An IBC approach for seismic microzoning at Cap-Haitien (Haiti)

Didier Bertil, Agathe Roulle, Gildas Noury, Claude Prépetit, Ronaldine Gilles, Rochenel Sylvain, Julio Jean-Philippe

SECOND EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING AND SEISMOLOGY, ISTANBUL AUG. 25-29, 2014

AN IBC APPROACH FOR SEISMIC MICROZONING AT CAP-HAÏTIEN (HAÏTI)

Didier BERTIL[1], Agathe ROULLÉ[1], Gildas NOURY[1], Claude PREPETIT[2,3], Ronaldine GILLES[2], Rochenel SYLVAIN[2] and Julio JEAN-PHILIPPE[2]

ABSTRACT

A seismic microzoning was performed for Cap Haitien city in Haiti. This city is as much exposed to seismic hazard as Port-au-Prince struck by the January 2010 earthquake. Many complementary investigations in geology, geophysics and geotechnics were needed to define areas of homogeneous soil response. The cross-analysis of this information allowed us to distinguish five soil classes with lithological site effects. The soil columns responses were simulated through a 1D non-linear analysis using CyberQuake software. Design response spectra were produced with the shape defined for ASCE 7-05/IBC(2009) code and specific amplification factors Fa and Fv. The seismic microzoning highlight that the majority of the urban area is located on soft soil or very soft soil with strong lithological site effects over large areas.

INTRODUCTION

The magnitude 7.1 earthquake that struck Haiti on January 12, 2010, caused great damage and over 230,000 casualties in the metropolitan area of Port-au-Prince in the southern part of Haiti. This earthquake is one of the deadliest known after those of Tangshan in China in 1976 and Sumatra in Indonesia in 2004.

Haiti is located at the western part of Hispaniola Island lying along the boundary between the North American and Caribbean plates. Geodetic studies (i.e., DeMets et al., 1994) showed that the Caribbean plate moves eastward at about 20 mm/year with respect to the North American plate. In Haiti, this motion is mainly partitioned between two major strike-slip fault systems, the Enriquillo Plantain Garden fault (EPGF) in the south and the Septentrional fault (SF) in the north (Figure 1). The 2010 event had an epicenter close to the trace of the EPGF.

In the Northern coast, Cap-Haitien is the second largest city of Haiti with similar tectonic settings to Port-au-Prince: it is close to the Septentrional Fault system and very long time has passed since the last highly destructive earthquake. The city was completely destroyed by the M8 earthquake of May 8, 1842.

Following the 2010 earthquake, a program of seismic microzoning for the most vulnerable cities of the country was initiated by the Haitian government. These studies are conducted in partnership between LNBTP, BME for Haiti and BRGM for France. In the North, those microzonings are part of a United Nation Development Program started in 2012: "The Seismic risk reduction plan for northern Haiti".

[1] Seismic Risk Unit, BRGM, Orléans-France, d.bertil@brgm.fr
[2] LNBTP, Port-au-Prince, Haïti, claudeprepetit@hotmail.com
[3] BME, Port-au-Prince, Haïti

The seismic microzoning of Cap-Haitien covers an area of 40 km^2 for its extension until Quartier Morin at East. It assesses topographic and lithological site effects, liquefaction and landslide hazards. This paper focuses on lithological site effects.

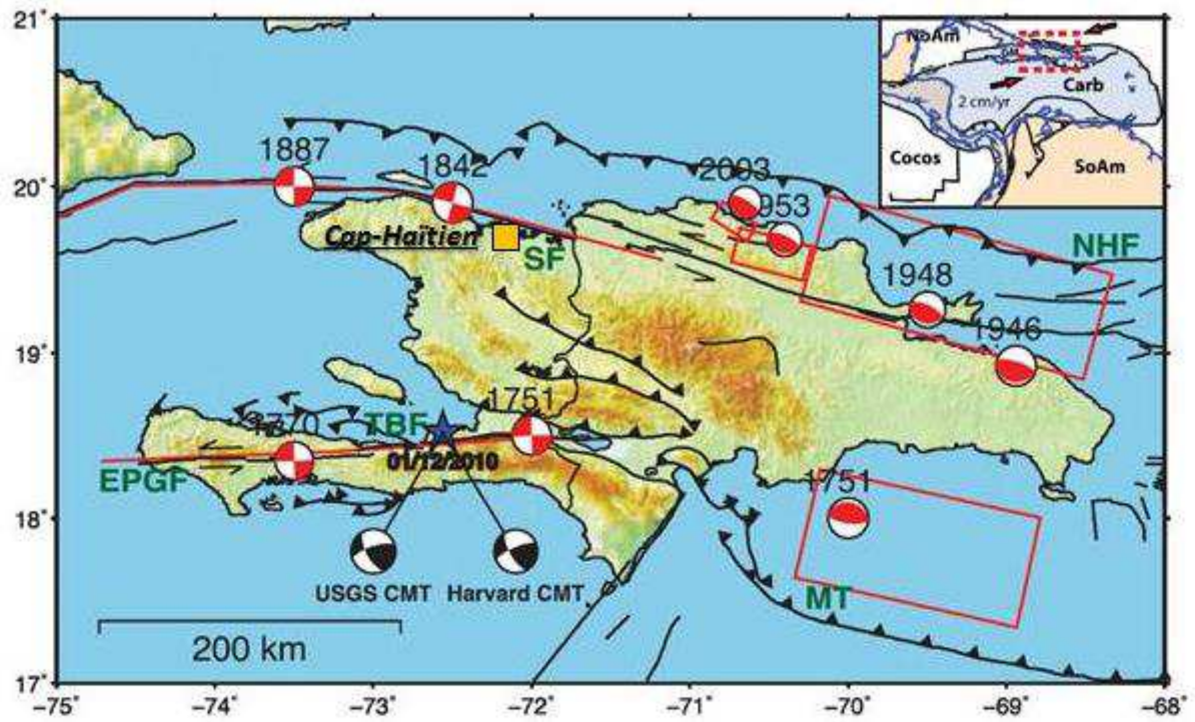


Figure 1. Seismotectonic setting of Hispaniola from Douilly et al. (2013). The January 2010 earthquake is shown with a blue star and black focal mechanisms. Cap-Haitien is displayed as a yellow square. The city is on the vicinity of the Septentrional Fault (red line named SF) and has been totally destroyed by the M8 earthquake of 1842. Other main historical earthquakes are shown (years in black and red focal mechanisms)

METHODOLOGY

To take into account lithological site effects, microzoning aims at defining specific soil classes based on a cross analysis of geological, geotechnical and geophysical information collected on the studied area. Regional hazard is not redefined but is based on the works of Frankel et al. (2010) representing the seismic hazard for rock conditions and a probability of exceedance of 2% in 50 years (return period of 2475 years). We follow the recommendation of the future Haitian seismic code CNBH2012 which advocates the use of these maps in the current state of knowledge.

This zoning is performed following several steps:

- mapping of surficial geological formations;
- compilation / analysis of geological, geophysical, geotechnical existing data;
- geophysical and geotechnical surveys to supplement existing data;
- cross-analysis of geological, geophysical and geotechnical information;
- identification of homogeneous areas in terms of seismic response;
- definition of one or more 1D representative soil columns for each zone;
- calculation of seismic responses for each soil column;
- fusion of areas with equivalent seismic responses.

Expected ground motions are very strong. Frankel et al. (2010) found pga=0.35g for 475-y return period and pga=0.60g for 2475-y return period on rock site. Soils consist mostly of recent colluvium and very soft alluvium. In this context, a non-linear behavior is expected for some kind of soils and must be taken into account for seismic response spectra calculation.

The seismic design response spectrum of each class of soil is based on those described in ASCE 07-5/IBC(2009) building code on which the CNBH2012 will rely in the future. For our specific soil classification, we choose to keep the same shapes for design response spectra but considering specific amplification factors Fa for short period (0.2s) and Fv for mid-period (1.0s).

MAPPING OF SUPERFICIAL FORMATIONS

The most precise available geological map was produced by BME (Bureau des Mines et de l'Energie) at 1 / 250 000 scale (Boisson and Pubellier, 1987, for North East of Haiti) and is not detailed enough to be usable for the microzoning (Figure 2). The boundary between rock and recent sediment formations is too imprecise. Sedimentary facies of the Quaternary are grouped into a single unit. A re-assessment of geological mapping was performed at the scale of the urban agglomeration to improve our understanding of superficial deposits (Monthel and Bialkowski, 2013, Figure 2). 14 superficial formations are described. This new geological mapping shows that the historical city center (labeled as "Cap Haïtien" in figure 2) is located on colluvium at the foot of a Cretaceous mountain and that the new districts at East extend over thick Quaternary alluvial deposits in the plain and coastal zones.

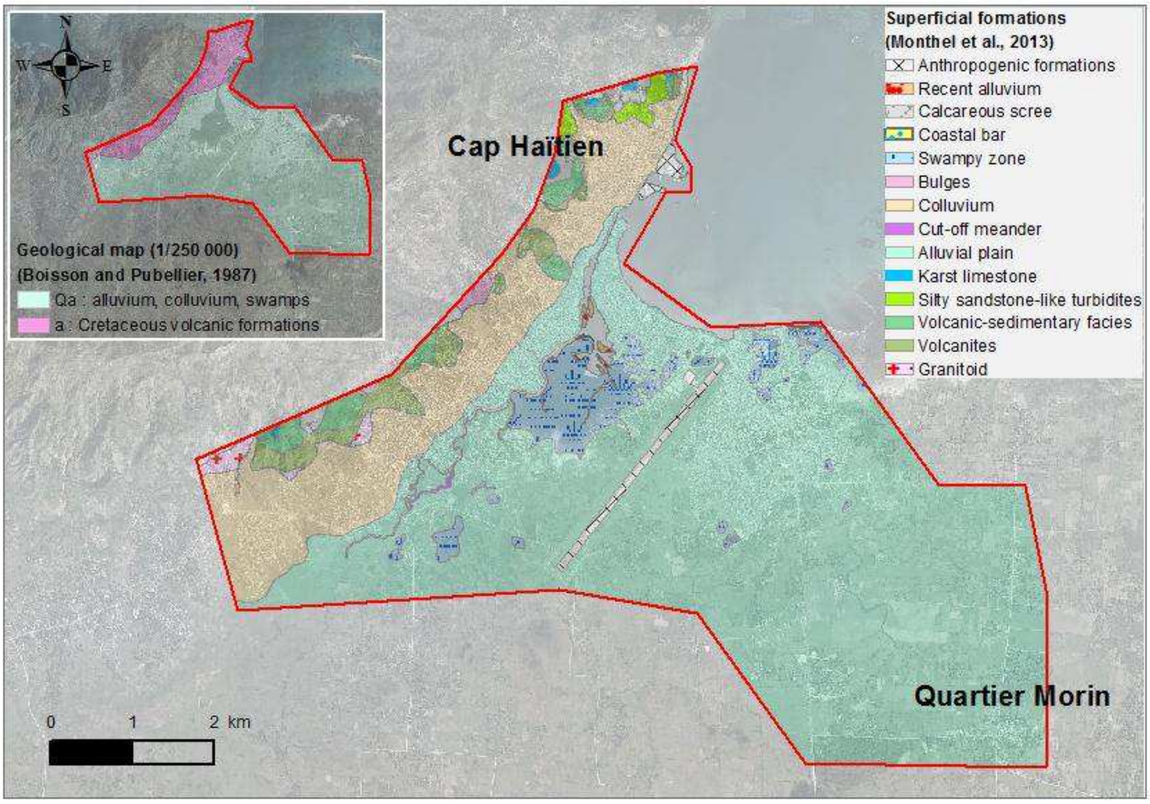


Figure 2. Geological map reassessed for the project at a 1: 25 000 scale. On top left, the geological map at 1:250 000 from Boisson & Pubellier (1987). The studied area is represented by the red line.

GEOPHYSICAL AND GEOTECHNICAL DATA

The existing data collection brought together 23 georeferenced geotechnical drilling profiles unevenly distributed over the area and more concentrated around the historical city center. Geophysical data (H/V, MASW) concern only some isolated point. Those data were completed by a geophysical and geotechnical campaign operated by the LNBTP in order to refine our knowledge on mechanical properties of superficial deposits and to improve the spatial distribution of the data. These new data consist in: MASW profiles at 31 sites, H/V measurements at 54 sites and 12 geotechnical drillings with CPT or SPT values and laboratory tests (Figure 3).

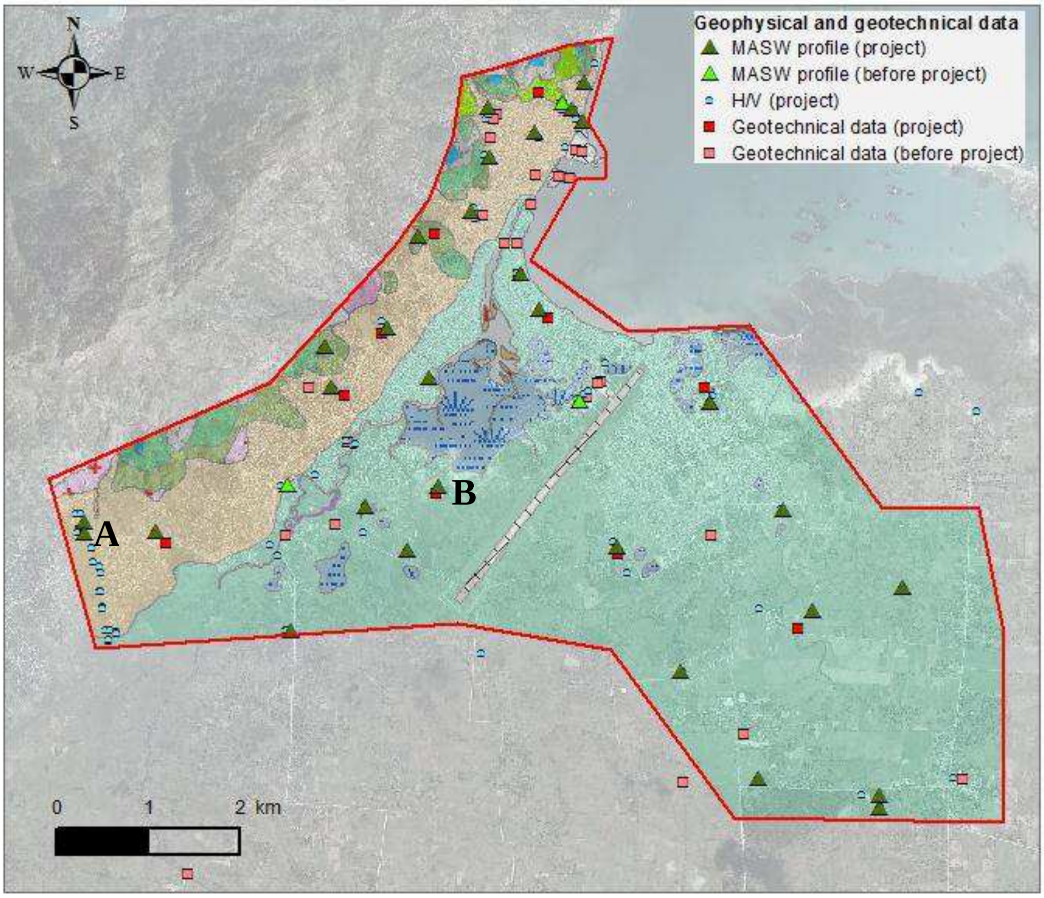
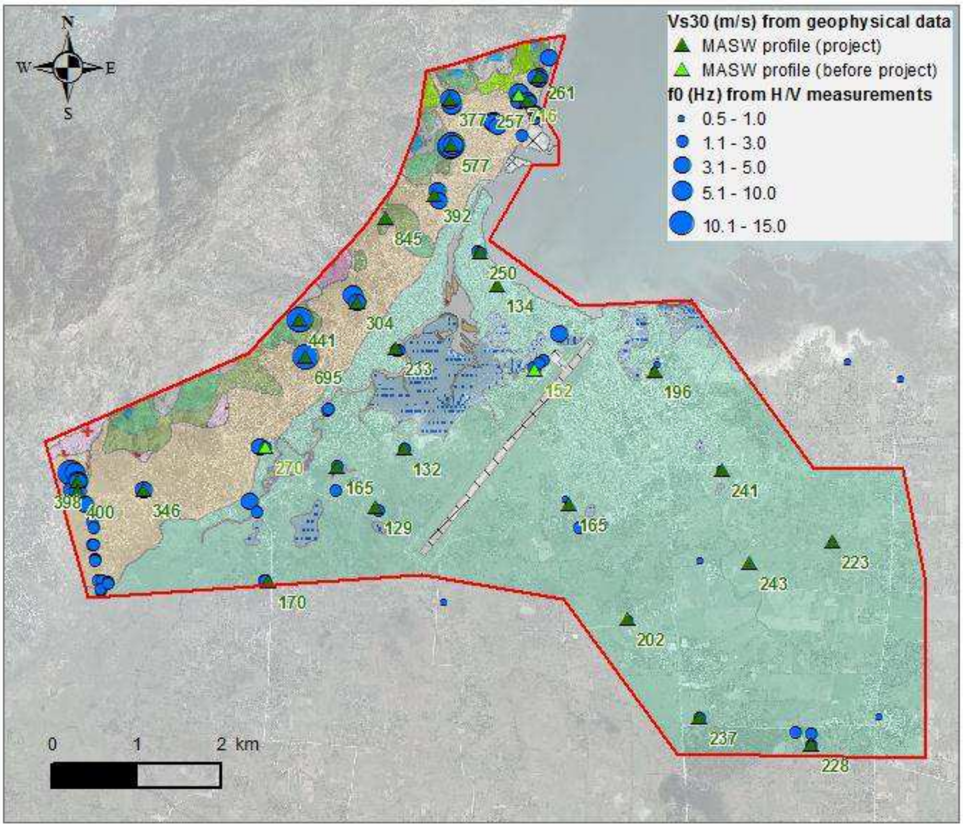


Figure 3. Main data used for site effect zoning. See the legend of Figure 2 for geological background. H/V spectral ratios, MASW and SPT profiles for the sites A (cité administrative) and B (centre éducatif Suzanne Flon) are illustrated on Figure 5 and Figure 6.

CROSS-ANALYSIS OF INFORMATION

Figure 4 shows geophysical interpretations superimposed with the superficial formations map. Recent alluvium of the coastal plain are characterized by H/V peaks between 0.5 Hz and 1.2 Hz and VS_{30} values between 130 and 250 m/s. Colluvium of the historical center (Northern area) and to the west along the foot of the mountain also show strong H/V peaks but with higher frequencies 3-5 Hz and higher Vs30 values (350 to 600 m/s).

On some sites, geotechnical and geophysical information can be confronted directly. Figure 5 shows MASW, H/V spectrum and SPT profiles at point A located on superficial colluvium. We see a soft soil on the first 8 meters then stiff soil. The seismic bedrock is reached at 25 m. At point B on a site of the alluvial plain (Figure 6), the thickness of very soft soil is at least 30 m



.

Figure 4. Joint interpretations of geological and geophysical measurements.

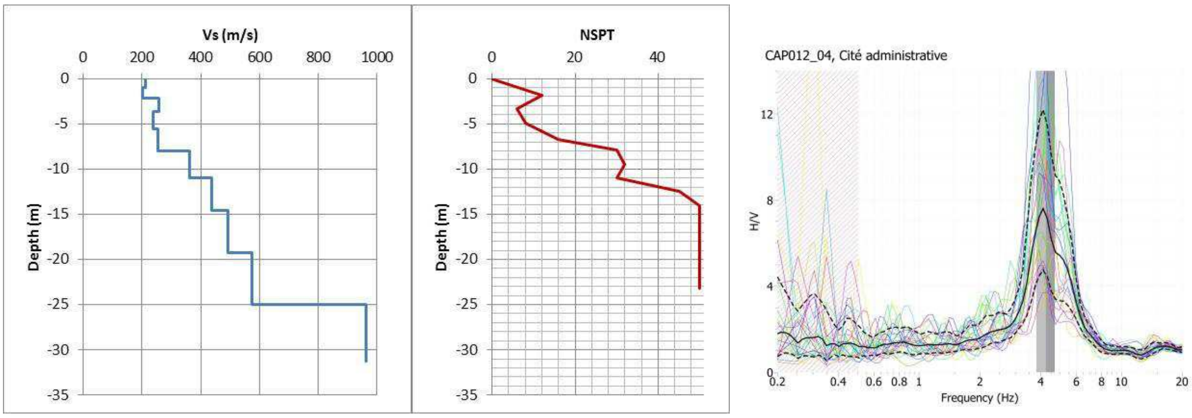


Figure 5. MASW profile, SPT profile and H/V curves for Point A

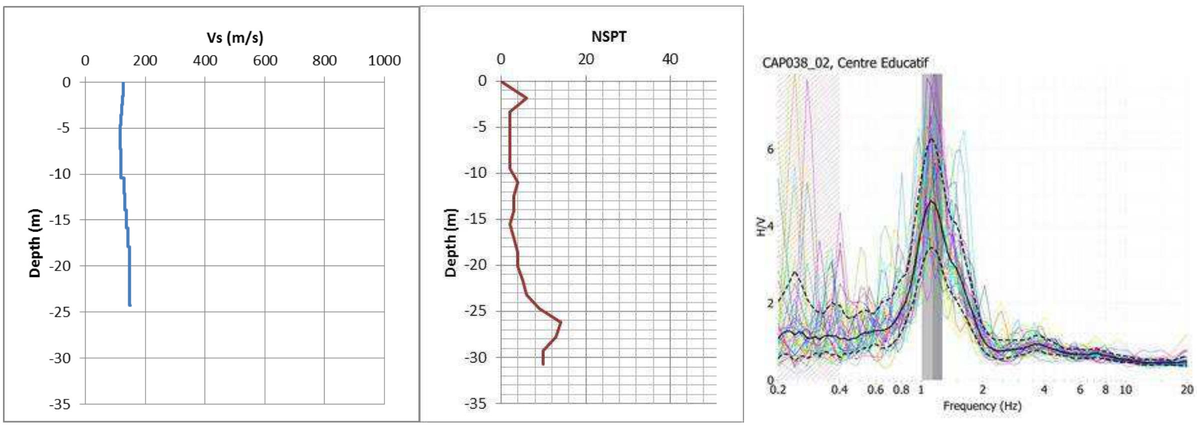
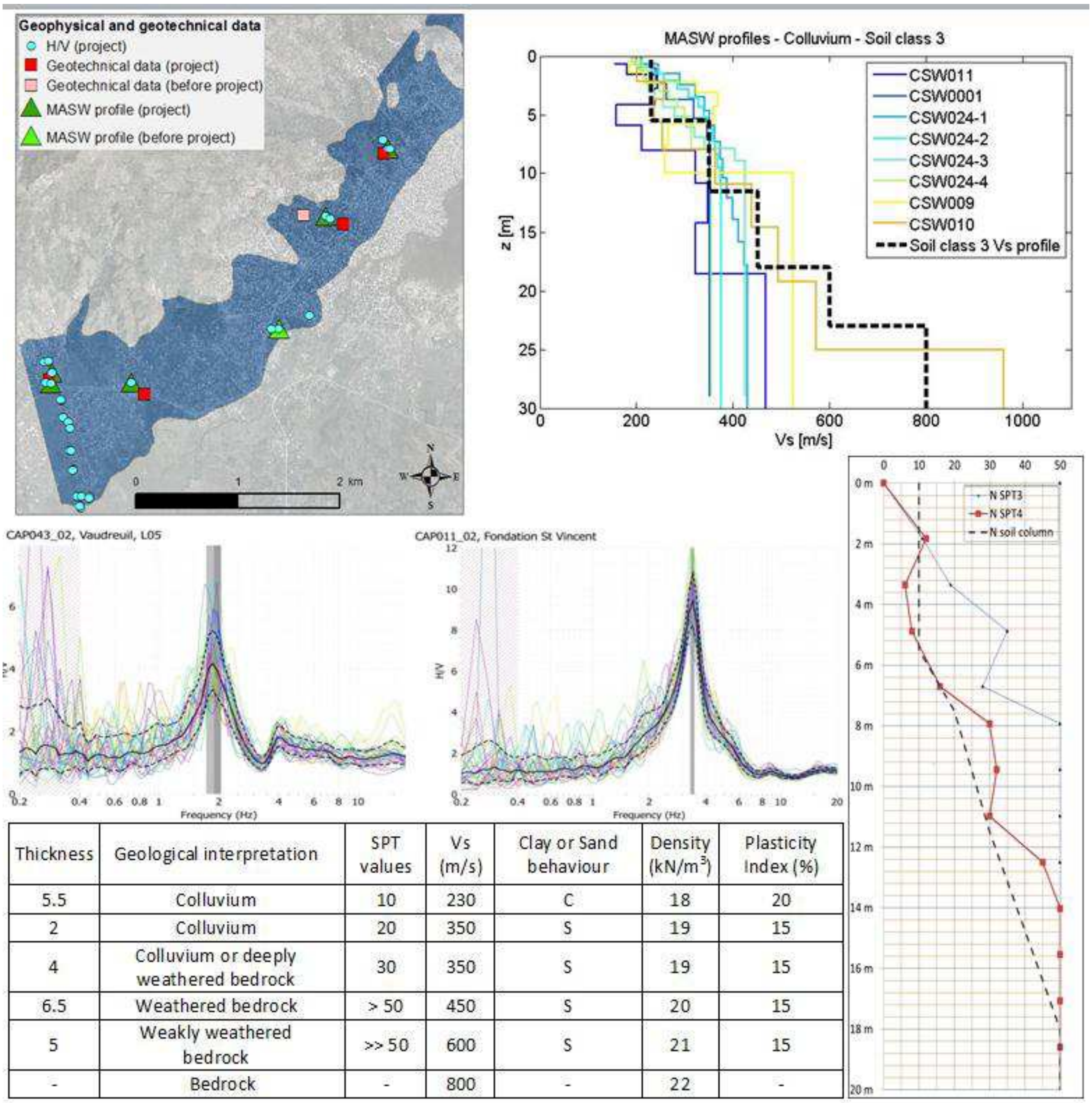


Figure 6. MASW profile, SPT profile and H/V curves for Point B.

A cross analysis of all available data is performed to define homogeneous zones in terms of geology, resonance frequency and mechanical properties. Then, for each zone, representative soil columns are defined to perform 1D seismic response simulations. For each layer of the soil columns, the following parameters are defined: thickness of the layer, geological interpretation, Nspt from SPT drillings, shear waves velocity Vs from MASW profiles, material property (either sand, clay or gravel behavior), density γh, plasticity index IP The coherence between the resonance frequency derived from H/V measurements and the characteristics of the soil column was also checked before simulations. Figure 7 shows the cross-analysis realized for soil class 3 dominated by superficial colluvium and the resulting soil column.



Thickness	Geological interpretation	SPT values	Vs (m/s)	Clay or Sand behaviour	Density (kN/m^3)	Plasticity Index (%)
5.5	Colluvium	10	230	C	18	20
2	Colluvium	20	350	S	19	15
4	Colluvium or deeply weathered bedrock	30	350	S	19	15
6.5	Weathered bedrock	> 50	450	S	20	15
5	Weakly weathered bedrock	>> 50	600	S	21	15
-	Bedrock	-	800	-	22	-

Figure 7. Column of soil for the colluvium area (part of class 3 of the final microzoning) and examples of H/V peaks, MASW profiles and NSPT profiles.

CALCULATION OF SEISMIC RESPONSES

Seismic responses are first estimated using CyberQuake software (Modaressi et al., 1997) through 1D non-linear simulation. The input bedrock motions consist in 4 accelerograms (2 are real ones and 2 are modified from real ones) with response spectra close to the design spectrum for rock sites. Seismic responses were first simulated for 9 initial zones. After calculations, results were compared and similar seismic response zones were grouped to obtain finally 5 specific soil classes to complement the outcropping rock class 0 (Figure 8).

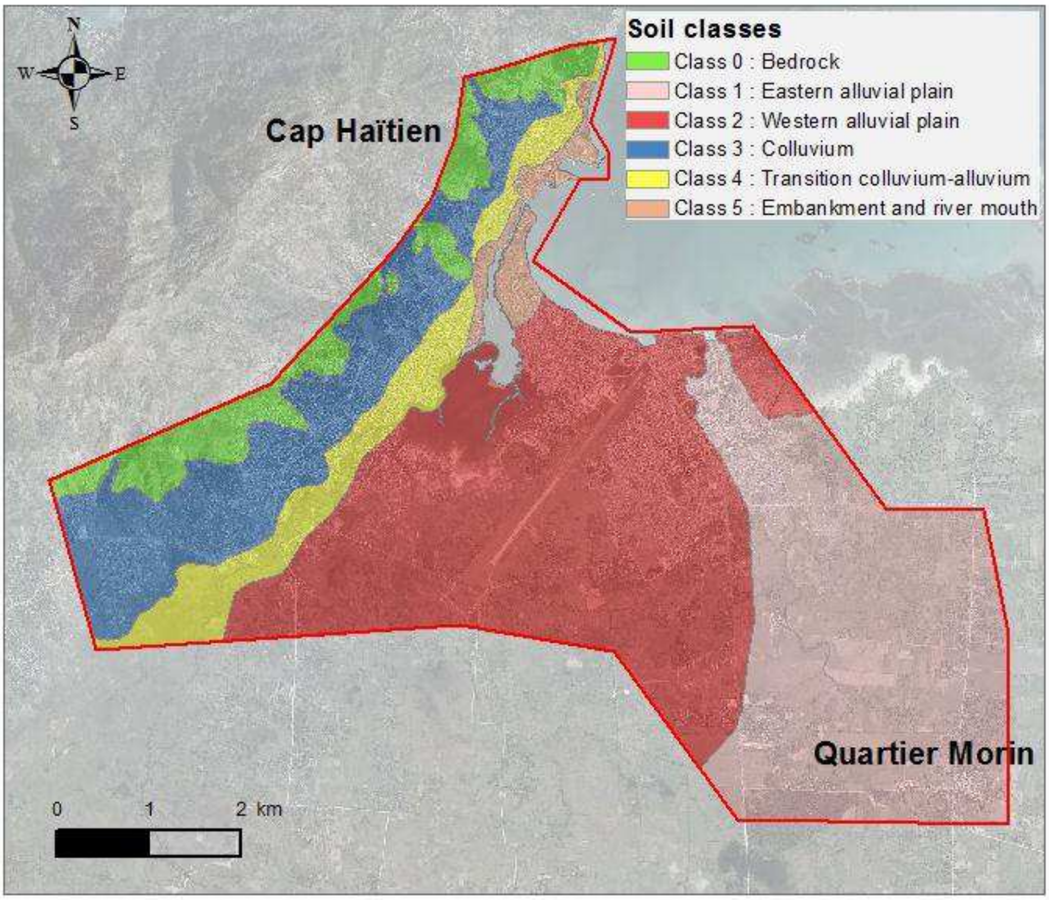


Figure 8. Soil classes zoning for Cap Haitien area. Class 0 represents bedrock at the outcrop surface.

Five-percent-damped design spectra are constructed on basis of 1D response spectra simulations with the same shapes as those recommended by IBC (2009). The design ground motion parameters are the ordinate values S_{DS} and S_{D1} that equal to accelerations at short periods and 1 second period respectively. S_{DS} defines the plateau of the design spectrum between periods T0 and TS. Between TS and TL the constant velocity branch is given by S_{D1}/T and beyond TL the constant displacement branch is given by S_{D1} TL / T^2. TL is considered to be higher than 4.0 as defined for U.S. in NEHRP.

S_{DS} and S_1 are derived from S_S and S_1, the spectral accelerations of the hazard maps of Frankel et al. (2010) for Haiti from PSHA at 2475-y return period and from individual amplification coefficients Fa (low-period) and Fv (mid-period) defined for each class of soil.

The seismic design response spectra are represented in Figure 9 and associated parameters in Table 1.

Table 1. Soil Classification for the microzoning and main design ground motion parameters

Soil Class	Name	Fa	Fv	PGA (g)	SDS (g)	SD1 (g)	T0 (s)	TS (s)	VS_{30} (m/s)
Class 0	Bedrock	1.0	1.0	0.40	1.01	0.39	0.08	0.38	800
Class 1	Eastern alluvial plain	1.3	2.0	0.51	1.28	0.77	0.12	0.60	265
Class 2	Western alluvial plain	1.0	2.5	0.40	1.00	0.95	0.19	0.95	140
Class 3	Colluvium	1.2	1.5	0.50	1.24	0.60	0.10	0.48	425
Class 4	Transition colluvium-alluvium	1.5	2.0	0.62	1.55	0.78	0.10	0.50	250
Class 5	Embankment and river mouth	1.7	2.4	0.70	1.74	0.94	0.11	0.54	225

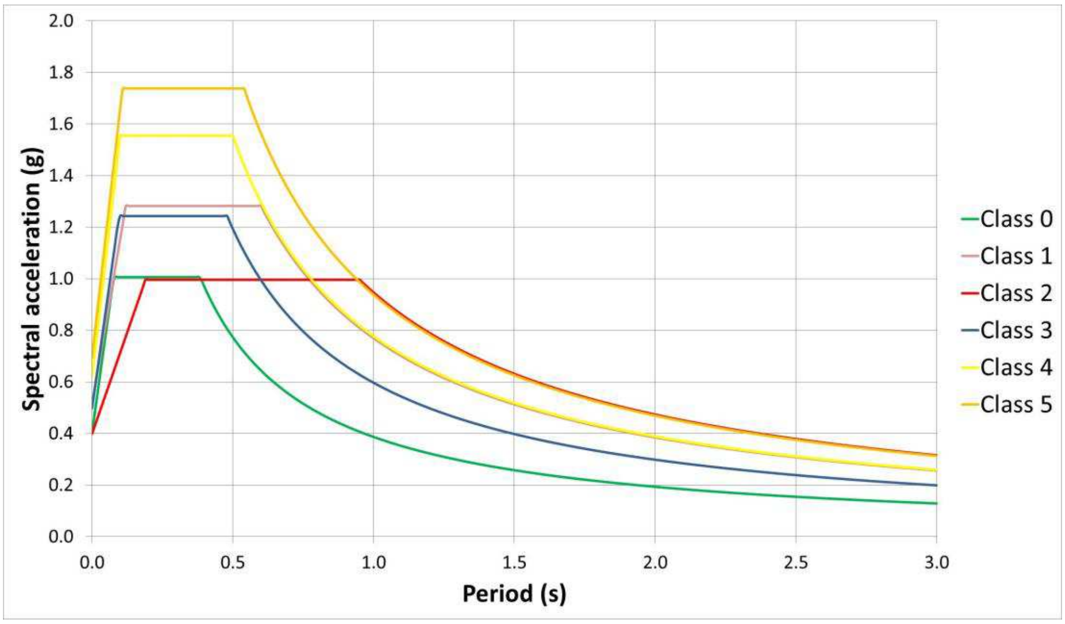


Figure 9. Elastic response spectra for the 6 soil classes. Spectrum for outcropping bedrock (Class 0) is represented in green.

The alluvial plain is characterized by very soft soils and spectra with a very broad constant acceleration branch (0.19-0.95s for class 2) and with a low acceleration plateau spectrum. Class 3, 4 and 5 correspond to a transition between the outcropping rock of the mountain and the alluvial plain. They are characterised by increasing amplification for low-period (Fa 1.2-1.7) and for mid-period (Fv from 1.5 to 2.5) when getting closer to the alluvial plain.

Amplication factors Fa and Fv are then compared to those proposed by ASCE 07-5/IBC(2009) for soils with equivalent Vs30 and the same level of rock site acceleration (Figure 10). As for IBC, Fv increases when Vs30 value decreases. But no such correlation is seen for Fa.

In this study, we choose to keep the simplified shapes of the design spectra proposed by ASCE 7-05/IBC(2009) and to represent the specific classes of soils only by modifying Fa and Fv factors. In that way, microzoning results are easily usable by engineers familiar with IBC. Secondly, it allows a partial decoupling of the local hazard due to soil response and the regional hazard. Provided that the acceleration levels do not change a lot in the future updates of the regional hazard assessment, design spectra could be reproduced without modification of the study.

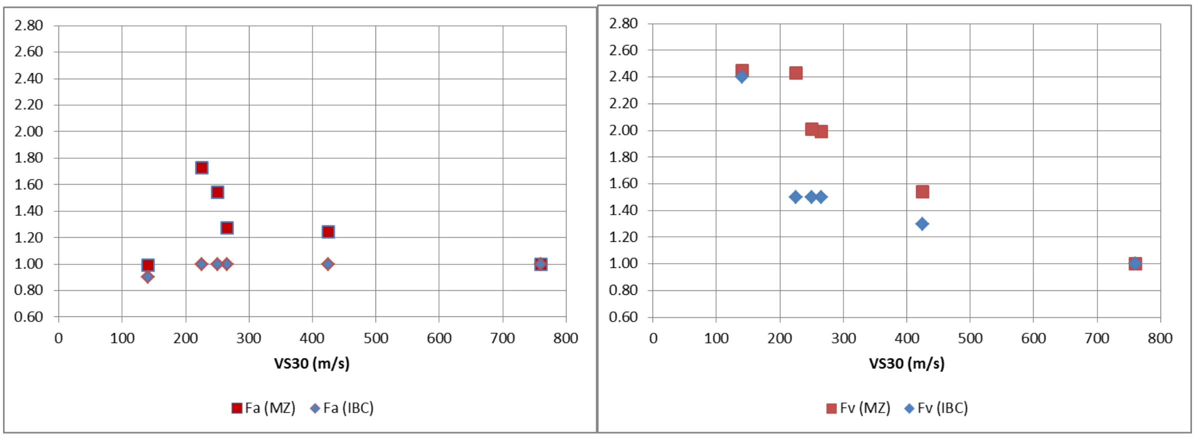


Figure 10. Comparisons of amplification factors Fa (left) and Fv (right) found for this microzoning (MZ) and proposed in IBC code.

We have noted, however, that the very simplified forms of design spectra do not fit perfectly with the spectra output from 1D simulations and require compromises in the choice of Fa and Fv.

Fa and Fv are different than those proposed with the standard classification in ASCE 7-05/IBC(2009). This justifies the implementation of microzonings on the basis of crossing geological, geotechnical and geophysical information instead of a simple characterization of the VS30 velocity.

CONCLUSIONS

The level of local seismic hazard knowledge for this region of Haiti is low. Geology and tectonics need to be updated at a scale compatible with an urban area scale. Lack of seismic monitoring involves great uncertainty about the regional hazard. The site effects microzoning presented here required numerous additional geological, geophysical and geotechnical investigations to characterize the different kind of soils of the studied area.

Five specific soil classes were defined with amplification factors Fa and Fv globally higher than those proposed in the IBC code for similar values of VS_{30}. Short period amplification factor Fa is particularly high on the west side of the area where we have soft shallow formations and where the substratum is shallower. In the alluvial plain, very soft soil is present at great depth and low bearing capacity of foundation soil is expected. An aggravating factor is a high liquefaction hazard that has not been detailed here.

Cap Haitien is then heavily exposed to seismic risk, because of its proximity to seismic sources, of its great seismic vulnerability of buildings, its high concentration of population but also because of the very poor soil quality. The seismic microzoning highlight that the main part of the urban area is located on soft soils or very soft soils with strong lithological site effects over large areas.

REFERENCES

ASCE 7-05 (2005) Minimum Design Loads for Buildings and Other Structures, American Society of Civil Engineers, 2005,

Boisson D., Pubellier M. (1987) Carte géologique à 1/250 000 de la République d'Haïti. Feuille Nord-Est (feuille de Cap Haïtien). B.M.E (1982-1988).

CNBH (2012). Code National du Bâtiment d'Haïti. Ministère des Travaux Publics, Transports et Communications (MTPTC). République d'Haïti.

DeMets, C., D. Gordon F. A., Argus D, and Stein S. (1994). Effect of recent revisions to the geomagnetic reversal timescale on estimates of current plate motions, *Geophysical Research Lett*ers, 21, 2191–2194.

Douilly R., Haase J.S., Ellsworth W.L., Bouin M.P., Calais E., Symithe S.J., Armbruster J.G. , Mercier de Lépinay B., Deschamps A., Mildor S-L., Meremonte M.E. and Hough S.E. (2013) "Crustal Structure and Fault Geometry of the 2010 Haiti Earthquake from Temporary Seismometer Deployments", *Bulletin of the Seismological Society of America*, 103(4): 2305–2325.

Frankel, A., Harmsen, S., Mueller, C., Calais, E. and Haase, J. (2010). Documentation for Initial Seismic Hazard Maps for Haiti. United States Geological Survey Open-File Report 2010-1067.
IBC (2009) International Building Code, International Code Council, ICC, 4051 West Flossmoor Road, Country Club Hills, Il. 60478, USA, 1ST printing, 650p.
Modaressi H., Foerster E., Mellal A. (1997) Computer aided seismic analysis of soils. *Proceedings of the 6th International Symposium on numerical models in geomechanics*, *NUMOG VI*, Montréal, Québec, Canada, July 2-4.
Monthel J., Bialkowski A., Jean Ph., Jean-Baptiste M. (2013) Cartographie géologique des villes de Cap-Haïtien, Fort-Liberté et Ouanaminthe (République d'Haïti). Rapport final. BRGM/RP-61951-FR, 55 p.