clay was identified. The shear wave velocities ranging from 400 to 1000 m/s. Again, sampling was impossible.

The geotechnical characterization of the area of study shows that the subsoil varies considerably over a relatively small extension.

This founding was encouraging to believe that the influence of the peculiar subsoil stratigraphy played an important role on the development of damage.

Table 3. Physical soil indexes

Parameter	Range of values
Liquid limit	22.9 – 48.0
Plastic limit	14.5 – 23.3
Plasticity indexes	6.0 – 27.7

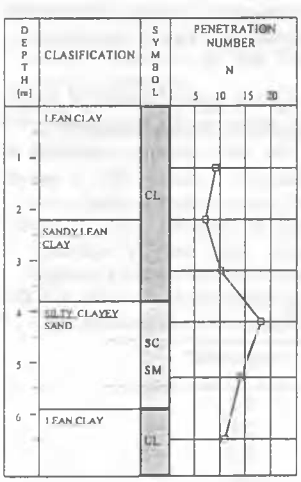

Figure 4. Typical soil profile in the most affected area

4 RELATIVE AMPLIFICATION FACTOR

As no more data were known, a simplified procedure was adopted. Equation 1 (Midorikawa, 1987), included in the Manual for Zonation (TC4, 1999), allows the estimation of the relative amplification factor (A) from the shear wave velocity (V_S) expressed in [m/s].

$$A = 68 \cdot V_S^{-0.6} \tag{1}$$

The relative amplification factor is a measure of the susceptibility of a soil deposit to amplify ground motion.

Although this factor not only depends on the shear wave velocity, investigations based on the observation and analysis of ground motion have revealed that the average shear wave velocity of surface soils show strong correlation with the relative amplification.

The results of this evaluation are summarized in figure 5. It shows the spatial distribution of the A-values. The amplification factors range from 1, where V_S is maximum, to 3, where V_S is minimum.

The susceptibility distribution from SASW measurements in figure 5 shows good agreement with the actual structural damage distribution (Fig. 1).

One should be aware that figure 5 clearly relates to information directly linked to the soil conditions, while figure 1 implements both soil conditions and structural vulnerability.

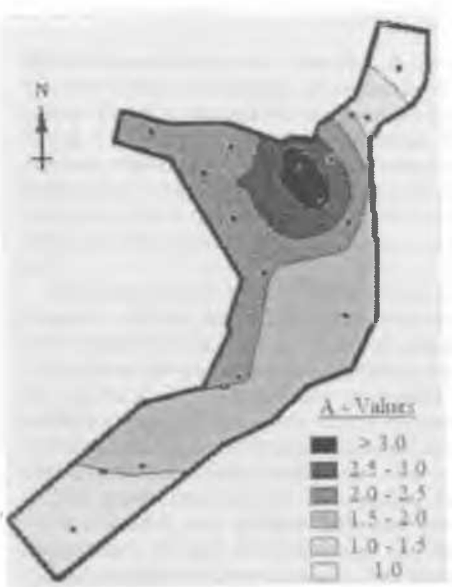

Figure 5. Relative amplification factors in Aiquile

5 CORRELATION N_{SPT} - V_S

In addition, a comparative analysis was carried out aiming at selecting an appropriate correlation between the shear wave velocity (V_S) and the penetration number (N_{SPT}).

The simplest general form is given by equation 2 where C and D are constants.

$$V_S = C \cdot N_{SPT}^{\ D} \tag{2}$$

There are several of such correlations in literature. Three of them were chosen: Imai & Tonouchi, 1982; Ohba & Trauma, 1970; Ohsaki & Iwasaki, 1973. They can be used for any type of soil.

Table 4. Coefficients equation 2

Parameter	C	D
Ohba & Trauma (1970)	84.0	0.31
Ohsaki & Iwasaki (1973)	81.4	0.34
Imai & Tonouchi (1983)	97.0	0.314

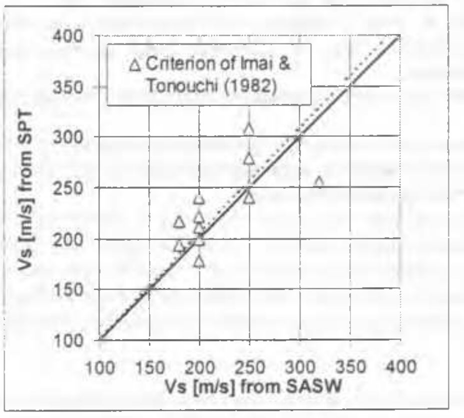

Figure 6. Comparison between V_S correlated from N_{SPT} and V_S obtained from SASW test.

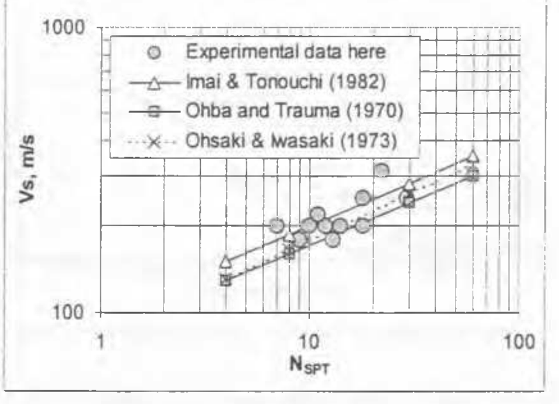

Figure 7. Shear wave velocity (SASW) vs. N_{SPT}

Table 4 shows the values of C and D (equation 2) according to its author and figures 6 and 7 show the results of the analysis.

Although few data useful for comparison is available, it was possible to state some conclusions.

According to our data, the correlation following the Imai et al. (1982) criterion provides the closest values to the V_S measured by the SASW technique, while the other correlations tend to underestimate V_S, especially Ohba & Trauma (1970).

That fact would allow the employment of Imai et al. (1982) criterion on Bolivian soils. It is a very useful tool to rapidly asses the shear wave velocity since the standard penetration test is commonly practiced for site investigation in Bolivia.

6 SUMMARY AND CONCLUSIONS

The influence of local soil conditions played a predominant role in the response of the soil deposits in the town of Aiquile.

Although limitations on the testing equipment available reduced the extent of the work, the results obtained were useful for preliminary planning purposes in the reconstruction phase of the town.

The data correlation making use of the Imai & Tonouchi (1982) criterion was shown to be suitable in estimating the shear wave velocity of Bolivian soils from N_{SPT}.

7 REFERENCES

Cabré R. & Vega A. 1989. Sismicidad en Bolivia. *San Calixto observatory press. No.40. In spanish*

Crespellani, Ghinelly & Vannucchi 1989. An evaluation of the dynamic shear modulus of a cohesive deposit near Florence, Italy. *Proc. XII Intern. Conference on SMFE, Rio de Janeiro.*

Haegeman, W. & Van Impe, W.F. 1995. Developments in SASW testing. *Proc. 11th European Conf. on SMFE, Copenhagen. Vol.1*

Imai, T., Tonouchi, K. 1982. Correlation of N value with S-wave velocity and shear modulus. *Proc. 2nd European Symp. on Penetration Testing. Amsterdam.*

Kramer, S.L. 1996. *Geotechnical earthquake engineering.* Prentice Hall, USA.

Technical Committee for earthquake geotechnical engineering TC4. 1999. Manual for zonation on seismic geotechnical hazards (Revised version).*Japanese Geotechnical Society.*