Meded. Zitt. K. Acad. Overzeese Wet.
Bull. Séanc. Acad. R. Sci. Outre-Mer
56 (2010-4): 485-495

Haiti – All the Ingredients for a Major Disaster*

by

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KEYWORDS. — Earthquake; Active Fault; Magnitude; Vulnerability; Site Effects.

SUMMARY. — The earthquake that struck Haiti on 12 January 2010 was one of the most destructive seismic events worldwide. It caused about 230,000 deaths and more than one million homeless; death toll and casualties amounted to about 15 % of the population of Port-au-Prince.

With a magnitude of 7.1 this earthquake was a heavy one, but no earthquake of this magnitude up to now had caused more than 35,000 deaths. In that note, based on the published investigations on the earthquake, we present the tectonic context of that part of the Caribbean and the contribution of the data collected about the earthquake in terms of future hazard assessment. We also discuss the different explanations of the disaster scale and discriminate the causes that are directly related to the Haitian context from the more global observed increase of vulnerability towards natural disasters.

MOTS-CLES. — Tremblement de terre; Faille active; Magnitude; Vulnérabilité; Conséquences topographiques.

RESUME. — *Haïti – tous les ingrédients pour une catastrophe de grande ampleur.* — Le tremblement de terre qui a secoué Haïti le 12 janvier 2010 est un des plus destructeurs dans le monde. Il a causé plus d'un million de sans-abri et la mort de plus de 230 000 personnes; le coût total en termes de morts et de blessés est d'environ 15 % de la population de Port-au-Prince.

Ce tremblement de terre de magnitude 7.1 fait partie des grands tremblements de terre, mais aucun séisme de cette magnitude n'avait à ce jour été à l'origine de plus de 35 000 morts. Dans cette note, basée sur des études publiées du séisme, nous présentons le contexte tectonique de cette partie des Caraïbes et la contribution des données collectées sur le séisme en termes d'évaluation de l'aléa sismique futur dans la région. Nous discutons aussi les différentes explications de l'étendue du désastre, en distinguant les causes qui sont liées directement au contexte haïtien de celles liées à l'observation globale de l'accroissement de la vulnérabilité par rapport aux catastrophes naturelles.

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* Paper presented at the meeting of the Section of Technical Sciences held on 25 November 2010. Text received on 6 April 2011.

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TREFWOORDEN. — Aardbeving; Actieve breuk; Magnitude; Kwetsbaarheid; Topografische effecten.

SAMENVATTING. — *Haïti – de ideale mix voor een omvangrijke catastrofe.* — De aardbeving die Haïti op 12 januari 2010 trof is één van de meest destructieve ter wereld. Deze aardschok veroorzaakte meer dan één miljoen daklozen en meer dan 230 000 doden; het totaalaantal slachtoffers bedraagt 15 % van de bevolking van Port-au-Prince.

Deze aardbeving met magnitude 7.1 is een zware aardbeving, maar nooit eerder had een aardbeving met zulke magnitude meer dan 35 000 doden veroorzaakt. In dit artikel, gebaseerd op gepubliceerde studies over de aardbeving, stellen we het tektonische kader voor van dit deel van de Caraïben en de bijdrage van de verzamelde gegevens over de aardbeving voor de inschatting van de toekomstige seismische gevarenkans. We bediscussiëren ook de verschillende verklaringen voor de omvang van de ramp en onderscheiden de oorzaken die direct verbonden zijn met de Haïtiaanse context van de meer globaal toenemende kwetsbaarheid voor natuurrampen.

1. Geodynamic Context and the Earthquake of 12 January 2010

1.1. PLATE TECTONIC CONTEXT

Haiti, on the western side of Hispaniola Island, is located on the Caribbean plate, near the active boundary with the oceanic part of the American plate (fig. 1). The relative motion between the two plates is a highly oblique plate convergence of about 20 mm/yr west-northwestwards relative to the North-American plate (ALI *et al.* 2008, MANAKER *et al.* 2008). This oblique convergence is partitioned in Hispaniola between plate-boundary parallel motion on the *Septentrional* and southern Haiti fault zones in the overriding plate and along the thrusting zone at the subduction interface, along the northern Hispaniola fault zone. The *Septentrional* and Enriquillo-Plantain Garden transform faults accommodate lastly left-lateral strike slip motion, with a rate of 9 ± 2 mm/yr on the *Septentrional* fault and 7 ± 2 mm/yr on the southern peninsula fault zone. This has been evidenced by Global Positioning System (GPS) measurements for the present time and confirmed by paleoseismic investigations for the most recent geological time (MANAKER *et al.* 2008).

This relative motion measured by GPS is continuous, while the motions along the fault zones are discontinuous, because of the frictional resistance on the fault zone. Strain accumulates along the fault zone during hundreds of years and is eventually released during an earthquake when frictional resistance is overcome. In Haiti, major earthquakes severely struck Port-au-Prince on September and November 1751, and June 1770. Although the location of these historical events is poorly known, they are thought to have ruptured the Enriquillo-Plantain Garden (EPG) fault zone, and their magnitude estimates range M_w = 7.5 - 8 (PRENTICE *et al.* 2010, ALI *et al.* 2008).

Given the strain accumulated since the last major events, MANAKER *et al.* (2008) estimated that the EPG fault was capable of producing a M_w 7.2 event today. So, the January 12, 2010 $M_w = 7.1$ earthquake was not really a surprise and at that time, the seismologists were convinced that a 30 km-long surface fracture would offset the two sides of the valley of the EPG fault, by about one or two metres, which is typical of magnitude 7 events.

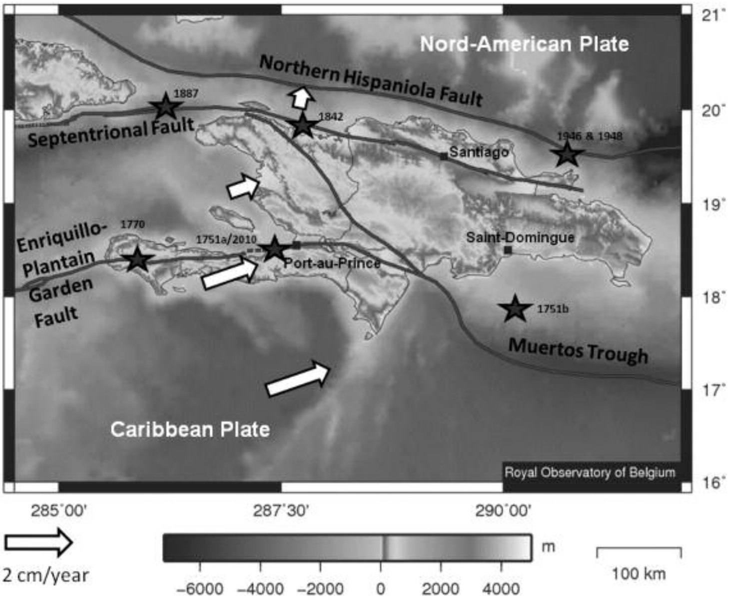

Fig. 1. — Geodynamic context and large historical earthquakes of Hispaniola Island.

1.2. THE 12 JANUARY 2010 EARTHQUAKE AND THE HIDDEN FAULT

Although the 2010 Haiti earthquake did not come as a surprise, several of its characteristics were unexpected and it revealed a much more complex structural pattern than expected. As a first surprise, no surface rupture was found, but GPS and satellite radar data clearly evidenced relative surface movements after the earthquake. As expected, about a metre of relative ground deformation occurred. This is associated with a transpressional motion north of the EPG fault, near the town of Léogâne (BILHAM 2010b). Although thrust motion is consistent with the long-term pattern of strain accumulation in Hispaniola, this cannot be explained by a simple strike slip movement of the EPG transform. However, the EPG fault does not perfectly parallel the direction of plate motion, causing compression throughout Haiti (BILHAM 2010b, CALAIS *et al.* 2010). This compression has been evidenced by the thrust faults mapped for example in the northern Hispaniola fault zone and along the *Chaîne des Matheux*, north of Port-au-Prince, but such faults were not known in the vicinity of the EPG fault zone (fig. 2).

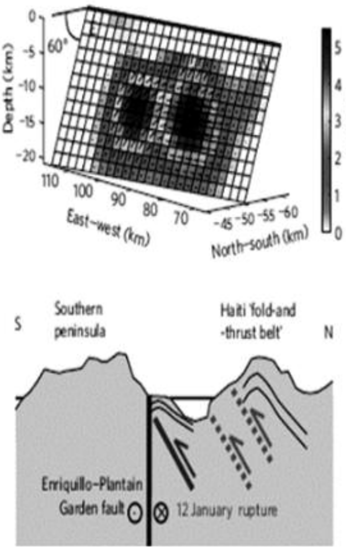

Fig. 2. — Total slip distribution along the Léogâne fault (top) and interpretative cross-section, with the red line as the supposed coseismic rupture. Reprinted by permission from Macmillan Publishers Ltd, *Nature Geoscience*, 24 October 2010 (doi:10.1038/NGEO992).

An ongoing debate is to know whether the transpressional motion occurs on the same Léogâne fault (Calais *et al.* 2010) or if several faults were involved, with the slip starting on the EPG transform fault and then followed by slip on the Léogâne thrust fault. Note that such a complex transpressional earthquake is not uncommon. This type of event was observed in 1957 (Gobi-Altay, Mongolia, M = 8.1), 1988 (Spitak, Armenia, M = 7.8), 1989 (Loma Prieta, California, M = 6.9), 1997 (Zirkuh, Iran, M = 7.2), 2002 (Denali, Alaska, M = 7.9), 2003 (Bam, Iran, M = 6.6) and 2008 (Wenchuan, China, M = 7.9).

At least part of the fault responsible for the 2010 earthquake was probably an unmapped surface structure, now referred as "Léogâne fault". The question is to know whether the January 2010 event is either atypical, or indicates a modern reorganization of the fault system (Hayes *et al.* 2010). Answers can be provided by performing comprehensive paleoseismic investigations, as well as by providing Haiti with modern geodetic and seismic networks, allowing the seismologists to investigate in detail the long-term deformation and the seismic activity.

1.3. The Future Seismic Hazards

The Haiti main earthquake of 12 January 2010 was followed by numerous aftershocks, mostly located to the west of the ruptured area and thus, west of Port-au-Prince. Today, although the accumulated elastic energy along the Léogâne segment is spent, stresses have increased east of the rupture, toward Port-au Prince. Moreover, it is very likely that little, if any, accumulated strain was released on the EPG fault in the 2010 earthquake (Prentice *et al.* 2010, Calais *et al.* 2010, Hayes *et al.* 2010). So, the EPG fault remains a significant seismic hazard, both in the vicinity of Léogâne and in Port-au-Prince, which will experience stronger ground shaking when the eastern segment ruptures.

North of Haiti, the *Septentrional* transform fault is also known to pose a risk. Ali *et al.* (2008) found that coseismic stress changes often encourage subsequent events. For instance, the observed westward propagation of earthquakes on the *Septentrional* Fault (1842, 1887), the EPG fault (1751, 1770) and along the North-Hispaniola megathrust (1787, 1943, 1946, 1953, 2003) were all associated with the earlier events in each sequence that increased the stress load on these faults to the west. So, the recent thrust movements have increased the shear stresses on the *Septentrional* fault, which, given the slip deficit of 8 mm/yr over the past 770-960 yr, is capable of producing a M_w 7.5 to 7.7 event in a populated area of vital economic importance for the Dominican Republic.

2. Why were the Consequences of the Earthquake so Catastrophic?

The earthquake in Haiti on 12 January 2010 was one of the most destructive seismic events worldwide. It caused about 230,000 deaths and more than one million homeless; death toll and casualties amounted to about 15 % of the population of Port-au-Prince. Bilham (2010a) studied the impact of the destructive earthquakes that occurred during the 20th century (fig. 3). With a magnitude of 7.1 the Haiti earthquake was a heavy one, but no earthquake of this magnitude up to now had caused more than 35,000 deaths. It has to be noted that other recent heavy earthquakes — Bam (2003), Sumatra (2004), Kashmir (2005) and Sichuan (2008) — are also among the most deadly seismic events. This suggests that even if the impact of the 2010 earthquake in Haiti can be partly the consequence of local Haitian conditions, there are also more general societal characteristics at global scale favouring an increase of seismic risks and earthquake consequences.

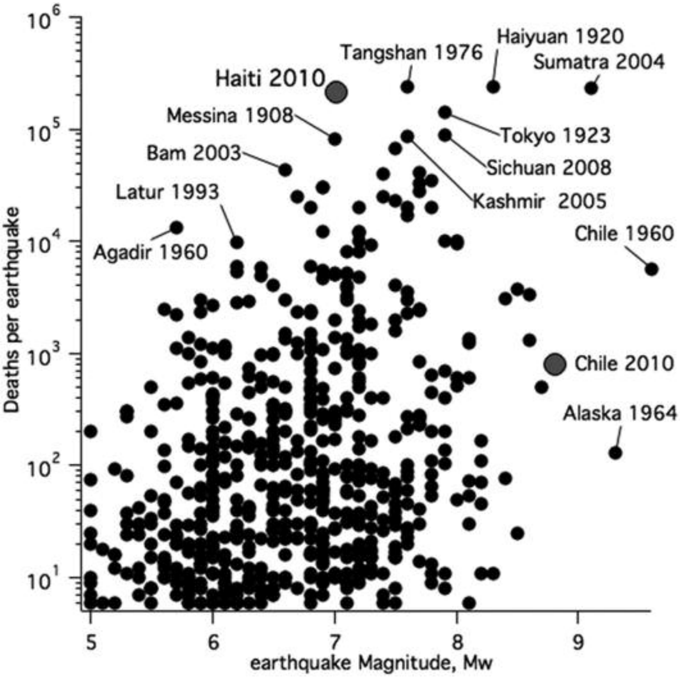

Fig. 3. — Fatalities during earthquakes as a function of earthquake magnitude (updated version of Bilham (2010a), available on http://cires.colorado.edu/~bilham/).

2.1. The Population Global Increase

The study of Bilham (2010a) shows a gloomy picture of the consequences of future heavy earthquakes, mainly in developing nations as a result of the spectacular increase of worldwide population in a very short time period. The projected population doubling in the next fifty years will require the building of one billion houses. The tendency towards earthquake-resistant building, despite being relatively successful in developed nations, is neglected in developing countries. The reasons can be attributed largely to indifference, ignorance, and lack of financial support and also in some cases, corrupt practices. The consequence is that earthquakes, which in a recent past had little impact on villages and towns, may in the future strongly affect urban agglomerations of one to some tens of million inhabitants with catastrophic consequences in terms of human lives.

This global explanation is of course valid in the case of the 12 January 2010 earthquake in Haiti where more than three million people lived in the potentially affected region of a M_W 7.1 earthquake. In the future, similar earthquakes in the upper crust in different regions of the world will have the same type of consequences.

The effects of the Haiti earthquake were aggravated by the important poverty in the country and the lack of a really organized State. This situation complicated the rescue operation and prevented saving part of the injured. Nevertheless, one positive aspect of the country's poverty was the presence in Haiti of international nongovernmental organizations (NGOs) that were able to quickly provide important help to the population. It has also to be noted that international help has been complicated by the fact that the rescue teams had to reach an island.

2.2. STRONG GROUND MOTIONS

During an earthquake strong ground motions cause severe damage to buildings when they are poorly built. For big earthquakes, the extension damage area depends on the length of the fault rupture. In other words, the damage extent depends strongly on the magnitude. For example, the rupture of a fault during an $M_w = 6$ earthquake is about 10-15 km long and 7-10 km wide. In the case of the Haiti event, this area becomes 65 km × 30 km (15 km on each side of the fault). Accordingly, the actual impact of the earthquake is related to the magnitude and to the population density and the vulnerability of the buildings in the region where strong ground motions are important.

The earthquake impact also depends on the tectonic context. In Haiti, if an earthquake occurs in the overriding plate, like the 12 January 2010 event, the seismic rupturing energy is directly released near the earth's surface. If a seismic event occurs along the thrusting zone at the subduction interface, the seismic waves must first propagate over a length of a few tens of kilometres through the upper crust before reaching the surface where their amplitudes will be less important, implying less catastrophic consequences.

Strong ground motions are also highly dependent on topography and local geologic structures. Moreover, sediment- and topography-induced amplifications are key factors in the distribution of damage during earthquakes. The sediment-induced effect is controlled by the impedance of near-surface layers and the depth to bedrock, with more amplification on less stiff soils and sediments (HOUGH *et al.* 2010). Topographic effects are due to energy focalization owing to typical geometrical setting of the deposits (fig. 4). These site effects induce non-linear, frequency-dependent amplification patterns both in amplitude and duration, leading to high and long-lasting accelerations.

For the Haitian event, there were about three million people living in the strongly shaken area, where structural damage was due to a great extent to poor construction and site effects. As expected, the ground accelerations on the soft sediments in the northern part of Port-au-Prince were twice those experienced on firm rock. More surprising are the strongest ground motions which did not occur on soft sediments but on the foothills which part of the city is built on. HOUGH *et al.* (2010) evidenced a striking correspondence between damage severity and topography. They showed that topographic amplification effects are likely to be significant on any narrow, steep ridges, and can be equally or more important than amplification by shallow sedimentary layers.

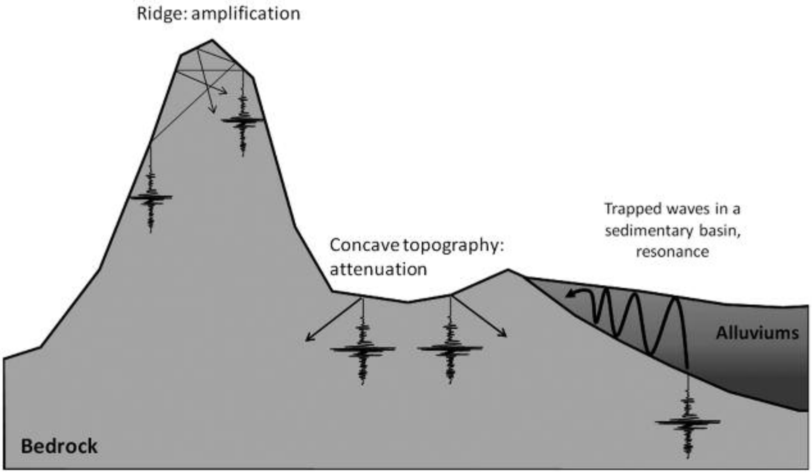

Fig. 4. — Site effects induced by topography and the low consolidated surface sediments, which modify the duration, amplitude and frequency content of seismic waves (redrawn from Zacek 1996).

2.3. Building Poorness

In principle, earthquakes do not kill people, buildings do. In Port-au-Prince most buildings are poorly built: insufficient proportion of cement, dirty, salty beach sand, rounded pebbles, lack of steel and poor design. Paraseismic construction, however, is not only a question of high technology, but mainly of good building practice. A good example is the way the stirrups are placed in concrete beams (fig. 5). Provided they are correctly installed, the stirrups can prevent a beam from bending outwards and exploding. By providing a few simple construction principles (*e.g.* at school), fatal design mistakes can easily be avoided in constructions.

In Haiti and elsewhere, if buildings are not made earthquake-resistant, the toll illustrated on figure 3 is likely to keep on rising as cities grow in population. Cities like Teheran, Istanbul, Kathmandu and Srinagar are notable for their seismic settings and the uneven application of appropriate building codes. The question is not whether, but when an earthquake shakes these cities (Bilham 2010a).

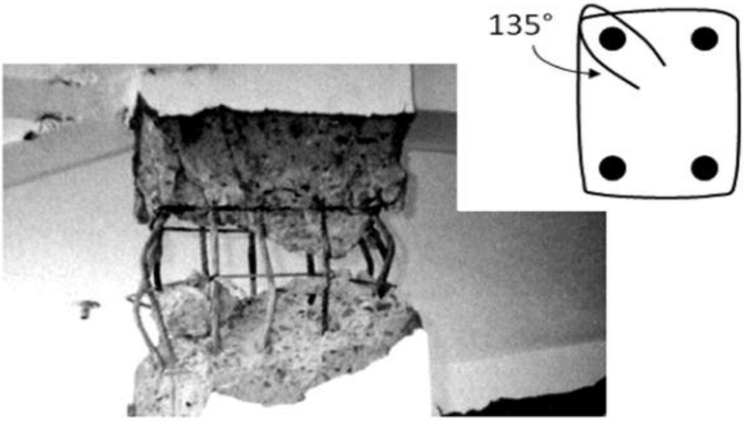

Fig. 5. — Effect of weak stirrups: they are not only in place simply to hold the steel rods in place when pouring the concrete, but especially to prevent longitudinal bars from bending outwards. The interval, size and shape (closed loops so that the stirrups do not open during shaking, see inset) of the stirrups are important parameters when designing paraseismic buildings (Picture © Auroville Earth Institute).

3. Perspectives

When the earthquake occurred, Haiti was the only country with an earthquake history without any detection equipment; the only seismometre was installed in a school as a teaching tool. While such equipment could not prevent an event from occuring, it would have allowed to know more about the seismic activity and contribute to mapping unknown faults and investigating the sites effects, which amplify the destructive seismic waves. Today, Eric Calais, a geophysicist at Purdue University, Indiana, leading the UN disaster risk reduction programme in Haiti, has found funding to install six seismic stations and about ten accelerometres (E. Calais, interview by Jones, *Nature*, 2010). Some young Haitians also benefit from grants, allowing them to study seismology. This will provide local talent able to keep the seismic network alive, to establish a nationwide hazard map, to ensure that good building codes are applied and more generally, to participate in the earthquake education of Haitians. Overall, beyond earthquake science, building a scientific and technical capacity is more than just a matter of training. It involves supporting a culture of curiosity and innovation and resources (Lerner-Lam 2010). Belgian development cooperation is already supporting projects oriented towards the geotechnical field in Haiti. They should be continued with the purpose of developing a real experience on how to reduce effectively the impact of geological hazards.

4. Conclusion

The tragic earthquake of Haiti illustrates the behaviour of society in relation to natural catastrophes and their mitigation. As usual, risks are ignored by everybody but a few scientists, until the deadly event occurs. This is especially true for earthquakes, because the return period of big earthquakes, even in active seismic zones, is about one or several centuries. This means that previous earthquakes are beyond living memory, so much so that whole populations and the authorities are unaware of the threat. In other words, they forgot about previous destructions and the possible safety regulations, which were applied at the time of the previous earthquake.

It is also well understandable that public authorities, even if they are able to sustain the challenges of society, have to solve short-term socioeconomic problems requiring most of their care and action. Consequently, they often ignore the prevention of possible natural disasters and the apprehension of scientists. They hope that the catastrophic event will not occur and if it occurs, they consider it as a fatality and try to manage it at best.

In Haiti, when looking at the amount of money spent for emergency management and reconstruction at the time of and after the earthquake, a question is to know whether such an amount might have been possible to decrease significantly the number of victims and destructions by adequate prevention. Of course, Haiti is one of the poorest countries in the world, with consequently a chronic weakness in the state organization. In this case, first prevention is of course a stronger support for country development. It is also essential that rebuilding the Port-au-Prince area follows criteria to prevent the effects of future earthquakes but also of other potential natural hazards, like hurricanes. These actions include the definition of building measures adapted to the regional context, an urban planning taking into account soil conditions and an adequate apprenticeship of all the actors involved in the building business. Financial backers should consider these issues if they want present generosity not to be limited to one shot that risks being obliterated at the next natural catastrophic event.

ACKNOWLEDGEMENTS

We thank Eric Calais, Roger Bilham and *Nature Geoscience* for giving permission to use their figures, and Koen Verbeeck for editing the text.

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