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INSTRUMENTATION OF A SANDY/MANGROVE SITE FOR PREDICTION OF SEISMIC LIQUEFACTION

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ABSTRACT

A site of border-coast sediment material presenting a high risk of seismic liquefaction has been instrumented in the Guadeloupe Island (French Antilles) close to the Caribean subduction zone. The project included extensive in-situ geotechnical and geophysical surveys (drilling boreholes and laboratory testing on sample, SASW, H/V seismic noise ratio survey, seismic piezocone), pore pressure measurements and accelerometric ground motion sensors combined with numerical analysis. The particular soil profile consists in an upper sandy/silty layer subjected to liquefaction overlaying a mangrove type clayey soil with very low penetration resistance, rather common in tropical coastal areas. This paper presents first the results of the seismopiezocone tests performed on the site, including dissipation tests and downhole measurements of shear wave velocities. An analysis of the risk of liquefaction using the combined data of tip resistance, friction ratio, excess pore pressure and Vs is discussed. In a second part, the instrumentation of the site is presented. It includes a vertical array composed of three synchronized triaxial accelerometers (Episensor) placed at GL-0m, GL-15m and GL-39m, where GL means "ground level", and five pore pressure sensors installed at different depths in the potentially liquefying zone. The safety factors deduced from excess pore pressure measured during the 2010 moderate earthquake M= 4.8 are compared to the prediction by classical methods. Finally the seismic response of the soil column is analyzed, with a special attention to the role of the mangrove layer.

Keywords: Seismic liquefaction, Seismocone, Accelerometers, Pore pressure, H/V survey

INTRODUCTION

The validation of the numerous existing methods for prediction of seismic liquefaction implies their implementation on fully instrumented sites, with a particular attention in pore pressure sensors installed in the potentially liquefying layers. Many methods for predicting liquefaction have been developed, using either laboratory undrained cyclic triaxial or shear tests, with all the shortcomings due to difficulties in sampling in liquefiable, i.e loose to medium sands or in-situ tests results, SPT, CPT, CPTU, shear wave velocities. On another hand, a large development has been devoted in numerical modelling using sophisticated models taking into account the most important mechanisms governing liquefaction. But both practical and numerical methods need to be validated and improved by a recollection of field data, which can only be achieved from highly instrumented sites. Such sites have already been developped in Japan

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(Ishihara 1987), California (Zeghal and El Gamal 1994), Greece (Pitilakis et al., 1999), Canada (Hofman et al 1996), among others. The metropolitan French territory is not highly seismic, but the new Eurocodes imply to take into account the risk of liquefaction for moderate earthquakes in most of Civil Engineering projects. Within the framework of the Belle Plaine French National research project (ANR- 06-CATT-003), a site known as potentially liquefiable was instrumented in the Guadeloupe Island (French Antilles). This area is subject to frequent moderate earthquakes and sometimes high magnitude earthquakes, and more data can be expected to be recollected. In addition, the particular soil profile consists in an upper sandy/silty layer subjected to liquefaction overlaying a mangrove type clayey soil with very low penetration resistance, rather common in tropical coastal areas, and the response of such typical case is also interesting to analyze.

The project included first an extensive in-situ geotechnical and geophysical surveys (drilling boreholes and laboratory testing on samples, SASW, H/V seismic noise ratio survey, seismic piezocone CPTU, pressuremeter). The site was instrumented by an array pore pressure measurements and accelerometric ground motion sensors. Finally other partners of the project are involved in numerical modelling of the site response and numerical prediction of liquefaction with several computing codes.

This paper presents the field tests and the site instrumentation implemented by two of the partners of the project: Laboratoire 3S-R for the geotechnical part, and LGIT for the geophysical part, both from the University of Grenoble and on behalf of the French Accelerometric Network (RAP) at the origin of this project. Some classical method of liquefaction prediction from in-situ tests are compared to the seismic data and excess pore pressure measured during a moderate earthquake M=4.8 occurred in May 2010.

BELLE PLAINE SITE INVESTIGATION

Site description

The "Belle Plaine" investigated area lies on the southern coast of the Grande-Terre Island of Guadeloupe, close to the Caribean subduction zone. It is a border-coast site in the city of Gosier, surrounded by mangrove vegetation. The upper-layers velocity model is known from the synthesis of borehole drillings and downhole seismic piezocone penetrometer presented hereafter. After a shallow 1 m-thick layer with S-wave velocity β1 of 200 m/s, it consists of a 4 m-thick stiff sandy layer (β2=470 m/s) overlaying a soft mangrove layer (33 m thick) with S-wave velocity of 220 m/s. The bedrock lies at GL-38m and it is made of reef coral limestone in which no S-wave velocity information are available.

CPTU tests

Laboratoire 3S-R carried out 5 cone penetration tests with additional pore pressure measurements (CPTU) using its own seismocone. As the aim of these tests was to quantify the properties of the superficial liquefiable layer, only the first 14m were investigated. A pre-boring hole was done in order to install the tip with its pore pressure sensor under the level of the water table, around 1.7m. Cone penetrometer was pushed into the ground with constant velocity of approximately 2cm/s, with a continuous registration of the cone resistance qc, sleeve friction fs . The pore pressure u_2 was measured throughout the penetration and measurements were made behind the cone. A dissipation test was performed each meter, when adding a new rod. A correction was applied to the cone resistance to take into account the effect of the pore pressure sensor and a net cone resistance qt was used in the interpretation. The results of the five penetration tests were remarkably similar, showing a good homogeneity of the stratigraphy of the site.

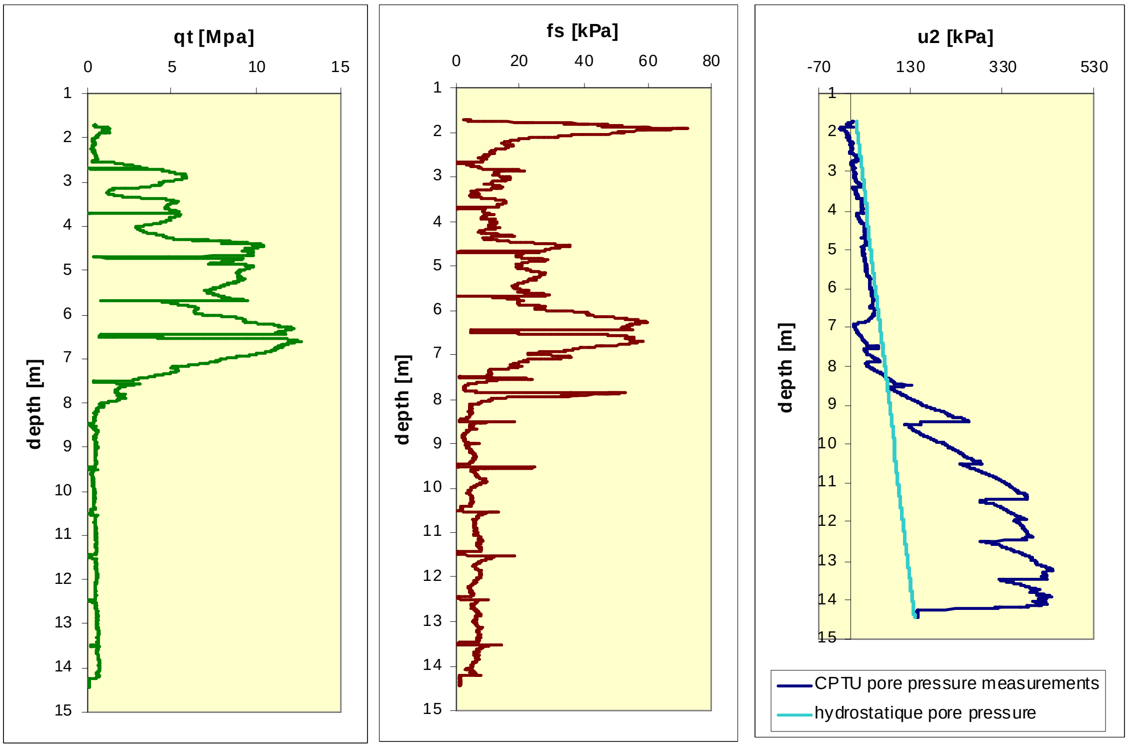

Figure 1. CPTU measurements: cone resistance (qt), sleeve friction (fs), pore pressure (u2)

A typical CPTU profile within the Belle Plaine is shown in Figure 1. An identification of the soil layers has been obtained using the normalized tip resistance $Q = (qt - \sigma_v)/\sigma'_v$, friction ratio *FR*, and pore pressure factor $Bq = \Delta u/(qt-\sigma_v)$. The dissipation tests performed each meter give an indication of the horizontal permeability of the soil and can be correlated to the fine content. All the data confirmed the identification of the layers obtained from the borings and gave quantitative information on the mechanical properties of the potentially liquefiable sandy layer.
CPTU data and dissipation test results were used for soil classification and stratigraphy interpretation of the *Belle Plaine* soil profile. Resulting soil profile is summarized below:

- 0m - 1.9m: An artificial layer of compacted gravel/fill with high strength properties.
- 1.9m – 2.5m: Peat layer
- 2.5m - 3.5m: Transition between the peat horizon and the under laying sand.
- 3.5m - 7.5m: A layer of very fine mid-dense sand with a tip resistance between 4 and 12 MPa
- 7.5m - 8.5m: Transition between the sand and clay horizon.
- 8.5m - 14.6m: Clay layer with possible presence of clay lenses with sensitive nature. The tip resistance of this “mangrove” layer is low, around 0.5 to 1 MPa. The borings have shown an extension of this layer up to the rock substratum at a depth of 38m.

Shear wave velocities from seismocone tests

During each change of rods of, every meter, down-hole tests were performed hammering a plate at the top of the soil surface at a distance of 1.1m from the rod axis, and measuring the arrival time of the waves on the three geophones behind the cone tip. The interpretation was performed through the direct method and the interval method (de Nichilo 2009). A typical profile of the shear wave velocities Vs is shown on

Figure 2. As measurements are made only each meter, the discretization of Vs is not as accurate as for qc. Nevertheless the same tendency as for qc is observed : the Vs profile identifies an upper layer with values of Vs in the order of 400-500m/s and a lower soft layer with Vs in the order of 200 m/s and an interface between the two layers at a depth of 7-8 m. These values are in agreement with the CPT identification and the usual correlations between qc and Vs for sands and clays.

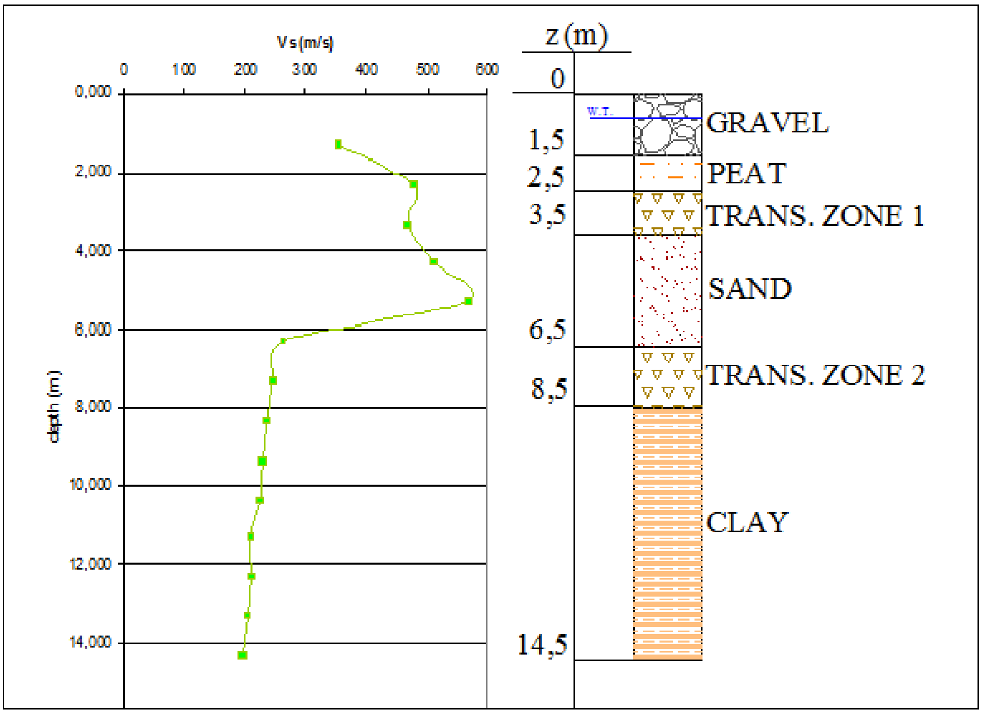

Figure 2: Vs profile from seismocone tests

H/V spectral ratio using noise

In the context of this study, an extended survey of seismic noise measurements for noise spectral ratio method (HVSRN) was carried out in the Belleplaine site. In practice, the HVSRN experiment consists in recording seismic noise with a 3-D velocimeter placed on the ground and connected to a CityShark^{TM} station, a user-friendly digital acquisition system designed for noise measurement (Chatelin et al., 2000). The station was connected to a 3C Lennartz 5-second sensor with a flat velocity response between 0.2 and 50 Hz. The seismic noise data were acquired and processed according to the recommendations outlined in the deliverables of the SESAME European project (D23.12, 2005). The description of the method is given in Guéguen et al. (2007).

Among the 30 points recorded on a regular 5 m x 5 m mesh distributed over the Belleplaine site. The main goal of the HVSRN survey was first to identify the seismic site response and second to control the lateral variability of the site amplification. Figure 3 shows the high stability of the HVSRN method on the site, within a very close distance. The fundamental resonance frequency is 1.3 Hz, the same value as that obtained from earthquake data collected in the borehole (see after). The peak is clearly shown that let us assume a strong impedance contrast in depth generating high amplification and no highest amplification are observed above the fundamental frequency of the site. Using the oversimplified relationship for estimating the 1D fundamental frequency of the site F_o=Vs/4H, for H=38m we obtain Vs close to 200m/s, i.e. a very soft average shear wave velocity conform to the shear wave velocity of the mud/clay materials.

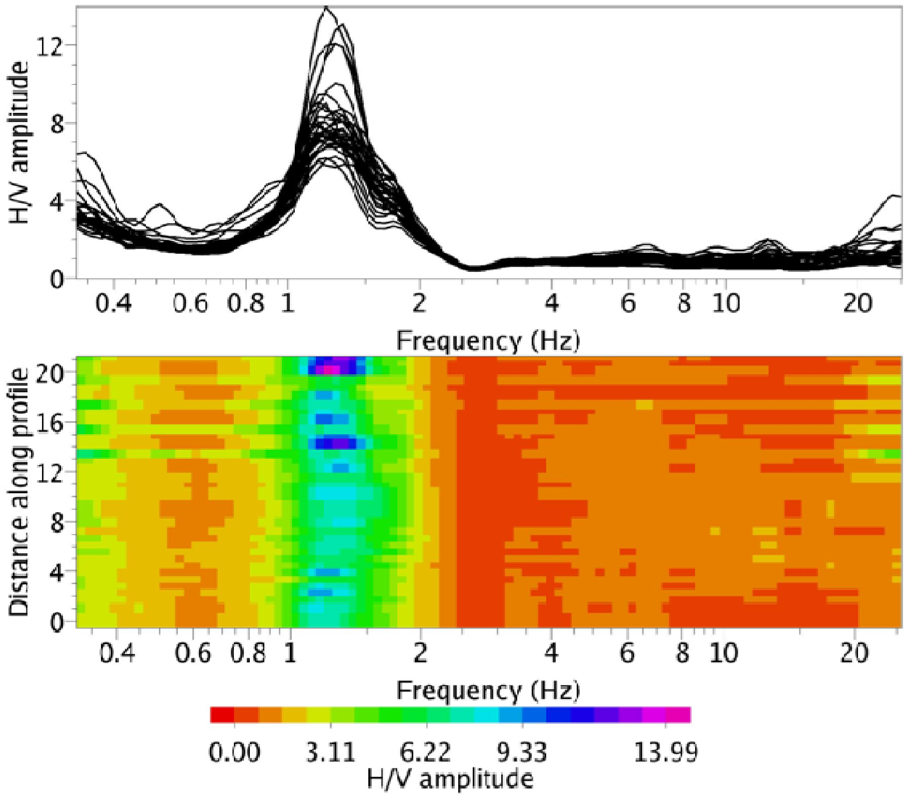

Figure 3 : Synthesis of the HVSRN curves performed in the Belleplaine test.

Liquefaction prediction for strong earthquake

A first analysis of the results of the field tests was performed to evaluate the liquefaction potential of the site under a strong earthquake, M=7, a_{max} = 0.5g. Seed and Robertson methods were used to analyse the CPTU results and Andrus and Stokoe method was applied to the shear wave velocity profile. Figure 4 shows the safety factors calculated from the two CPT methods. They put into evidence the risk of liquefaction of a large part of the sandy layer, except the zone where high values of qc had been recorded, and of the upper and lower transition zones, from peat to sand and from sand to mangrove. The methods could not be applied to the mangrove, as it was classified as clay and had values of the Ic factor, taking into account the fine content, much higher than 3.

The method of Andrus and Stokoe indicates no risk of liquefaction for the whole layer. This is due to the lack of precision in the Vs data, as measurements were performed only each meter.

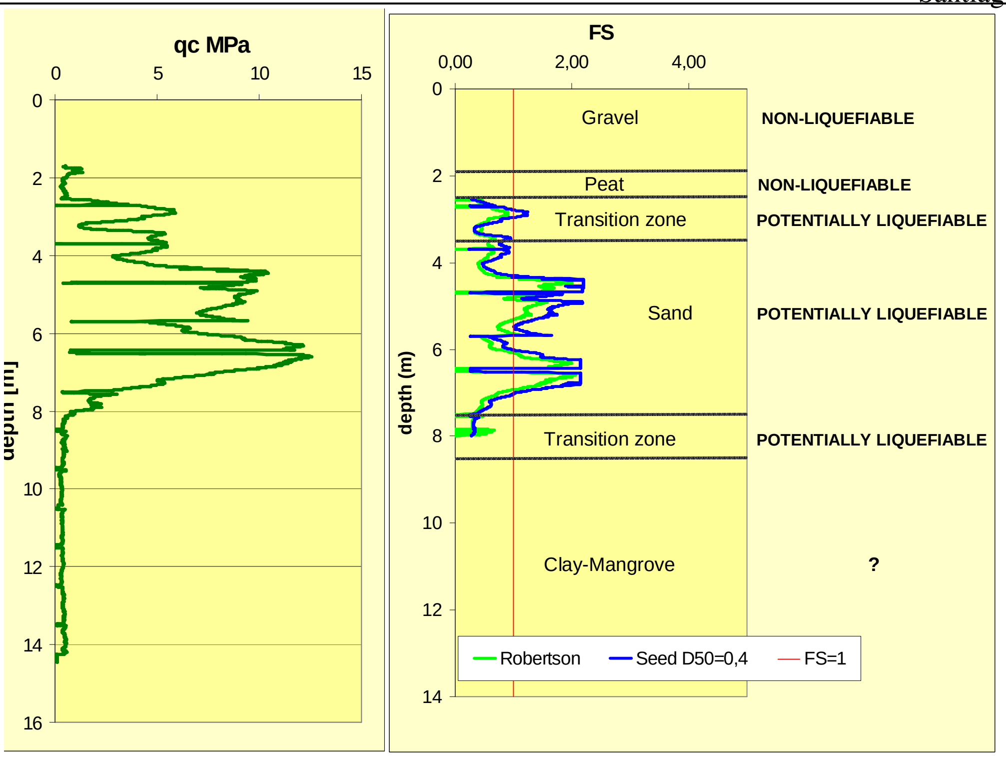

Figure 4 : Analysis of liquefaction for strong earthquake

MONITORING OF THE SITE

Acceleration monitoring

The vertical array is composed of three synchronized triaxial accelerometers (Episensor) placed at GL-0m, GL-15m and GL-39 m, where GL means "ground level" hereafter identified as LIQH, LIQM and LIQB, respectively. The LIQM sensor is located within the mangrove layer, 10 m below the mangrove/sand inter- face and LIQB immediately under the mangrove/bedrock interface. All the channels of acquisition are connected to the same 24 bytes A/D device, the recordings are at 125 Hz of sampling rate and in the continuous recording mode. All the data are real-time transmitted through internet connection to the French Accelerometric Network National Data Center (RAP-NDC, Pequegnat et al., 2008). A set of data have been recorded since the beginning of the test site (Figure 5). We observe the amplification effect of the seismic ground motion between the bottom (LIQB) and the top and intermediate depth (LIQH and LIQM respectively). This amplification is produced by the soft buried layer of mangrove. Nevertheless, we observe a low amplification effect between LIQH and LIQM, having the same peak ground acceleration value, which confirms that the amplification is essentially produced by the buried mangrove.

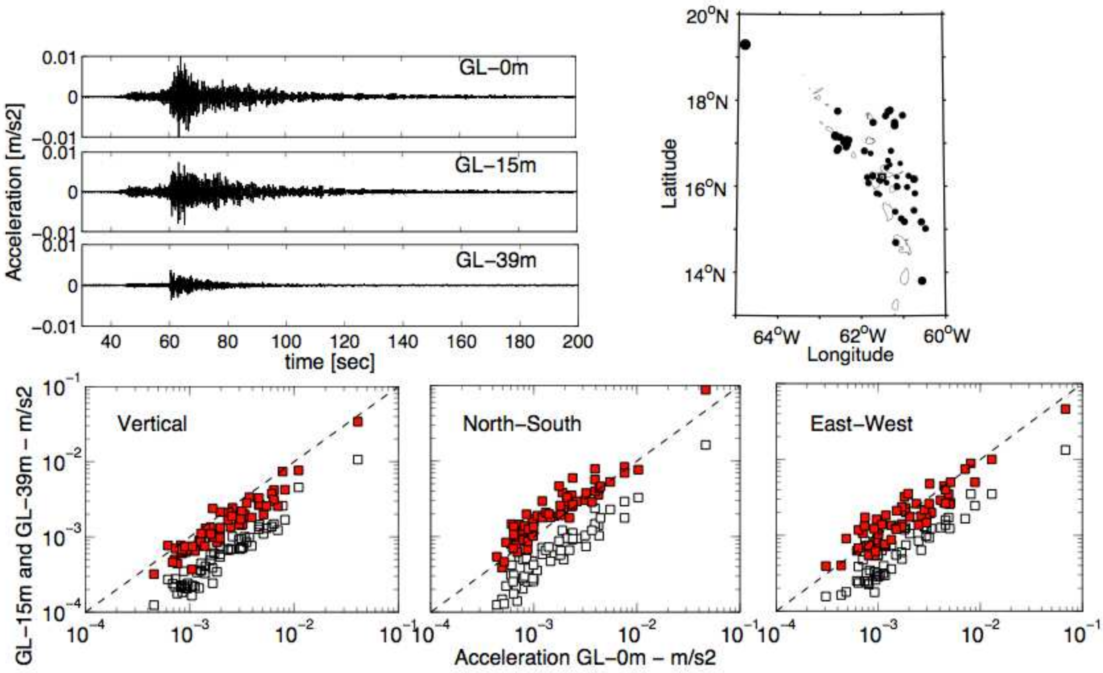

Figure 5 : Example of the seismic ground motion (East-West component) recorded at the LIQH (GL-0m), LIQGM (GL-15m) qnd LIQB (GL-39m) sensors and localisation of the epicenters of events recorded at the Belleplaine site. The row below shows the Peak Ground Acceleration PGA value between LIQH and LIQH or LIQM for the three components (red: LIQM versus LIQH; white: LIQB versus LIQH)

Pore pressure monitoring

A total of five pore pressure sensors were installed on the site, during the period 2008-2009. Four of them were installed at different depths in the layer offering the highest risk of liquefaction: PZ1 at 3.8 m, PZ2 at 5.2 m, PZ3 at 6.3 m and PZ4 at 7.5 m in the lower transition zone. In a second step, considering the high interest in following the seismic response of the mangrove layer, a fifth sensor PZ5 was installed at 10.5 m. Each pore pressure monitoring system consisted in a FGPXPM10-A1 sensor mounted inside the tip of an equivalent CPT cone with a porous stone, as shown on Figure 6. The sensitivity and capacity of the sensors were adjusted to the highest values expected for the pore pressure. Pore pressure sensors are connected to the same A/D 24bytes acquisition system, sampled at the same frequency as the accelerometers and then all the signals (pore pressure and accelerometers) are perfectly synchronized.
After a careful saturation of the sensor with de-aired water, the tip was connected to a set of rod with a standard 36mm diameter and was installed to the given depth in the same way as a penetration test. Dissipation tests were also performed when adding new rods.
The position of the pore pressure sensors with respect to the borings SC1 and SC2 where the accelerometers are installed is presented on Figure 7, and Figure 8 indicates the depths at which the pore pressure sensors were installed, in comparison with the tip resistance profile of the CPT.

Figure 6: Pore pressure sensors mounted in CPT rods

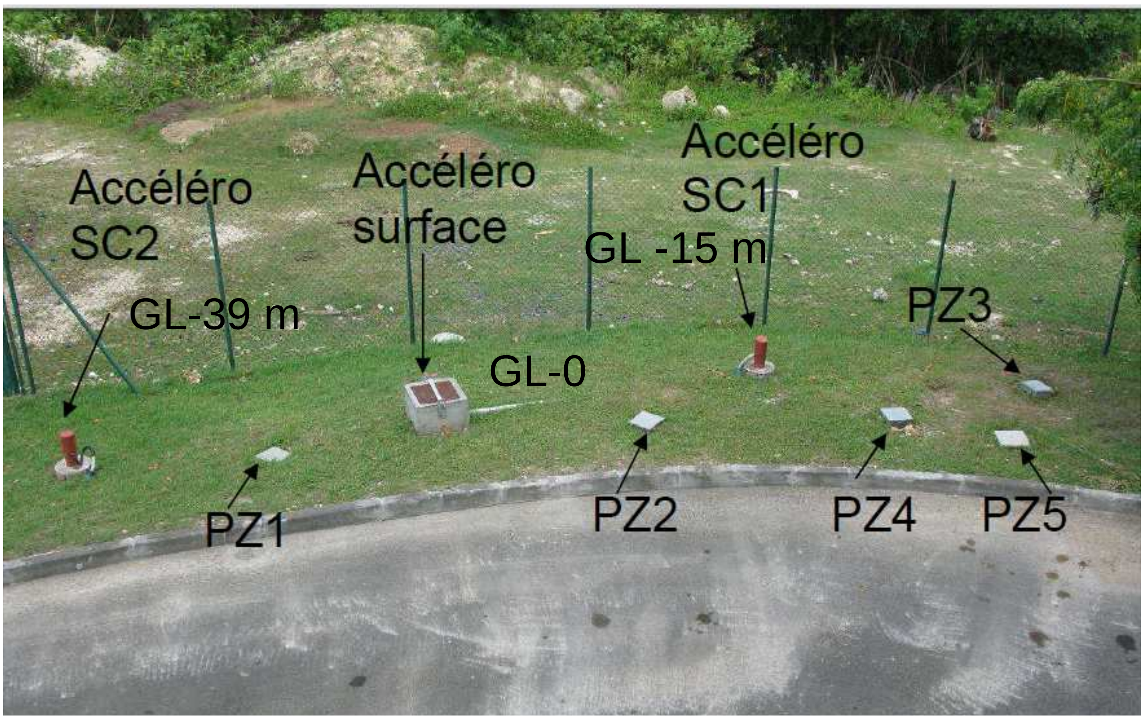

Figure 7 : Photo of the Belle Plaine site, showing the two borings SC1 and SC2, the surface accelerometer and the position of the pore pressure sensors. The Cone Penetration Tests were performed behind the fence

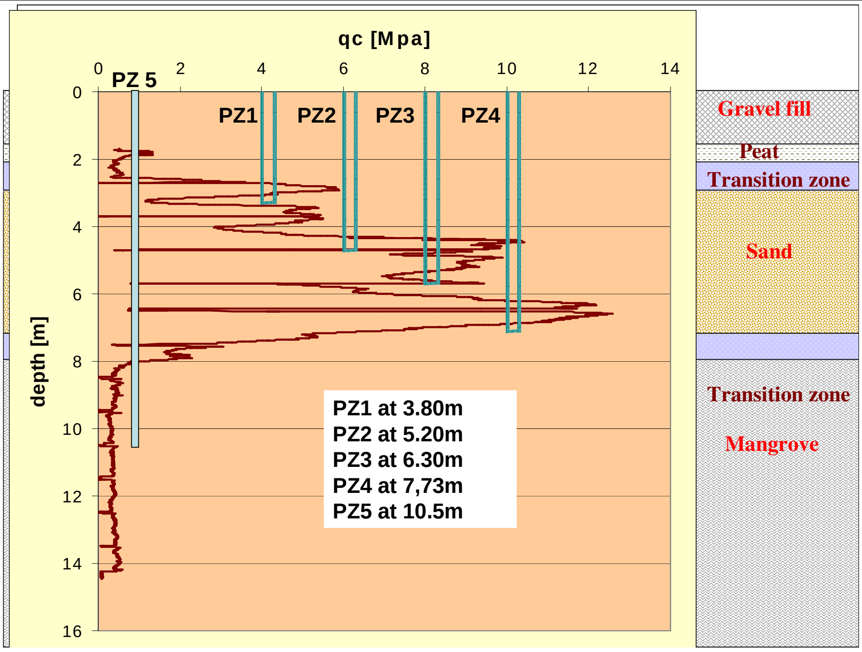

Figure 8 : Depths at which the pore pressure transducers were installed, compared with the tip resistance profile of the CPTU

Records obtained for the May 7th 2010, M_L=4.8 earthquake

The 07th, May 2010 occurred a M_L 4.8 earthquake located close to the test site (R=50km). We observe the same amplification between motion at GL-0, GL-15 and GL-39 (Figure 9). The pore pressure response of the sensors is shown Figure 10.

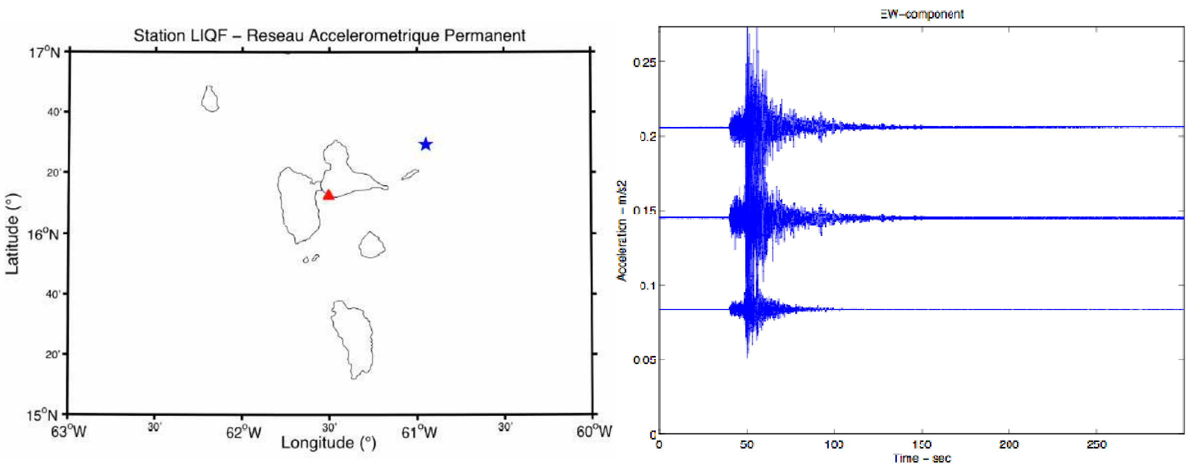

Figure 9 : Localization of the 07th, May 2010 M_L= 4.8 earthquake (star) with respect to the Belleplaine Test site (triangle) and EW recording at GL-39m, GL-15m and GL-0m plotted at the scale

Registered maximum values of the relative excess pore pressure $r_u = \Delta u/\sigma'_v$ were respectively 0.25 for PZ2 at 5.2 m, 0.04 for PZ3 at 6.5 m, 0.4 for PZ4 at 7.7m, and 0.03 at 10.7 m in the mangrove layer. The low value at 6.5 m may correspond to the high values of the tip resistance qc in this area, indicating a lenses of dense sand. The values at 5.2 m and 7.7 m are significant with respect to the relatively low magnitude of the earthquake, and indicate that liquefaction may be reached for a stronger earthquake. The highest value of r_u corresponds to the transition zone between the sand and the mangrove. Due to the low seismic acceleration, no accumulation of the excess pore pressure was observed, except at 10.5 m in the mangrove (PZ5). In the same way, despite a low value of Δu developed, a much longer dissipation could be noted at 10.5 m in the mangrove, due to the low permeability of this soft layer. This may indicate a strong softening of this kind soil for highest values of the accelerations, as confirmed by the results of undrained cyclic triaxial tests performed at Ecole Centrale Paris.

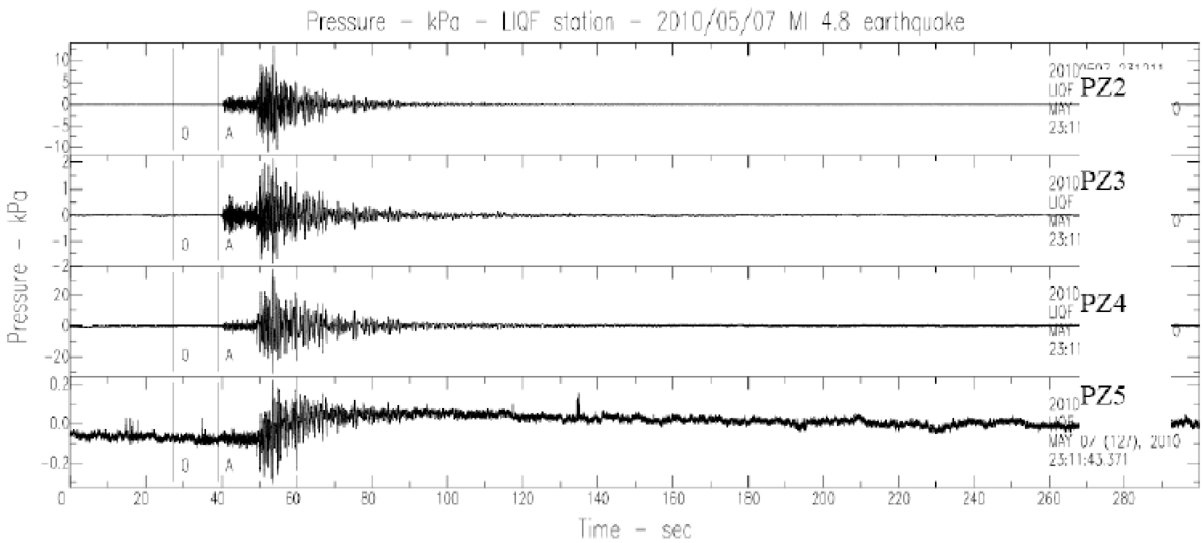

Figure 10 : Pore pressure records during the 07th, May 2010 Mw= 4.8 earthquake

ANALYSIS OF THE SITE RESPONSE BASED ON THE MAY 2010 EARTHQUAKE RECORDS

Liquefaction potential evaluation based on the field tests

The same semi-empirical method of Robertson et al (1998) based on CPTU data was applied to evaluate the liquefaction potential for the Guadeloupe May 2010 earthquake. For our analysis, a_{max} was assumed to be 0.11g, i.e. the maximal acceleration registered by the accelerometers.

The upper compacted fill and the peat layer are not considered as potentially liquefiable. In the same way, the methods could not be applied to the lower mangrove layer, as it is identified as clay. Figure xxx shows safety factor of the sandy layer, based on Robertson analysis. This evaluation indicates that some loose sub-layers of the sand horizon could liquefy even for a seismic excitation of amax= 0.11g, in contradiction with the field observations. The method seems to give conservative results for the present case. On the opposite, the average high values of Vs discard any risk of liquefaction if we consider Andrus and Stokoe's method. But local lower values of Vs may be missed in the seismocone downhole measurements.

Comparison with the registered excess pore pressures

The values of the safety factors measured on the site at depths of 5.2 m and 7.7 m, respectively 4 and 2.3, have been plotted on Figure 11 to be compared with the predictions. It is interesting to note that they are in the same order as those predicted, but with higher values. Again, the prediction method from CPT seems to be conservative in this case. An explanation may be found in the presence of the soft mangrove layer under the sand. Its low stiffness may absorb part of the seismic energy and reduce the movement of the upper sandy layer.

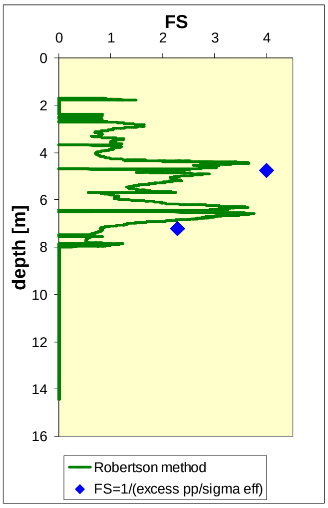

Figure 11 : Comparison between the safety factors predicted from the field test and measured by the pore pressure sensors for the May 2010 Guadeloupe earthquake

Analysis of the mangrove site response

The Belle Plaine site is representative of many coastal areas in the West Indies, where mangrove-clay type soils are covered by natural loose to medium dense sand layers which are highly sensitive to seismic liquefaction. However the analysis of the seismic response of the global site has to take into account the effect of the low stiffness of the under laying mangrove. Guégen et al (2010) computed the seismic response of the soil column using three methods: the spectral ratio method in the vertical array, numerical method using the geotechnical properties of the layers and operative modal analysis method (Frequency Domain Decomposition). They showed that the buried flexibility of the mangrove layer reduces the distortion and the stress in the sandy upper layer, and then the potential of liquefaction of the site. These results may explain the conservative character of the prediction methods.

CONCLUSIONS

An extensive campaign of geotechnical and geophysical field testing was performed on the Belle Plaine site, giving complete information on the physical and mechanical properties of the layers. The site has been instrumented with an array of sensors installed at different depths, allowing recording simultaneously excess pore pressures and accelerations induced by earthquakes.

First results for a moderate earthquake seem to indicate that the safety factors with respect to liquefaction estimated from the results of the field tests are lower than those measured. This is possibly due to the specific behaviour of the soft mangrove layer underlying the sand, which may absorb most of the deformation and dissipate more seismic energy. Data from future earthquakes and the evaluation of the shear strains in the mangrove layer from the accelerometer data are necessary to check if these conclusions can be extrapolated to strong movements.

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